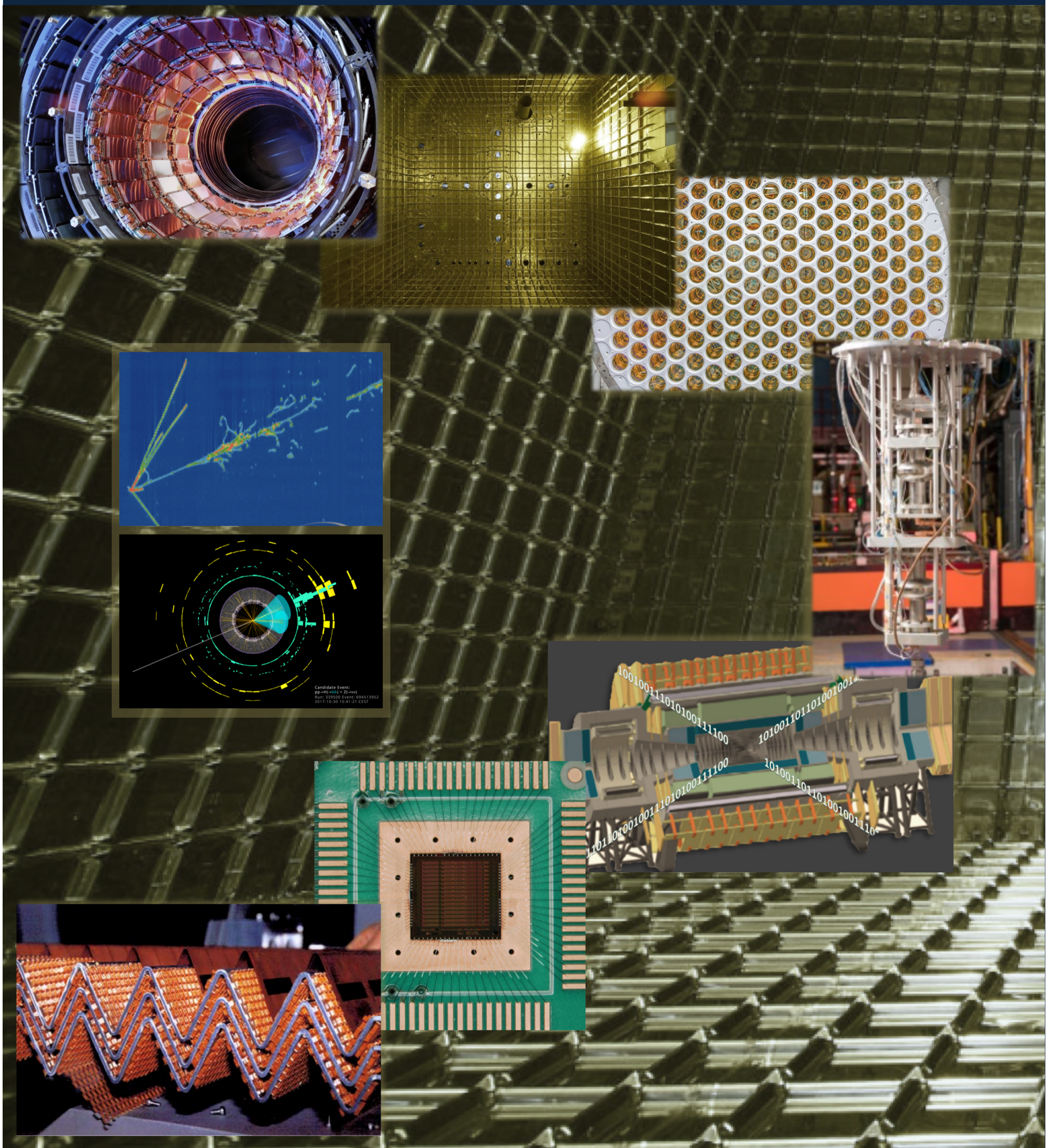
Basic Research Needs for High Energy Physics Detector Research & Development



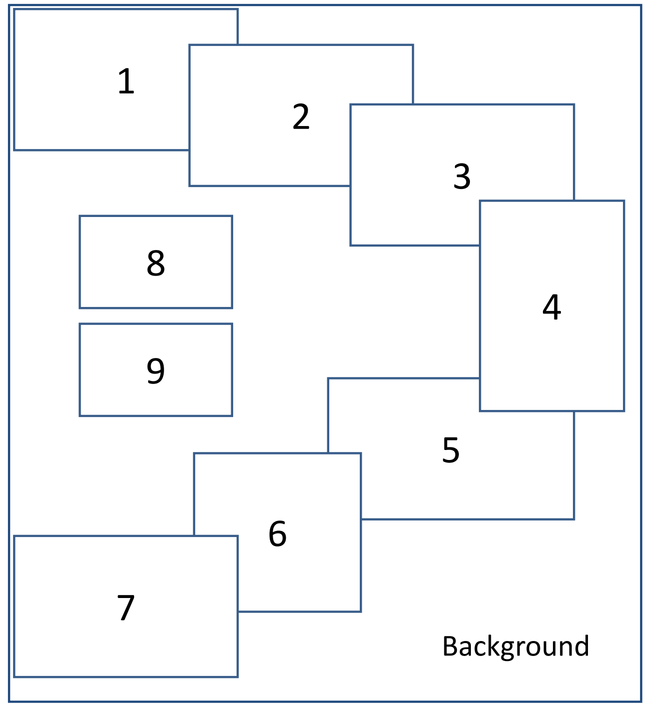
Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development

December 11-14, 2019

Background image: The ProtoDUNE detector at CERN is a 10x10x10-metre Liquid Argon Time Projection Chamber that can hold 800 tonnes of liquid argon (photo credit: CERN).

1. The Compact Muon Solenoid solid state silicon tracker at the Large Hadron Collider at CERN (photo credit: CERN).
2. ProtoDUNE. is a prototype of the future Deep Underground Neutrino Experiment (DUNE) detector, at the Sanford Underground Research Facility, South Dakota (photo credit: CERN).
3. An array of photomultiplier tubes for the LUX-ZEPLIN dark matter search experiment at the Sanford Underground Research Facility, South Dakota (photo credit: Matt Kapust/SURF).
4. Niobium cavities used in the Dark SRF dark photon search experiment at Fermilab (photo credit: A. Grasselino/Fermilab).
5. Next generation experiments at a future high energy circular hadron collider will produce raw data rates from their detector systems approaching an exabyte per second (a million terabytes per second) that will need to be processed in real-time (image credit: CERN modified for this report).
6. A readout Application Specific Integrated Circuit LArASIC designed for wire readout of Liquid Argon TPCs and able to operate at temperatures as low as 77K (photo credit: Brookhaven National Laboratory).
7. The Liquid Argon Electromagnetic Calorimeter of the ATLAS experiment at the Large Hadron Collider at CERN (photo credit: CERN).
8. . A neutrino interaction in a Liquid Argon Time Projection Chamber (image credit: Fermilab).
9. An image of a proton-proton collision at the CERN LHC (image credit: CERN).

Basic Research Needs for
HEP Detector Research & Development



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Throughout this report, “Instrumentation” and “Detector R&D” are used interchangeably. Throughout this report, the terms "Particle Physics" and "High Energy Physics" (HEP) are used interchangeably when referring to the scientific discipline. HEP is also used to denote a program, project, experiment, facility or institute funded in part or in whole by the Office of High Energy Physics of the Department of Energy.

DOE Basic Research Needs Study on High Energy Physics Detector Research and Development

Contents

1 Executive Summary

Transformative discovery in science is driven by innovation in technology. Our boldest undertakings in particle physics have at their foundation precision instrumentation. To reveal the profound connections underlying everything we see from the smallest scales to the largest distances in the Universe, to understand its fundamental constituents, and to reveal what is still unknown, we must invent, develop, and deploy advanced instrumentation.

Investments in High Energy Physics (HEP) enabled by instrumentation have been richly rewarded with discoveries of the tiny masses of the neutrinos, the origin of mass itself: the enigmatic Higgs boson, and the surprising accelerating expansion of the Universe. What we have learned is remarkable, unexpected, exciting and mysterious; raising many new questions waiting to be answered. The quest to answer them drives innovation that improves the nation's health, wealth, and security, inspiring the public and drawing young people to science. Excellence and innovation come most effectively from diverse teams of people. Success, therefore, depends critically on attracting, engaging, and supporting a diverse cadre of young people to the field, and ensuring an inclusive environment at all levels.

The program laid out in the 2014 Particle Physics Projects Prioritization Panel (P5) report "Building for Discovery - A Strategic Plan for U.S. Particle Physics in a Global Context" guides current and near future experiments to exploit these and other discoveries, and the instrumentation innovation they require, to push the frontiers of science into new territory. To explore this territory HEP will soon embark on planning the next generation of experiments. Realizing these experiments will require giant leaps in capabilities beyond the instrumentation of today. Accordingly, now is a pivotal moment to invest in the accelerated development of cost-effective instrumentation with greatly improved sensitivity and performance that will make measurable the unmeasurable, enabling a tool-driven revolution to open the door to future discoveries. Historic scientific opportunities await us, enabled by executing the instrumentation research plan outlined here.

In this report we summarize the need for new technologies in terms of four Grand Challenges. The technologies envisioned to address them are described in the body of the report. The Grand Challenges are:

1. **Advancing HEP detectors to new regimes of sensitivity**
2. **Using integration to enable scalability for HEP sensors**
3. **Building next-generation HEP detectors with novel materials and advanced techniques**
4. **Mastering extreme environments and data rates in HEP experiments**

These can be addressed only on the foundation of a diverse, highly trained, and advanced workforce, access to unique capabilities and facilities, deep connections to the programs of other offices in DOE, other federal agencies, commercial partners, and global collaborations.

The technical teams building today's experiments include professional engineers highly experienced in microelectronics design, advanced mechanical design, computing and data acquisition as well as scientists from HEP, Basic Energy Sciences (BES) and other Science, Technology, Engineering and Mathematics (STEM) disciplines. These experts, in turn, educate the next generation in advanced HEP instrumentation techniques and development transforming not only HEP but other fields too. These young STEM professionals go on to careers in a wide range of areas of today's high technology economy including academia, physics-based and big-data analytics, nuclear medicine, national security, and finance.

Addressing the Grand Challenges requires access to unique capabilities and facilities. Access to advanced microelectronics design tools and semiconductor foundries is critical as the use of application specific integrated circuits (ASICs) is ubiquitous in HEP instrumentation. In addition, unique irradiation facilities, test beams, characterization facilities, low background, and low-temperature facilities are crucial for preparing and testing the detector systems used in HEP.

The HEP community has been an important contributor to broadly applicable innovation in instrumentation, from the invention of the World Wide Web to advances in MRI, PET scanners and detectors for X-ray science. The instrumentation plan described here will lead to the development of new technologies that hold the promise to be as broadly applicable and equally transformative.

New investment in basic research and instrumentation is essential to meet the Grand Challenges outlined in this report. If history is our guide, these investments will lead to paradigm-changing discoveries and transformative applications for the benefit of humankind.

Organization of the Report

The BRN Study and this report are organized as follows. Section 2 introduces the field of HEP instrumentation. The physics motivation to pursue instrumentation and the Grand Challenges are described. We next state the deep commitment of the HEP community to the principles of Equality, Diversity and Inclusion in HEP Instrumentation R&D. These principles equate to excellence. The HEP instrumentation development ecosystem, connections to other science disciplines and benefits to Society, and how this report relates to the national and global particle physics programs conclude Section 2.

The BRN Study structure diagonalises the field of HEP instrumentation first by physics and then by technology. The physics diagonalization identifies physics objectives and the Technical Requirements (TRs) to meet them. The technology diagonalization determines the Priority Research Directions (PRDs) and actionable Research Plans to meet the TRs. This structure was chosen to most effectively address the charge.

Explicitly the structure consists of five Physics Panels one for each of the five Science Drivers as laid out in the 2014 P5 report. These Science Drivers lay out a 10 year plan with a 20+ year vision for particle physics experiments. The Science Drivers are: the Higgs as a tool for discovery, the physics of neutrino mass, the new physics of dark matter, cosmic acceleration: inflation and dark energy, and exploring the unknown: new particles, new interactions and physical principles. The seven Technology Panels in alphabetical order are: Calorimetry, Nobel Liquids, Photodetectors, Quantum Sensors, Readout and ASICs, Solid State (including vertexing and tracking), and TDAQ (including Machine Learning).

In Section 3 each Physics Panel identifies the physics objectives associated with a Science Driver and the TRs to meet them. In Section 4 each Technology Panel determines PRDs each with research Thrusts and actionable Research Plans to meet the TRs. The four Grand Challenges summarize the 26 PRDs (as illustrated in Table 1). This structure and flow is described by the Venn Diagram of Figure 1.

A Cross-cut Panel identifies connections and synergies between and across the Physics and Technology Panels as well as foundational issues for the Panels in Section 4.8. The current and needed future facilities to accomplish this program are described in Section 5.

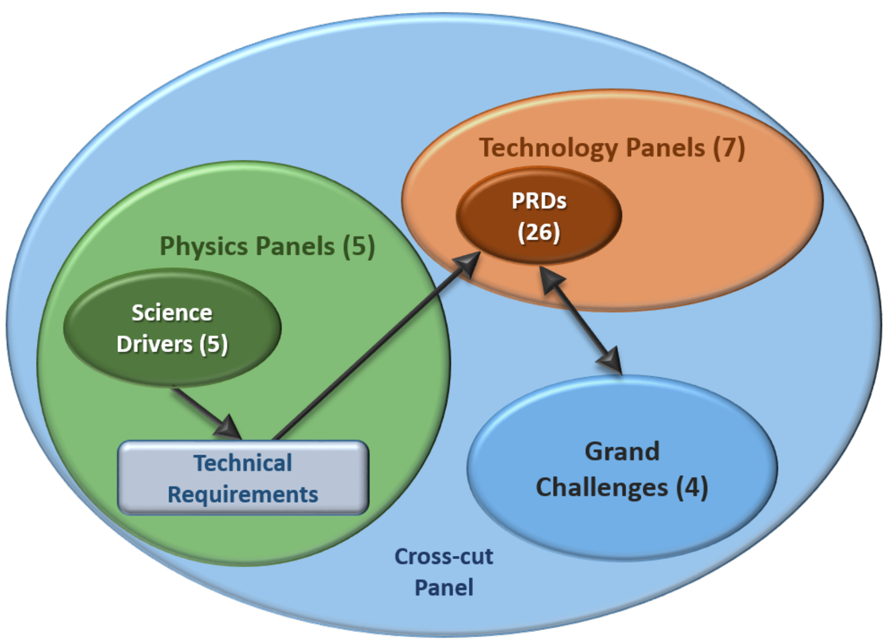

Figure 1: Structure and flow of the report. Five Physics Panels define Technical Requirements (TRs) to address the Science Drivers. Seven Technology Panels define Priority Research Directions (PRDs) motivated by the TRs. The PRDs are summarized by 4 Grand Challenges. One Cross-cut Panel looks across all areas.

	PRD: Priority Research Direction	Grand Challenge
Calorimetry	PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	1
	PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	1,4
	PRD 3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors	1,3,4
Nobles	PRD 4: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity	1,2
	PRD 5: Develop new modalities for signal detection	1
	PRD 6: Improve the understanding of detector microphysics and characterization	1
Photodetectors	PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity	1,3
	PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties	2,3
	PRD 9: Adapt photosensors for extreme environments	2,4
	PRD 10: Design new devices and architectures to enable picosecond timing and event separation	1,2,4
	PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection	1,2,3
Quantum	PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit	1,3
	PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics	1,2
	PRD 14: Advance the state of the art in low-threshhold quantum calorimeters	1,3
	PRD 15: Advance enabling technologies for quantum sensing	1,2,3
ASIC	PRD 16: Develop process evaluation and modeling for ASICs in extreme environments	3,4
	PRD 17: Create building blocks for Systems-on-Chip for extreme environments	1,4
SolidState	PRD 18: Develop high spatial resolution pixel detectors with precise high per-pixel time resolution to resolve individual interactions in high-collision-density environments	1,4
	PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	2,3
	PRD 20: Realize scalable, irreducible-mass trackers	2,3
TDAQ	PRD 21: Achieve on-detector, real-time, continuous data processing and transmission to reach the exascale	2,4
	PRD 22: Develop technologies for autonomous detector systems	2
	PRD 23: Develop timing distribution with picosecond synchronization	1
Xcut	PRD 24: Manipulate detector media to enhance physics reach	1,3
	PRD 25: Advance material purification and assay methods to increase sensitivity	1,2,3,4
	PRD 26: Addressing challenges in scaling technologies	2,3

Table 1: Priority Research Directions (PRDs) by technology in the order in which they appear in the report, and their mapping to Grand Challenges. Their order does not reflect any prioritization. (Xcut denotes Cross-cut PRDs that are common to many technologies important for HEP).

2 Introduction

The field of particle physics can look back to monumental achievements in explaining the natural world from the smallest to the largest scales. It reveals the profound connections between everything we see on this wide range of scales. Exploring the fundamental constituents of matter and energy has led to the development of the Standard Model of particle physics, a remarkable achievement that describes natural phenomena in some cases to a precision up to one part in ten billion. This is complemented by the development of the Standard Model of cosmology that has been very successful at describing nature at the largest length scales. Investments over the past five decades were rewarded with discoveries of the non-zero mass of neutrinos, the acceleration of the Universe's expansion, and the particles that verified the Standard Model of particle physics (the top quark and the W, Z, and Higgs bosons, the latter being the first and only scalar fundamental particle). Current experiments exploit these and other discoveries and push the frontiers of science into new territory at the highest energies and earliest times imaginable. Contemporaneously, these breakthroughs have revealed significant limitations in our understanding of the observed Universe. The matter-antimatter asymmetry of the Universe is not explained by the known properties of the Standard Model particles. Furthermore, the relatively low value of the Higgs mass, the inference of the existence of dark matter, and the perplexing value of the dark energy density are strong hints that new physics awaits discovery. The successes and challenges of research in particle physics inspires young people to engage with science.

The current U.S. particle physics program has been guided by the strategic plan laid out in the 2014 Particle Physics Project Prioritization Panel (P5) report "Building for Discovery - A Strategic Plan for U.S. Particle Physics in a Global Context". The P5 plan for the subsequent decade of U.S. particle physics was based on a year-long community-wide study, Snowmass 2013, and a nearly year-long P5 process. With this comprehensive effort by the broad community, P5 identified five compelling lines of inquiry, the five intertwined Science Drivers, that show great promise for discovery over the next 10 to 20 years:

- **Use the Higgs boson as a new tool for discovery**: By measuring the Higgs boson interactions with the other Standard Model particles to percent-level precision, new physics can be explored at energy scales that are well beyond the beam energies of contemporary accelerators. Studying the Higgs self-interactions can verify what causes the Higgs field to produce the masses of the other fundamental particles. The search for Higgs boson decays to undetected ("invisible" or "dark sector") particles may reveal critical clues that unlock the mystery of dark matter.

- **Pursue the physics associated with neutrino mass**: Propelled by surprising discoveries from a series of pioneering experiments, neutrino physics has progressed dramatically over the past two decades. A diverse research program exploiting particle astrophysics, accelerator, and reactor experiments has uncovered a new landscape in neutrino physics with a very promising future for continued discovery. Powerful new facilities are needed to probe many aspects of the puzzling and experimentally incomplete picture of neutrino physics.

- **Identify the new physics of dark matter**: Astrophysical observations imply that the known particles of the Standard Model make up only about one-sixth of the total matter in the Universe. The rest is dark matter, presumed to be particles that are all around us and are passing through the Earth. Dark matter represents a bizarre shadow world of fundamental particles that are both omnipresent and largely imperceptible. Discovery of the identity of Dark matter would transform the field of particle physics, advancing the understanding of the basic building blocks of the Universe.

- **Understand cosmic acceleration: inflation and dark energy**: The study of the origin and evolution of the Universe indicates the existence of two periods during which the expansion of the Universe accelerated. A primordial epoch of acceleration, called inflation, occurred during the first fraction of a second of existence. A second distinct epoch of accelerated expansion began more recently and continues today. The cause of these periods of expansion of the Universe is unknown but most likely involves new physics. Resolving these mysteries could fundamentally alter our understanding of the makeup and working of the Universe.

- **Explore the unknown: new particles, interactions, and physical principles**: History has shown that new physics appears in surprising and unexpected venues. A broad-based strategy, employing high-energy colliders, precision measurements, searches for rare processes, and the study of cosmic and low-mass particles, provides the greatest potential for both explaining current mysteries and for revealing new surprises.

Success in addressing these science endeavors depends critically on instrumentation. Along with the five Science Drivers, the 2014 P5 report identifies the importance of Instrumentation R&D in one of its highest level recommendations where it calls for a "balanced mix of short term and long-term R&D" in the current era.

The physics section of this report is organized around these five lines of inquiry prioritized by P5, focusing on the science opportunities expected to be the center of the particle physics program after completion of the present round of experiments operating or under construction. The new projects lead to Technical Requirements (TRs) that can be addressed by technologies spanning seven instrumentation sub-fields and this determines the organization of the technical section of the report. The work in each instrumentation sub-field leads to Priority Research Directions (PRDs) divided into actionable research Thrusts and associated Research Plans. In addition, timelines are provided for both the potential new physics experiments and the required technical work in the physics section of the report. In this report we summarize the need for new technologies in terms of four Grand Challenges. A map between the Grand Challenges and the PRDs by technology in order of appearance in the text is provided in Table 1.

2.1 Grand Challenges in Advanced Detector R&D

Recently, resources have been focused toward directed instrumentation R&D for the nearer-term high-priority projects as identified in the P5 report, which will make progress on key physics questions, but leave many questions to be answered. With the technical challenges of the immediate projects being met, the focus needs to turn towards the development of innovative instrumentation that has the potential to be disruptive to provide answers to some of the most fundamental questions about the nature of energy, matter, space, and time.

Now is a pivotal moment to accelerate advancing our understanding of the natural world through instrumentation development that will enable a tool-driven revolution to open the door to future discoveries. A rich spectrum of challenging physics experiments is being conceived that requires advances in instrumentation that make measurable what currently is unmeasurable. In order to achieve these scientific goals a robust program in advanced detector R&D is vital. Many of the experiments envisioned today require significant advances in technology including orders of magnitude more precision and sensitivity, vastly improved radiation tolerance, real-time on-detector data processing to manage the vast amounts of data the detectors will produce, and orders of magnitude lower background. It is only through investments in the development of advanced, cost-effective new technologies that the science goals can be met. Historic opportunities await us, enabled by carrying out the research plan outlined in this report.

The research plan is summarized in four Grand Challenges:

- **Advancing HEP detectors to new regimes of sensitivity**
  Future HEP detectors will probe nature at unprecedented levels of precision to identify the tiniest of signals. To make the unmeasurable measurable will require the development of sensors with exquisite sensitivity with the ability to distinguish signal from noise. These sensors and networks of sensors will be based on emerging and future technologies, exploiting improvements in, e.g., light or charge collection efficiency, time resolution and synchronicity, or exploiting quantum superposition, squeezing, and entanglement. Research will be needed to develop these sensors with maximal coupling to the quanta to be sensed and push their sensitivities to ultimate limits.

- **Using integration to enable scalability for HEP sensors**
  Future HEP detectors for certain classes of experiments will require massive increases in scalability to search for and study rare phenomena. Increases are projected for the size of the detectors, the granularity and precision of the readout elements, and the energies of the particles to be measured, to name a few. Research and development will be needed to demonstrate scalability of innovative sensor technologies to real detection systems. A key enabler of scalability is integration of many functions on, and extraction of multidimensional information from, these innovative sensors.

- **Building next-generation HEP detectors with novel materials and advanced techniques** Future HEP detectors will have requirements beyond what is possible with the materials and techniques with which we are familiar. Meeting these challenges will require identifying novel materials that provide new properties or capabilities and adapting them to our needs as well as taking advantage of advanced techniques for design and manufacturing.

- **Mastering extreme environments and data rates in HEP experiments** Future HEP detectors will involve extreme environments and exponential increases in data rates to explore elusive phenomena. Very high radiation doses, extraordinarily low temperatures, and environments incredibly pure in isotopic composition, pose enormous challenges that require engagement with allied fields such as materials science, chemistry, and engineering. Exabyte per second data-rate environments will require real-time analysis at the sensor, rendering the signal patterns into an accurate map of the physics processes that have taken place reducing the data volume by many orders of magnitude. To do so requires the intimate integration of intelligent computing with sensor technology.

2.2 A Commitment to Equality, Diversity and Inclusion in HEP Instrumentation R&D

HEP Instrumentation has long been a field in which women, and even more so, people of color, have been underrepresented, even when compared to the broader HEP community. This must change to enable the best possible science and instrumentation development, to engage and train a diverse workforce that will have impacts in and beyond particle physics, and for the good of society as a whole.

Innovation is often driven by "out of the box" thinking. New ideas best arise in diverse teams of people approaching problems from different directions. Support for diverse teams and novel ways of thinking will lead to Instrumentation development in particle physics, and naturally have impacts far beyond. To accomplish the best science, we must commit, as a community, to action, to overcome the social injustices in our own backyard, and realize the impact of a diverse workforce. We must find, develop, and invent new ways to attract, encourage, recruit, and support a diverse community. We must enact an inclusive environment within instrumentation and within particle physics at all levels and across the areas in which we work and that we touch including academia, in universities and national laboratories, and in industry.

Although very far from sufficient some small steps are being taken to draw young people from diverse backgrounds to instrumentation. Outreach programs by our national laboratories and our universities introduce the k-12 population to particle physics and the unsolved mysteries of the Universe. These great unanswered questions draw young people to particle physics and science more generally. The accelerators and detectors of particle physics fill the k-12 population and the public with wonder and awe and the curiosity to learn more, see Figure 2. We must build much more than in the past on this platform. The NSF Research Experience for Undergraduates program gives many young people from non-intensive research institutions the opportunity to participate in summer research programs at research-intensive institutions. At the graduate level the DOE OHEP has created, jointly with the American Physical Society Division of Particles and Fields Coordinating Panel for Advanced Detectors (CPAD), the Graduate Instrumentation Research Awards see Figure 3 and the DPF following an initiative by CPAD has created instrumentation awards recognizing young scientists see Figure 4 The scale of these initiatives must be dramatically increased and new initiatives developed with urgency.

2.3 The HEP Instrumentation Development Ecosystem

The field of high energy physics expands the boundaries of our understanding of the origin and evolution of matter and its fundamental interactions. The tools to engage in this endeavor rarely exist commercially and the field has historically developed the technologies and instruments itself required to carry out the experiments. Due to the unique nature of the projects and their complexity, this has been done in a collaborative way with other science disciplines and industry and has led to the field being an important contributor to broadly applicable innovation in instrumentation. The detector research and development envisioned in this report for the next generation of experiments will be even more demanding and multi-disciplinary and will require the training of students and experienced scientists in challenging technical areas.

Figure 2: Three teenagers examining the Compact Muon Solenoid silicon tracker test stand at CERN with an image of the Crab Nebula in the backgound. Photo credit: Michael Hoch (CERN).

Three areas are highlighted here to ensure success: the development of an appropriate and diverse workforce, university national lab partnerships, and access to shared infrastructure and unique facilities.

2.3.1 Workforce Development and Support

The detector effort envisioned in this report will require the training of students and experienced scientists in challenging technical areas. A broad range of expertise will be required ranging from electronics and computer science to technical teams that include professionals in data acquisition, mechanical engineering, cryogenic systems, composites design and fabrication, micro-fabrication and assembly, analytical chemistry, materials science, and many other fields. Excellence in the next generation of instrumentation depends on excellence in the next generation of inventors. The pipelines in these areas must train a diverse group, tapping into, and training our best talent across a diverse group. Given the increasing multi-disciplinary nature of the research, these interdisciplinary teams will be vital to the success of an advanced detector R&D programs and will only become more essential in the future to deal with the increasing challenges expected. It will be critical to maintain and augment the technical staff contributing to particle physics. An important aspect of engaging and maintaining relationships with this diverse, multi-disciplinary workforce is providing appropriate recognition and funding opportunities so that they feel fully engaged as part of the community and not merely a resource to be tapped. The advanced detector and accelerator R&D portfolios in HEP are the ideal avenue for providing these opportunities to more fully embrace our interdisciplinary team members who often bring many years of experience and have been key to building all aspects of detectors now existing or under design. A significant fraction of this new workforce will enter the U.S. and world labor market as highly skilled and sought-after professionals. The high energy physics ecosystem, with its use of cutting-edge technologies in an international collaborative setting, hones expertise in areas from project management to data analysis to high-speed communication to visualization. These abilities readily find a home outside HEP, mostly in the broader high-technology economy but also within government entities such as the nuclear

Figure 3: A photo of the award winners and honorable mentions in the DOE Graduate Instrumentation Award 2018. Left to Right Vetri Velan (UC Berkeley), Carolyn Gee (UC Santa Cruz), Peter Madigan (UC Berkeley), Dylan Temples (Northwestern) and Qing Xia (Yale).

Figure 4: Recipients of the DPF Instrumentation Awards 2019. Left to Right Hanguo Wang (UCLA), Ettore Segreto, and Anna Amelia Machado (both of the University of Campinas in Brazil).

nonproliferation security administration and the stockpile stewardship program.

2.3.2 University and National Lab Partnerships

There is tremendous value in nurturing a close partnership between universities and national laboratories. The national laboratories, with their unique expertise and unparalleled user facilities, provide an infrastructure that is indispensable to develop the future workforce. Some laboratories have distinct expertise motivated fundamentally by their missions; NIST, for example, advances metrological standards, which often lie at the intersection of pure science and technology development. While some universities have significant infrastructure and expertise it is difficult for most universities to match the infrastructure and expertise that is found at national laboratories. Moreover, many universities experience challenges maintaining full-time engineering or research scientist staff given the ebb and flow of projects and their associated funding. On the other hand, it is exactly the universities that provide the pipeline of students and postdocs who will constitute the next generation of scientists. Strong support for university-laboratory partnerships will be of tremendous benefit for advancing technologies for all sciences.

2.3.3 Facilities and Capabilities

A multitude of unique facilities and capabilities underpin the advanced detector R&D program. These facilities encompass ultra-low temperature experimental setups and facilities that enable characterization of materials and electronic components after having been exposed to large doses of radiation. It is critical that these core facilities continue to be supported and that new capabilities required for testing and evaluation of detectors for future experiments be created and maintained. Many facilities are synergistic with other experimental disciplines. The development of utral-low-temperature electronics is a high priority area of research for certain quantum computing technologies. Studies of materials under extreme conditions is shared with the plasma physics and stockpile stewardship programs. Given that the design of highly advanced application specific integrated circuits is essential to high energy physics, access to foundry capabilities, especially those with a research line, is also vital. Given the highly specialized nature of some of these capabilities and the large cost to establish and operate some of these facilities, this is a national priority. Some facilities can be viewed in an international context, where capabilities elsewhere in the world can be brought to bear to advance instrumentation. These facilities provide unique opportunities for training students and young researchers. They also train the technical experts needed to design, build and operate such facilities. A careful balance of reliance on international facilities versus domestic facilities is required. An overview of the facilities and capabilities required is presented in Section 5.2.

2.4 Connection to Other Science Disciplines and Benefits to Society

HEP shares with other basic sciences the need to innovate, invent, and develop tools, techniques, and technologies to carry out its mission to explore the nature of matter, energy, space and time. From the earliest days of HEP in the 1930s to the latest 21st-century initiatives, the field's bold and innovative ideas and technologies have not only advanced the current state of technology for HEP but have also enabled basic scientific research and applications in numerous other areas and have entered the mainstream of society, transforming the way we live. This strong interplay between research developments in HEP and in other scientific and technical disciplines has been broadening and strengthening over the past decade. We foresee the need to continue the expansion and strengthening of these relationships over the coming decades to enable the HEP mission and maximize the benefit of HEP to society.

2.4.1 Historical Context

Selected examples illustrate a long and growing list of beneficial practical applications with origins in HEP as well as ways in which HEP has benefited tremendously from advances in other areas of science (see [1] and references therein and Figure 5).

- The development of superconducting materials by the materials science community drove nuclear and particle physicists to adopt superconductivity for particle accelerators [4].
- Techniques used in the construction of pixel detectors for high-performance particle tracking led to the industrialization of interconnect technology used in the automotive industry.
- New crystal growth methods developed for particle detectors later found use in a large commercial market for these crystals in medical imaging (see Figure 6) [5].
- Semiconductor-based charged-particle track-detection technology from collider experiments has become a key tool at light-source facilities and is finding its way into national security applications for detecting undeclared production of special nuclear materials [6].
- There is, more broadly, a 50-year history of collaboration between the nuclear monitoring and low-background physics communities, where technologies and techniques for detection of trace effluents from nuclear materials production and weapons tests are also well-matched to measurements of rare nuclear decay processes and searches for dark matter.
- HEP experiments that detect neutrinos have provided valuable data to other scientific fields: precise measurements of neutrinos from radioactive isotopes deep inside the earth have been enormously informative to geoscience, and neutrino detectors that detect light created in the Antarctic ice have provided to climate science the most clearly resolved measurements of Antarctic dust strata during the last glacial period and thereby enabled exceptionally detailed reconstruction of paleo-climate records [7].
- The HEP-developed software framework GEANT for simulation of interactions of particles and matter has been used broadly outside of HEP, including in medicine when quantifying particle interactions is important (see Figure 7) [8–10].

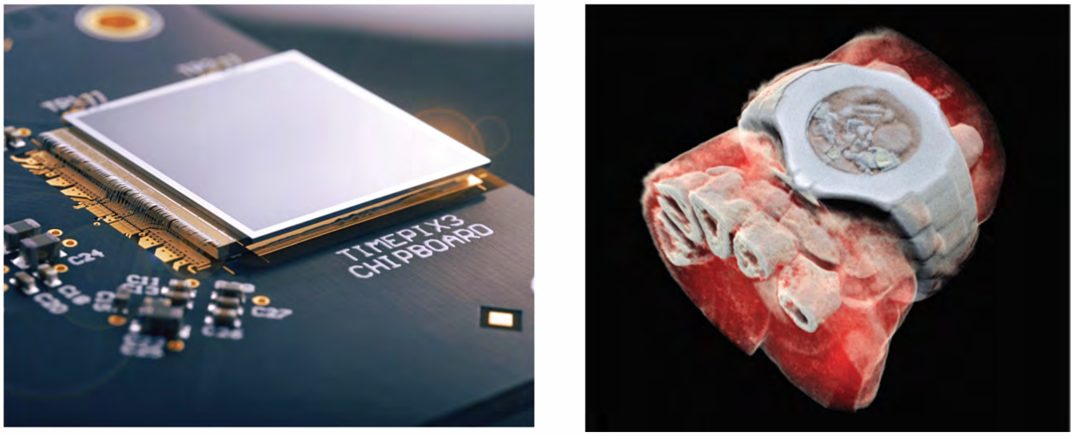

Figure 5: The development of large-area hybrid pixel detectors for high energy physics experiments quickly led to the realization of the potential of this new technology to provide noise-hit-free single-photon counting. Images could be recorded by processing photon-quanta one by one in a fully parallel manner in many thousands of cells with high spatial resolution. The Medipix collaboration was formed [2] creating a series of sophisticated integrated circuits with the most recent ones including timing information. The photo on the left shows an image of the Timepix3 chip (photo credit: CERN) and on the right is shown a 3D X-ray image of a wrist with a watch showing part of the finger bones in white and soft tissue in red (photo credit: MARS Bioimaging Ltd.) [3]. The circuit is being used in medical imaging, materials analysis, space dosimetry and climate studies among others

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- Optical methods developed by U.S. scientists for the accurate placement of silicon detectors for LHC experiments were adapted to enable non-destructive playback of the earliest audio recordings, bringing back to life a treasure trove of sounds and voices from that pioneering period in the late 19$^{\text{th}}$ century [11].

2.4.2 Current and Future Context

HEP provides not just technologies, techniques, and data to society more broadly but also training and expertise. Contributions in medicine and biology especially, are enabled not only by adaptation of HEP technology but also by contributions from personnel trained in the program. Examples in these fields are proton radiography, computed tomography, beam therapy and neural imaging. Moreover, the impact of HEP on society has been not just technological but also cultural. The introduction of the World Wide Web and web browsers by the HEP community is a particularly well-known case having both broad technological and cultural impact. We further substantiate the importance of these many types of interplay with six more detailed examples.

- In the realm of nuclear nonproliferation and national security, many HEP detector technologies and techniques are being applied to make the nation and the world safer, and those applications have also motivated the development of technology and expertise now being applied in HEP experiments. Without the advances made by HEP in the 1980s, it would not have been possible to develop and deploy the global International Monitoring System used to detect undeclared nuclear tests. Today's dark matter and neutrinoless double-beta decay experiments grew out of investments in detector R&D by the national security enterprise in the 1990s and early 2000s. The fully depleted, thick charge coupled device (CCD) technology developed by HEP for cosmological and astronomical survey applications beginning in the 1990s is being used to detect effluents from undeclared nuclear facilities. RF engineering challenges in the detection of wave-like dark matter are being addressed using expertise that was used to develop mm-wave body scanners deployed in airports.

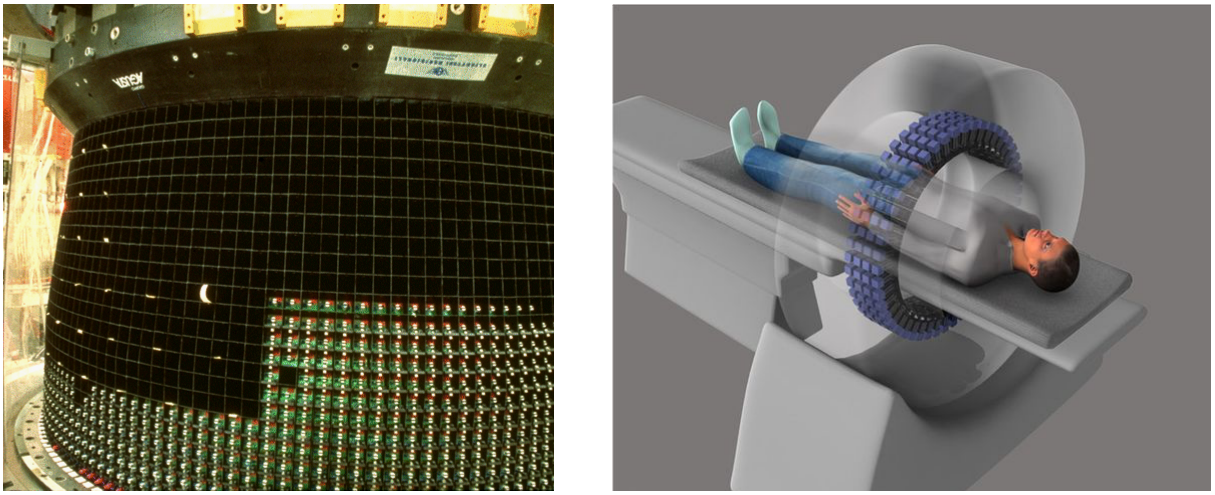

Figure 6: The development of the manufacturing process of BGO crystals for the calorimeter of the L3 experiment at the LEP collider at CERN (left) has contributed significantly to the advancement of Positron Emission Tomography (PET) scanners, illustrated in the right figure (photo credit: CERN and S.R. Cherry/U.C. Davis).

- In medicine, HEP instrumentation and expertise has been crucial to the use of proton beams for medical imaging and cancer therapy [12]. Because the ionization density due to protons and heavier ions peaks near the end of their range and has a sharp distal falloff beyond this peak, proton beams more precisely target cancerous tissue and cause less damage to healthy tissue along the beam than do X-rays and gamma rays. Planning the beam parameters requires a detailed image of the proton stopping power throughout human tissue, which is provided by proton radiography and computed tomography (pCT). HEP instrumentation has provided particle-detection and data-acquisition technology for several recent, successful prototype pCT and proton-radiography systems, and scientists trained in HEP technology are crucial to the development of these systems and the development of the accelerators to deliver the beams to the patients [13].

- HEP technology and techniques are having impact on not just medical applications but also fundamental biological research. Large-scale recording and simulation of neural activity are among the most important tools for discovering how our brain detects and processes information. Such efforts face technical challenges similar to those that confront HEP: signal levels are small, requiring low-noise readout electronics situated near the sensor; high sensor density and channel counts are required to fully sample neural activity; and the large data volumes require sophisticated data acquisition and analysis software. HEP expertise has been used to design, build, and test novel systems to address these challenges, leading to discovery of new neural pathways in the mammalian retina, improved knowledge of information processing in the retina, and detailed investigation of how visual and audio information is integrated by the brain. The development of new retinal prosthetic devices have been facilitated. Integration of optical techniques for interrogation of neural circuits is a new frontier in this work [14].

- Quantum Information Science (QIS) is a high priority research area for the nation, and that has led to support for a broad range of HEP-QIS collaborations. An early example consisted of an effort to apply quantum computing algorithms and systems to address data analysis challenges in HEP. This is now a burgeoning field. The historical overlap of materials science, condensed-matter physics and HEP detector technology provided a foundation for ongoing efforts to apply QIS platforms and techniques for HEP applications, especially for dark matter searches, both in the search for the spatially coherent effects of wave-like dark matter and in the detection of the ever-more-minute energy depositions of relevance for particle dark matter. HEP techniques are also being used to advance QIS, such as in the application of scalable HEP data acquisition and control architectures to enable QIS systems with large numbers of qubits and in efforts using HEP intellectual input (knowledge of the impact of ionizing particles) and techniques (particle detection and shielding) to test for potential sources of decoherence in QIS systems.

- Large data volumes are a problem common to HEP and many other fields. Collider experiments and astronomical surveys have to handle large data volumes in real time. To meet the data-sharing needs of the LHC experiments, U.S. LHCNet was launched, providing a high-performance network through the use of multiple links across the Atlantic and the U.S. The network was developed in cooperation with the U.S. Energy Sciences Network (ESnet) and in collaboration with Level 3 Communications, a leading international provider of fiber-based communications services, and Internet2, a U.S. advanced networking consortium led by the research and education community. The initiative has morphed into the world-wide LHC computing grid (WLCG) and has contributed substantially to the European Grid Initiative and the U.S.-based Open Science Grid, which facilitate access to distributed high-throughput computing and data for the whole scientific community. Such demanding applications have provided excellent training for HEP personnel, who permeate the field of commercial data science. Conversely, advances in artificial intelligence (AI) and machine learning (ML) may be crucial for handling the future challenge of exabyte-per-second data rates at the next high-energy colliders: in particular, implementing AI/ML in front-end readout systems may make it possible to limit data volumes at their source [1].

- A particularly pertinent example for today's world is the development of a video conferencing platform called the Virtual Rooms Videoconferencing System (VRVS). This system was developed to provide a low-cost, bandwidth-efficient means for videoconferencing and remote collaboration over networks within the high energy and nuclear physics communities. It went into production in 1997 and became quickly a standard part of the toolset used daily by a large sector of the HEP community. It expanded exponentially and was replaced in 2008 by the Enabling Virtual Organizations (EVO) system, built on an integrated software package that analyzed and processed network information in a distributed way for the LHC. The platform was broadly used by the community and was adopted by the company eZuce [15].

2.4.3 Building Relationships for the Future

Cutting-edge particle detectors are the hallmarks of particle physics research. As discussed above, many of the developments have been informed by science and technology advances from other disciplines. Strengthening and expanding these connections will enable the particle physics community to continue to discover innovative experimental pathways and create novel detector devices to explore the Universe. In return, developments within the particle physics community enable basic scientific research and applications in numerous other areas. This broad, connected scientific enterprise is only possible due to strong partnerships, not only between program offices within the DOE Office of Science, but also between the DOE and other funding agencies, in particular the National Science Foundation, between universities and national laboratories, and with industry.

To realize the ambitious goals of the field over the coming decades will require a period of increased R&D activity over a broad range of technical areas. The technology challenges for the field are sufficiently great that they will require participation of a significant fraction of the particle physics community. These challenges offer many opportunities for contributions but will require the development of organizational structures that foster collaboration within the U.S. and internationally. Participants working in specific technology areas should be organized across the country to maximize collaboration and input of ideas. A rotating leadership, chosen internally, should be instituted for each area with the goal of highlighting progress and fostering the next generation of new ideas. The participation should not be centered on a specific experiment but the potential for use of the technology should be an element guiding the choice of thrusts within each technology grouping. A National Laboratory could provide a home for each technology grouping. The CERN targeted

Figure 7: Voxelized image of a mouse based on the GEANT Monte Carlo software used in dosimetry studies for internal medicine.

R&D programs, which were created to address the experimental challenges of the LHC, have been very successful and provide a good model for how such programs can work. Other models such as the R&D consortia recently launched in the DOE-NNSA Office of Nonproliferation Research and Development are another example that might be followed. An expansion of the technological themes being addressed by focused consortia is needed to facilitate the instrumentation program outlined in this report.

2.5 The BRN Report and the National and Global Particle Physics Programs

The DPF Coordinating Panel for Advanced Detectors (CPAD) has the responsibility to promote excellence in the research and development of instrumentation and detectors to support the national program of particle physics in a global context. It has organized since 2015 a series of "New Technologies for Discovery" annual community workshops exploring and evaluating detector R&D opportunities and the critical needs and challenges of the field within the context of the P5 plan and beyond. These workshops and their reports have provide primary input for the assessment of the present state of the technology landscape relevant for HEP for this BRN. Among the many notable achievements of CPAD to date are the coordination of the Snowmass 2013 Instrumentation Frontier and its report [16], the creation of the DPF instrumentation awards, the creation of the DOE Graduate Instrumentation Research Award, the creation of an annual CPAD workshop and whitepaper "New Technologies for Discovery" [17] and the first truly interdisciplinary workshop on "Quantum Sensing for High Energy Physics" in 2017 and its report[18].

During the course of this BRN study the Division of Particles and Fields of the American Physical Society announced the year-long U.S. Particle Physics Community Planning Exercise "Snowmass 2021". This will be followed by a new meeting of the Particle Physics Project Prioritization Panel (P5). We encourage the particle physics community to build on the research plans presented in this BRN study by developing and refining them further and introducing and developing new instrumentation ideas during Snowmass 2021.

Particle physics is a global endeavor. Accordingly, the instrumentation R&D plan developed in this report exists in a global context. Recently the European particle physics community has completed an update of the European Strategy for Particle Physics (ESU) [19]. The ESU states: "Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels."

We agree with and support the stance the ESU articulates towards instrumentation. Furthermore, we encourage the U.S. particle physics community through the Snowmass process to play a role in the proposed global detector R&D roadmap exercise by contributing U.S. input. CPAD should continue to play an important role in developing this international roadmap and can be the vehicle for the realization of the program outlined in this report.

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3 HEP Science Drivers

The current U.S. particle physics program has been guided by the strategic plan laid out in the 2014 Particle Physics Project Prioritization Panel (P5) report "Building for Discovery - A Strategic Plan for U.S.Particle Physics in a Global Context". P5 identified five compelling lines of inquiry, the five intertwined Science Drivers, that show great promise for discovery over the next 10 to 20 years. The Science Drivers are: Use the Higgs boson as a new tool for discovery; Pursue the physics associated with neutrino mass; Identify the new physics of dark matter; Understand cosmic acceleration: inflation and dark energy; and Explore the unknown: new particles, interactions, and physical principles. This section is organized around these five lines of inquiry focusing on the science opportunities expected to be the center of the particle physics program after completion of the present round of experiments operating or under construction. The Physics Panels layout the physics objectives and measurements associated with the Science Drivers and the Technical Requirements needed to realize them. The Technical Requirements motivate the Priority Research Directions developed by the Technology Panels (see Figure 8).

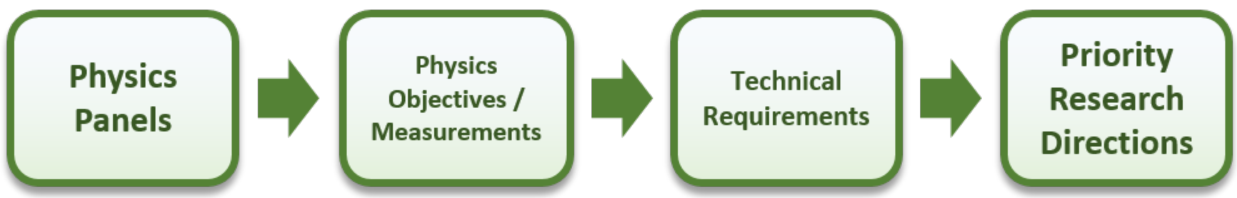

Figure 8: The Physics Panels layout the physics objectives and measurements associated with the Science Drivers and the Technical Requirements needed to realize them. The Technical Requirements motivate the Priority Research Directions developed by the Technology Panels.

3.1 Higgs and the Energy Frontier

3.1.1 Science Impact

The co-development of the theoretical description and experimental investigation of the electroweak sector of the Standard Model (SM), culminating with the 2012 discovery of the Higgs boson, ranks among humankind's most outstanding scientific achievements. Despite this great success, the electroweak sector of the SM remains puzzling. The naturalness principle suggests that the Higgs boson mass and its quantum corrections, which are related to the scale of potential new phenomena, should be of the same order. Instead, in the SM these quantities are found to differ by 17 orders of magnitude, indicating an extreme fine tuning of the theory. In addition to this theoretical peculiarity of the SM, the completeness of the SM is further challenged by experimental evidence for new phenomena beyond the SM (BSM), including the notable astronomically and cosmologically observed dark matter.

The next generation of energy frontier particle colliders and their associated detectors are ideal tools for studying both theoretical and experimental mysteries associated with the SM. On the one hand, heavy SM particles like the Higgs boson can only be studied through direct production at high-energy particle colliders, which by virtue of their high collision rates, allow scientists to achieve excellent precision for measurements of the properties of the Higgs boson, top quark, and electroweak bosons. On the other hand, while many experiments are currently striving to directly detect the dark matter permeating the galaxy via its deposition of minute signals in exquisitely sensitive detectors deep underground or indirectly detect dark matter through characteristic dark matter annihilation signals in the galactic halo, high-energy particle colliders provide a complementary opportunity to elucidate the nature of dark matter by producing it in high-energy collisions and measuring its properties in a more controlled environment. In this way, the next generation of ambitious, dual purpose, energy frontier particle colliders will address three of the five Science Drivers enumerated in the P5 report: using the Higgs boson as a tool for discovery; identifying the new physics of dark matter; and exploring the unknown including new particles, interactions, and physical principles.

Studies of the Higgs boson focus on making high precision measurements of the strength of the Higgs boson's interaction with other SM particles, with itself, and with potential new BSM particles. During the

Higgs and the Energy Frontier

The Energy Frontier of Particle Physics encompasses the construction and operation of high energy particle colliders and particle detectors in order to study the fundamental laws of nature at the smallest distances and highest energies. Energy Frontier research has two primary goals: First, high energy colliders are the only tools scientists have to produce and directly study previously unknown particles and phenomena. Second, high energy colliders allow scientists to make precise measurements of the behavior of the known particles and phenomena; by observing small deviations between these precise measurements and the expectation from our current theories, scientists are able to discover and study the influence of new phenomena indirectly. The former goal is similar to the discovery of the planet Uranus, which was achieved through direct observation with a new, powerful telescope. The second is similar to the discovery of the planet Neptune, the presence of which was first deduced not with a telescope but through precise observations of perturbations of the orbit of Uranus. In serving both purposes, the colliders and detectors of the Energy Frontier are simultaneously the ultimate direct discovery machines and precision measurement machines.

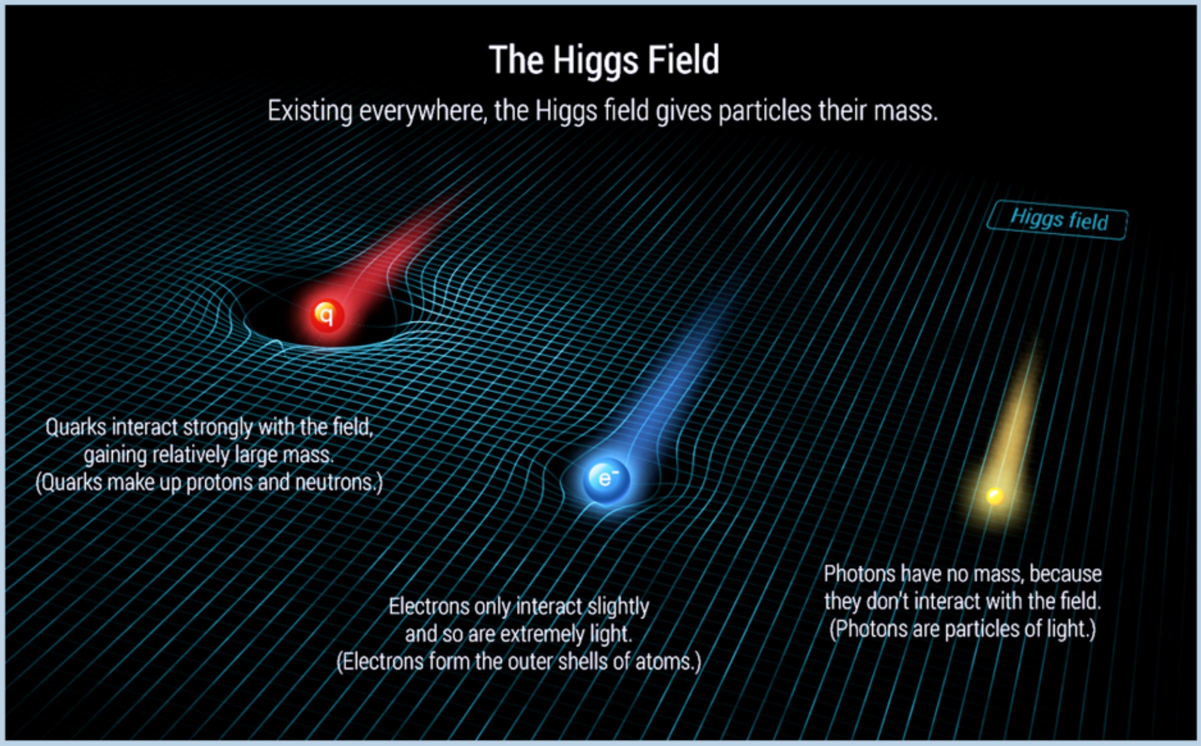

Figure I: The mass of a fundamental particle is related to the strength of its interaction with the Higgs field, which permeates all space. Image source: pindex.com

Since the 1960s, scientists have understood that the masses of particles could be related to the strength of their interaction with an unknown field permeating all of space (see Figure I) and that this field would have an associated particle that could be produced and studied at a particle accelerator, with the measured properties of the particle allowing scientists to understand the related field. In 2012, scientists from around the world discovered this particle, the Higgs boson (named for one of the scientists who originally postulated its existence), using the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. The reconstruction of a candidate Higgs boson decay using the CMS detector at the LHC is shown in Figure II.

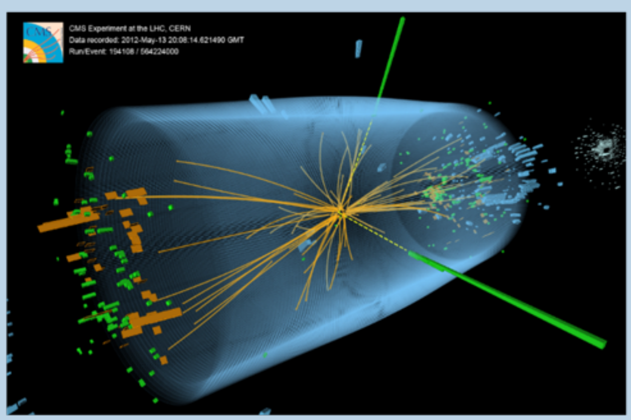

Figure II: Display of a collision event recorded on May 13, 2012, by the CMS experiment at the CERN Large Hadron Collider. The event is consistent with the decay of the Higgs boson to two photons. The two large green bars associated with the dashed yellow lines show how the photons from the decay of the Higgs boson candidate interacted with the detector. Image source: CMS experiment.

The highest priorities for Energy Frontier research are to continue the detailed study of the Higgs boson and direct searches for new particles at the LHC and its upcoming High Luminosity upgrade (HL-LHC), which will run through the 2030s. Beyond the 2030s, future colliders and their detectors (see Figure III which shows part of the muon detection system of the ATLAS detector currently operating at the LHC) will build on and surpass the science impact even of the ambitious HL-LHC: improving the precision of many Higgs boson measurements by more than a factor of ten relative to the HL-LHC and potentially producing new particles with masses ten times higher than achievable at the HL-LHC.

The currently envisioned next generation of Energy Frontier colliders (see Figure IV) include either a linear or circular e+e- collider starting operation as early as 2035 or a 100 TeV proton-proton (pp) collider with operation beginning as early as 2045. In addition, the HL-LHC experiments will need to replace their inner tracking detectors soon after 2030 when radiation damage to detector silicon will begin to cause significant harm to detector performance.

This replacement requires development of new detectors that will take advantage of technologies emerging in the next decade. The future e+e- colliders will require multi-system detectors with excellent resolution for particle reconstruction, while detectors at a 100 TeV collider require both excellent resolution and extreme radiation tolerance.

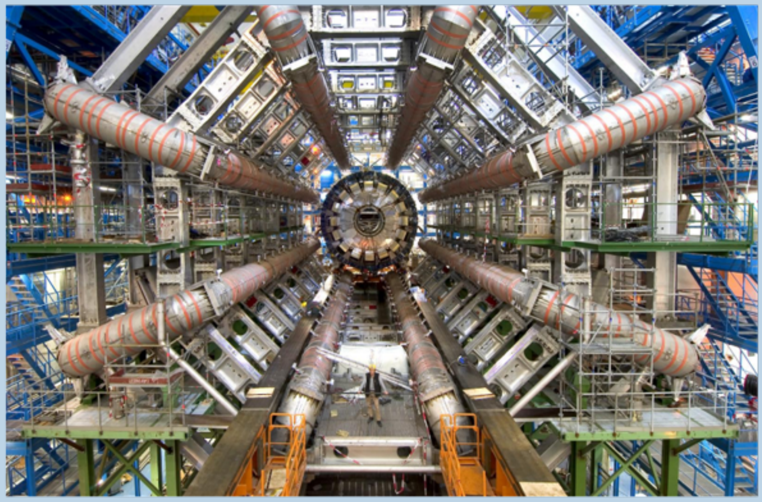

Figure III: The barrel toroidal magnet system of the ATLAS detector at the CERN Large Hadron Collider. These large magnets are used to measure the trajectory of muons produced in LHC collisions including those produced in decays of the Higgs boson. Image source: ATLAS experiment.

Detectors at any facility will benefit from advances in precision time measurements to improve overall reconstruction fidelity. The specific Priority Research Directions (PRDs) relevant to achieving the general detector requirements for the Higgs and Energy Frontier described in Sec. 3.1.2 are shown in the timeline for each detector technology area.

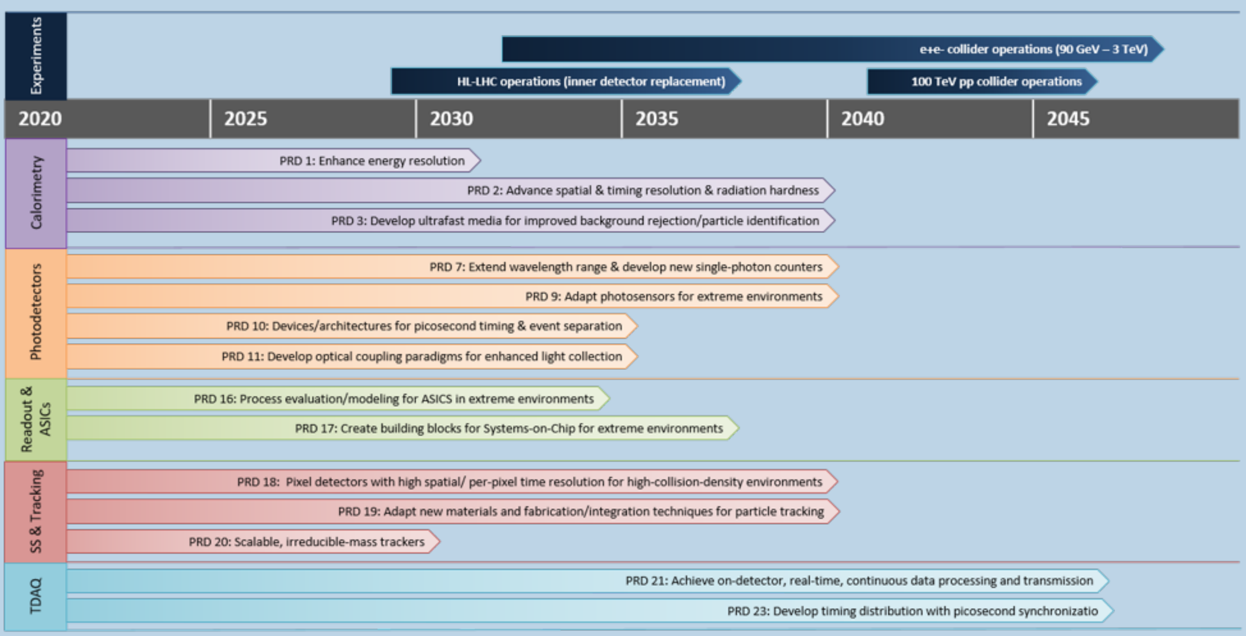

Figure IV: Higgs and Energy Frontier Timeline next two decades, these couplings will be measured at the HL-LHC with good precision in many final states, but some final states will remain almost entirely unexplored. The combination of measurements from next generation colliders will provide sub-percent precision for Higgs couplings to the fermions and bosons of the SM. Despite the ambitious goals of the HL-LHC, future collider measurements will improve precision by at least a factor four for all Higgs measurements, a factor of ten or more for many measurements, and in some cases will provide unique sensitivity unavailable at the HL-LHC [20–22].

The advancement of our understanding expected for some Higgs properties is striking. For example, where our current best knowledge still allows for the Higgs boson to decay to potential dark matter particles 20% of the time, the next colliders will measure or rule out Higgs decay rates to potential dark matter with 0.02% precision. Future lepton colliders will provide a crucial model-independent measurement of the Higgs total decay width. The most challenging Higgs property to measure is the strength of the Higgs interaction with itself to understand the shape of the Higgs potential. While the High Luminosity Large Hadron Collider (HL-LHC) will provide an initial understanding of this fundamental property of nature with 50% precision on the Higgs self coupling, the next colliders will improve this measurement by a factor of ten reaching a precision of 5%.

There are many theories that posit new phenomena beyond the SM to resolve the theoretical and experimental tensions described above. Some of these theories also provide natural solutions for dark matter or introduce more complex phenomenology for the dark sector. In addition to the "known unknowns," detectors must retain sensitivity to the "unknown unknowns" – new physics not previously conceived or expected. In the direct search for BSM phenomena, the next generation of proton-proton (pp) colliders will allow us to produce and detect new heavy particles with masses ten times larger than those achievable at LHC, which currently can reach a scale of ~ 2 TeV [20, 23]. Detection of these heavy particle resonance states imposes strong requirements on energy, momentum, and position resolution. Similarly, the very high luminosities of the proposed $\mathrm{e^+e^-}$ or pp colliders allow for the detection of low-mass particles that can only be detected through the very rare decays of SM particles such as the Higgs boson. In addition, the next pp collider will probe deep inside SM particles to search for internal structure at distances ten times smaller than those probed at the LHC, which currently reaches 1/100,000 the size of the proton or 1×10^{-20} m. Many theories predict the presence of massive long-lived particles that can only be observed once they decay deep inside the detector; such particles can be identified by precise measurements of the anomalous arrival time of their decay products at various detector components [24].

The currently envisioned next generation of energy frontier colliders include (i) linear or circular $\mathrm{e^+e^-}$ colliders with collision energy up to 3 TeV and rates 600 times those of CERN's Large Electron–Positron collider, the world's most recent $\mathrm{e^+e^-}$ energy frontier machine, and (ii) a 100 TeV proton-proton (pp) collider with collision energy and rate nearly 10 times those of the LHC. Timelines for potential general scenarios for the operation of future high energy colliders are shown in the Higgs and Energy Frontier sidebar. The pixel detector replacements planned for LHC Long Shutdown 4 in 2031 offer an excellent opportunity to develop detectors that benefit from the emerging technologies motivated by R&D towards the future colliders.

3.1.2 Transformative Detector Requirements

The proposed collision energies and data rates of the next generation of energy frontier colliders impose unprecedented requirements on detector technology. Collider detectors ultimately measure three independent quantities: position, time, and energy. Measurements of position and time, in particular, will need new and transformative methods compared to the expected evolution of existing technology. The detectors must maintain excellent precision and efficiency for all basic signatures (including electrons, photons, muon and tau leptons, hadronic jets, and missing energy) over an immense range of momentum and solid angle because the detectors must excel at measuring both the relatively low energy decay products of the Higgs boson and the highest energy particles ever produced at an accelerator. Future detectors will build on the "particle flow" methods developed for e^+e^- detectors and used with great success by LHC detectors to more fully optimize resolution. In particle flow reconstruction, all final-state particles are reconstructed by combining corresponding measurements from both the tracking detectors and calorimeters [25, 26]. Particle flow methods benefit from high calorimeter granularity, which allows precise separation of nearby calorimeter energy deposites (clusters) and precise matching of calorimeter clusters to charged tracks in the reconstruction of charged hadrons.

The 100 TeV pp collider will produce particles with momenta ranging between a few GeV and 20 TeV over $0 < |\eta| < 6$, with pseudorapidity defined in terms of the polar angle with respect to the colliding beam axis (θ) as $\eta \equiv -\ln[\tan\frac{\theta}{2}]$. These momentum and angular ranges are ten times and twice those achieved at the LHC, respectively. Highly collimated jets of decay products from W, Z, H bosons and top quarks will be ten times more narrow than those observed at the LHC. As the energy of the collision increases, more particles are produced in the forward region of the detector, where tracking systems and calorimeters are severely challenged by occupancy and radiation. At a 100 TeV pp collider, each interesting pp collision will occur simultaneously with many other pp collisions resulting in a dense "pileup" of collisions. Where current LHC detectors must disentangle only 40 pileup collisions per beam crossing on average, a 100 TeV pp collider pileup will produce 1000 nearly simultaneous pp collisions [20].

Disentangling the extreme pileup of overlapping particles will be achieved with complementary measurements of particle position and time of arrival at the detector. The requirements for time resolution demand a paradigm shift. While the most advanced detectors planned for the HL-LHC target a resolution of only 50 ps, future colliders will require 1-5 picosecond (ps) resolution. This radical improvement in timing performance will also benefit particle identification and searches for long-lived new particles, as it will provide a precise time-of-flight measurement.

Finally, detector components must perform well in high-radiation fluences and doses. At a 100 TeV pp collider, the innermost layer of the central tracking system is expected to be exposed to approximately 1×10^{18} n_{eq}/cm^2 and 300 MGy of total ionizing dose (TID), where n_{eq}/cm^2 is a unit of silicon lattice displacement damage corresponding to one 1 MeV neutron per cm^2. While the endcap calorimeter ($1.5 < |\eta| < 2.5$) must handle approximately 3×10^{16} n_{eq}/cm^2 and 4 MGy, the forward calorimeter ($2.5 < |\eta| < 6$), which is crucial for the study of vector-boson fusion, must operate at approximately 5×10^{18} n_{eq}/cm^2 and 5000 MGy [27]. Novel sensor technology and readout electronics will need to be developed for the inner tracker and for the forward calorimeter given radiation levels about 1000 times higher than expected at the HL-LHC.

Putting all of these requirements together, transformative and innovative technologies required for the next generation of energy frontier experiments focused on precision Higgs and SM physics and searches for BSM phenomena include (1) low-mass, highly-granular tracking detectors and (2) highly-granular calorimeters, both with high-precision timing capabilities, and (3) flexible trigger and readout systems closely integrated with the active detector components to handle the huge data rates associated with these highly granular, high dynamic range, precise detectors. The Technical Requirements for these detectors, which inspire a variety of specific Priority Research Directions (PRDs) in related technology areas, are summarized in Table 2 along with their related PRDs and elaborated in Sections 3.1.3-3.1.5 below.

3.1.3 Measuring charged particle momentum, trajectory, and time

At colliders, charged particle position and momentum are typically measured with exquisite precision with silicon-based tracking detectors that reconstruct many points along each particle's trajectory.

To allow for a complete and efficient measurement of Higgs branching fractions and rare Higgs decays, future e^+e^- colliders will require tracking detectors with excellent resolution on particle transverse momentum (p_T) over a wide range of momentum. Obtaining excellent resolution at low p_T requires very low-mass trackers. Linear e^+e^- colliders will be able to take advantage of the low frequency of collisions by pulsing their tracker power at frequency of a few Hz, thereby obviating the need for active cooling and the associated mass of a cooling system. For central particles with $p_T \lesssim 100$ GeV, multiple scattering results in resolution of $\sigma_{p_T}/p_T \approx 0.2\%$. These tracking detectors will also provide excellent impact parameter resolution of $\sigma_{r\phi} \approx 5 \bigoplus 15\,(p\ [\text{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$, where $\bigoplus$ implies a sum in quadrature. For central particles with $p_T \gtrsim 100$ GeV, the required resolution is $\sigma_{p_T}/p_T^2 \approx 2 \times 10^{-5}\ \text{GeV}^{-1}$ [28]. Maintaining excellent p_T resolution at high momenta requires multilayer, large radius detectors with excellent single-hit resolution.

The trackers at 100 TeV pp colliders will require similar p_T resolution for the bulk of the momentum range, with approximately 0.5% p_T resolution at low p_T dominated by multiple scattering. These detectors will have to withstand a very harsh environment, with a fluence at the innermost barrel layer of 10 GHz/cm^2 and with a pileup of 1000, corresponding to an average separation between vertices of 125 μm. To cope with the high occupancies, these detectors will require a small cell size of approximately $25 \times 50\ \mu m^2$ in inner layers. The single-hit position resolution will be about 5 μm to obtain two-track separation necessary for

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_\mathrm{T}}/p_\mathrm{T} = 0.2\%$ for central tracks with $p_\mathrm{T} < 100$ GeV, $\sigma_{p_\mathrm{T}}/p_\mathrm{T}^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_\mathrm{T} > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\mathrm{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\mathrm{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	**18, 19, 20, 23**
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.2.2: $\sigma_{p_\mathrm{T}}/p_\mathrm{T} = 0.5\%$ for tracks with $p_\mathrm{T} < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	**16, 17, 18, 19, 20, 23, 26**
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	**1, 3, 7, 10, 11, 23**
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) $\mathrm{n_{eq}/cm^2}$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	**1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26**
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	**16, 17, 21, 26**

Table 2: Technical Requirements [27, 28] to enable the physics program for Higgs and the Energy Frontier and map to Priority Research Directions. The Science column lists the goals of the science program. Progress towards each goal is realised both by electron positron colliders and proton proton colliders. Accordingly, there is no specific alignment between the goals in the Science column with the rows across the other columns.

reconstruction of highly collimated jets and to cope with the high pileup. In addition, the silicon tracking sensors and electronics will need to maintain good performance after unprecedented exposure to radiation of approximately $1 \times 10^{18}\ \mathrm{n_{eq}/cm^2}$ and 300 MGy of total ionizing dose (TID) [27]. The pixel detector replacements planned for the LHC Long Shutdown 4 in 2031 will offer an excellent opportunity to develop detectors which may benefit from some of the emerging technologies motivated by R&D towards a 100 TeV pp collider.

Finally, future tracking detectors will be 4D detectors as they will not only measure the position of particles, but also their time of arrival. This capability will allow the new generation trackers to cope with the extreme linear density of pileup vertices and particle rates expected at the 100 TeV pp collider and maintain reasonable detector occupancy levels. In addition to mitigating effects of pileup and high occupancy, precise measurements of particle arrival time allows the reconstruction and identification of new long-lived particles, which naturally occur in theories with new particles very weakly coupled to the SM.

In the past ten years, the timing technology has made substantial progress. Today, state-of-the-art dedicated timing detectors can obtain 30-40 ps resolution in medium scale systems, which is sufficient for HL-LHC pileup levels. At future hadron colliders, effective pileup rejection will require measurements of the individual arrival times of charged particles with 1-5 ps precision [27]. It is likely that these ambitious requirements will rely on making multiple redundant measurements of the time of each particle, which motivates integrating timing capabilities into multilayer tracking detectors.

3.1.4 Measuring particle energy and time

Future calorimeters must have excellent position and energy resolution for optimal performance within the particle flow (PF) framework. At a 100 TeV pp collider where W bosons with $p_{\mathrm{T}} \simeq 10$ TeV will decay into highly collimated jets with minute 10 mrad separation between constituents, good position resolution will also allow reconstruction of jet substructure. Position resolution is driven by granularity: future electromagnetic calorimeters (ECAL) will have cell dimensions as small as 5×5 mm^2 and hadron calorimeters (HCAL) will use cells with size of 1-3 cm^2 [27, 28].

Excellent jet energy resolution is critical for the physics goals mentioned in Section 3.1.1 by providing good mass resolution for hadronic decays of the Higgs boson and potential new particles, as well as good missing energy resolution for inferring the presence of non-interacting particles such as dark matter. At $\mathrm{e^+e^-}$ colliders specifically, measurement of the Higgs boson total width requires reconstruction and identification of hadronic decays of the Z boson produced in association with the Higgs, which in turn requires 4% energy resolution for particle flow jets [28]. The jet energy resolution for future hadron collider calorimeters is expected to have a 50% stochastic term and 3% constant term; while these resolutions will dominate at high momentum, particle flow techniques will provide improved resolution at low momentum [27].

Realizing the ambitious physics goals also depends on excellent resolution for the measurement of the energy of electromagnetically interacting particles, which provides good mass resolution for the Higgs boson, Z boson, and potential new particles decaying to photons or electrons. Minimal resolution requirements for future colliders involve a 10% stochastic term and better than 1% constant term; however, improvements beyond this level are achievable and would have clear impacts on the physics goals [27, 28]. More specifically, these minimal resolution requirements are very likely insufficient for ultra-precise measurements of the Z boson expected from dedicated $\mathrm{e^+e^-}$ collider operation on the Z resonance.

As introduced in Section 3.1.2, measurements of particle time of arrival with 1-5 ps precision are critical for removing pileup, particle identification, and identification of potential new long-lived particles. Just as the 4D tracking detectors described in Section 3.1.3 will provide precise time measurements for charged particle trajectories, future calorimeters must provide time measurements for showers of neutral (and charged) particles with similar precision.

3.1.5 Detector trigger and readout

The highly granular detectors – approximately 20 billion channels for a 100 TeV pp experiment – described above would produce over an exabyte per second of raw data without significant localized processing and reconstruction on detector. This is a factor of a thousand larger data flow than the HL-LHC, assuming similar per-channel occupancies, and would need correspondingly more data links, cooling, and processing capability. Reducing this big data challenge to the few petabytes of data that can be stored per year requires new research and development in low latency and low power processing using radiation-tolerant custom ASICs, Field-Programmable Gate Arrays (FPGAs), and Reduced Instruction Set Computer (RISC) processors capable of implementing Artificial Intelligence and Machine Learning (AI/ML) technologies amongst other more specialized algorithms. These hardware systems must produce initial decisions on which data to store and which to reject with very low latency of only a few microseconds. These ambitious latency goals are typically realized with a multi-stage system composed of an initial stage of on-detector custom circuits; an intermediate stage of off-detector semi-custom electronics; and a final-stage commodity computing farm. All stages are connected by high-bandwidth data links with specialized radiation-hard links on detector.

The intermediate stage connecting the on-detector custom hardware and commodity computer systems requires a data acquisition system capable of handling the full throughput of the experiment. Given the dozens of different detector technologies and electronics implemented for a single experiment, the data acquisition hardware should be flexible, modular, scalable, and should provide local intelligence for low-latency data analysis. Altogether, high-bandwidth data transmission hardware; radiation-tolerant, custom integrated circuits, large commodity computing farms, and highly modular data acquisition electronics will allow the next generation of collider experiments to successfully explore the physics of the Higgs boson and to search for new phenomena beyond the Standard Model.

3.1.6 Higgs and the Energy Frontier: Preparing for Discovery

In order to elucidate the theoretical and experimental mysteries associated with the Standard Model, including the hierarchy problem and nature of dark matter, the next generation of energy frontier particle colliders and their associated detectors must serve as both precision measurement machines and discovery machines. The transformative physics goals of future colliders and detectors include four inspiring and qualitatively distinct directions:

- Sub-percent precision on measurement of the Higgs interactions with SM particles
- Mapping the Higgs potential with 5% precision on the measurement of the Higgs self-coupling
- Using the Higgs boson to search for dark matter and other new phenomena
- Searching for new particles and phenomena at the multi-TeV scale

We must embark now on the necessary research and development to build the detectors that will meet performance requirements for taking full advantage of the unprecedented physics opportunities provided by future e^+e^- colliders and high-energy pp colliders starting around 2030 and beyond. The requirements described in detail above include (1) highly granular, radiation hard, low-mass tracking detectors with picosecond timing; (2) highly granular, radiation hard, imaging calorimeters with picosecond timing; and (3) high-bandwidth trigger and readout systems composed of radiation hard on-detector processing, radiation hard on-detector transmitters, and flexible off-detector compute systems.

3.2 Neutrinos

3.2.1 Science Impact

Over the past two decades it has been cleanly established that neutrinos have non-zero mass, through observations that neutrinos oscillate between their three types (flavors) during propagation, with the unitary 3×3 Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix relating three mass and three flavor neutrino states. Data from multiple experiments involving solar, reactor, atmospheric and beam neutrinos are consistent with this three-flavor paradigm. Of the three-flavor neutrino parameters, the mass ordering and the CP-violating phase are yet to be determined at better than the $\sim 3\sigma$ level; this is likely to be achieved by the ongoing neutrino program within the next decade. However, there are hints for physics in the neutrino sector that go beyond the three-flavor paradigm. New physics could reveal itself in the form of measurements inconsistent with the three-flavor picture, e.g., oscillations driven by mass-squared differences inconsistent with three states, or non-unitarity of the matrix. The science of accelerator neutrino experiments goes well beyond the primary measurements and includes a rich program of precision studies of the physics of neutrino–nucleus scattering, for which detailed understanding is critical to reduce uncertainties. Entirely new phenomena observed with neutrino detectors may also point the way to BSM physics, such as new interactions observed via anomalous scattering rates or interaction kinematics. Furthermore, some key questions in neutrino physics, such as the absolute mass scale, and the Majorana versus Dirac nature of the neutrino, cannot be answered with oscillation experiments.

The P5 Science Drivers most relevant to neutrino physics are "Pursue the physics associated with neutrino mass," and "Explore the unknown: new particles, new interactions, physical principles." Advances in instrumentation will address the P5 Science Drivers in three ways:

- **Precision tests of the three-flavor neutrino paradigm**.
- **Expanding the neutrino measurement regimes** in energy range, types of neutrino sources, and source intensities.
- **Searches for signatures of BSM physics** in neutrino detectors. These searches may involve neutrinos directly, but may also use neutrino detection technology to search for new physics outside the neutrino sector.

New technologies will enhance the science impact in all of these science directions. The range of neutrino physics and technology is very diverse. In many cases it is difficult to quantify the enhanced physics reach of a given technology advance, although we can be confident of improved capability. Therefore, in the following, we do not attempt to be comprehensive in describing the possibilities, but rather select several *non-prioritized* examples for which we can clearly quantify impact. We expect very broad impact on multiple neutrino experiments from a large number of PRDs.

3.2.2 Testing the three-flavor neutrino paradigm

Results from experiments over the past two decades have led to the unexpected conclusion that neutrinos have non-zero masses, although these masses are much smaller than the other known particle masses. An equally surprising observation is that the three types of neutrinos produced by the weak interaction (i.e. ν_e, ν_μ, and ν_τ) do not have definite masses, but instead are coherent quantum combinations of three mass states, ν_1, ν_2, and ν_3. Together these two properties result in the phenomenon in which a given neutrino oscillates among the three lepton flavors as it propagates through space and time. The physics governing these oscillations can be fully described by six parameters: three mixing angles, θ_{12}, θ_{13}, and θ_{23}, a phase δ_{CP}, and two differences in squared masses, $\Delta m^2_{ji} = m^2_j - m^2_i$, $i, j = 1, 2, 3$. The mixing angles and mass-squared differences have all been measured to at least modest precision. It is unknown whether the mass m_3 is greater or less than m_1 and m_2; the answer to this question is commonly called the neutrino mass ordering, or hierarchy. The phase δ_{CP} is currently only poorly constrained, but if it is non-zero then charge-parity (CP) symmetry is violated in the neutrino sector. This would be observed through differences in oscillations between neutrinos and anti-neutrinos.

Neutrinos

Neutrinos are some of the most intriguing of the fundamental particles: although not exactly massless, they are anomalously light, and interact with matter only via the weak interaction gravity. These abundant particles pervade the universe over a huge range of energies. We are bathed in a relic neutrino glow from the Big Bang. Neutrinos emanate from astrophysical sources – stars (including our Sun), core-collapse supernovae, cosmic ray collisions, active cores of galaxies – as well as from radioactive nuclei in the Earth and nuclear reactors. We can also create neutrinos in accelerators, as focused beams or isotropic sources. Experiments over the past two decades using both natural and artificial neutrinos (see Figure I) have elucidated some of the neutrinos' surprising properties, but many mysteries remain.

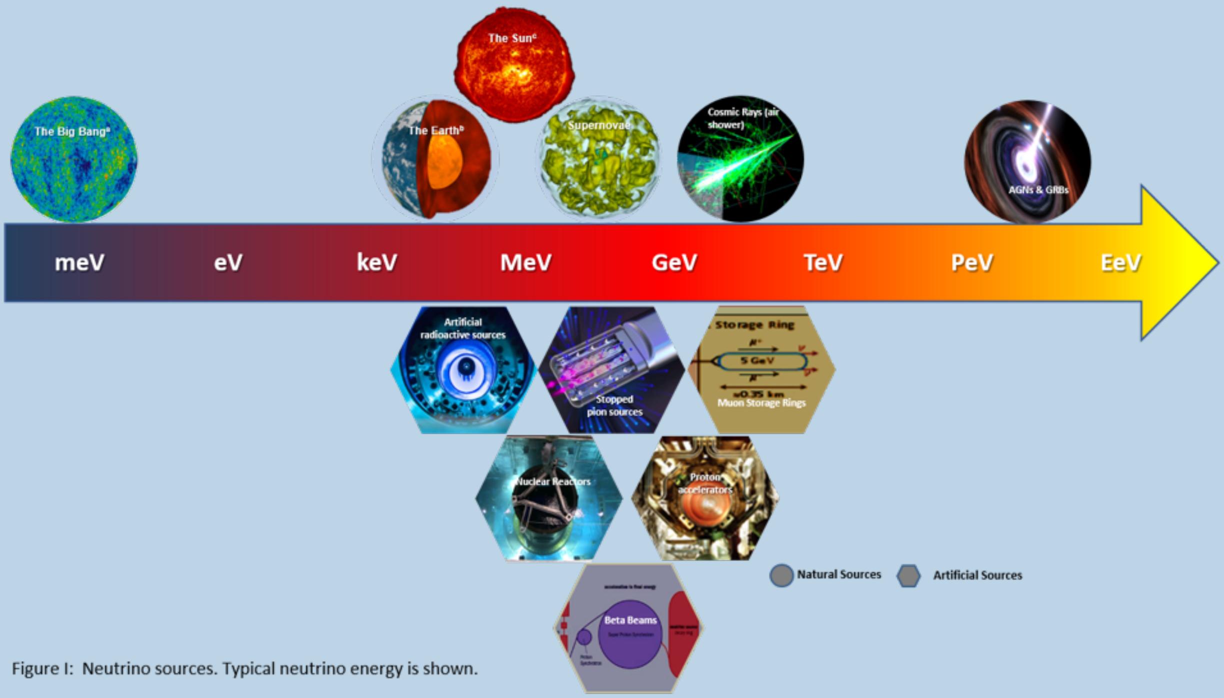

Figure I: Neutrino sources. Typical neutrino energy is shown.

Image credits: [a]Big Bang - The Cosmic Microwave Background temperature fluctuations from the 7-year Wilkinson Microwave Anisotropy Probe data seen over the full sky.[b]The Earth, NASA/JPL-Université Paris Diderot - Institut de Physique du Globe de Paris, March 9, 2011. [c]The Sun, NASA, June 12, 2017. [d]Supernova, Simulated 'engine of explosion' observed in supernova remnant, Oak Ridge National Laboratory, July 22, 2014. [e]Cosmic ray air shower created by a 1TeV proton hitting the atmosphere 20 km above the Earth. CC-BY-2.5. [f]AGNs & GRBs, Extragalactic astrophysical objects - Gamma Rays in Active Galactic Nuclei, April 16, 2008. [g]Artificial radioactive sources, Oak Ridge National Laboratory, U.S. Dept. of Energy; photographer Genevieve Martin. [h]Nuclear Reactors, U.S. Department of Energy. [i]Beta beams, CERN, July 27, 2004. [j]Stopped pion sources, Oak Ridge National Laboratory, Jill Hemman, July 2017. [k]Proton accelerators, Fermi National Laboratory, photographer Peter Ginter, February 20, 2013. [l]Muon Storage Rings, Fermi National Laboratory, Muon Accelerator Program.

Multiple experiments worldwide employing diverse technologies are testing our understanding of how neutrinos fit in to the big picture, using neutrinos from beams, reactors, and natural sources. These experiments are searching for "beyond-the-Standard Model" physics, including tests for signatures of new types of neutrinos, such as "sterile" neutrinos with no Standard Model weak interactions. The timeline of running and proposed neutrino experiments is illustrated in Figure II. The presently running and future experiments are shown, and their starting and duration times are indicated. Among the next-generation experiments, U.S. highlights are the DUNE experiment, a 40-kton liquid argon time projection chamber (TPC) detector to be coupled with the world's most powerful neutrino beam from Fermilab, but there are many others, including novel experiments for understanding neutrino interactions with matter, and new searches for probing the absolute neutrino mass scale and understanding whether the neutrino is its own antiparticle. Figure III shows an exploded view from inside ProtoDUNE, the 1-kton single-phase DUNE far detector prototype, operated at CERN. Advances in detection technologies are required for progress in many directions. One example involves the development of novel TPC charge readout techniques, such as scalable, low-power, low-noise pixelated charge readout (see Figure IV), with the potential to provide true 3D charge imaging from large LArTPCs, addressing current issues with signal ambiguities and reconstruction complications which arise from the existing 2D projective readout techniques.

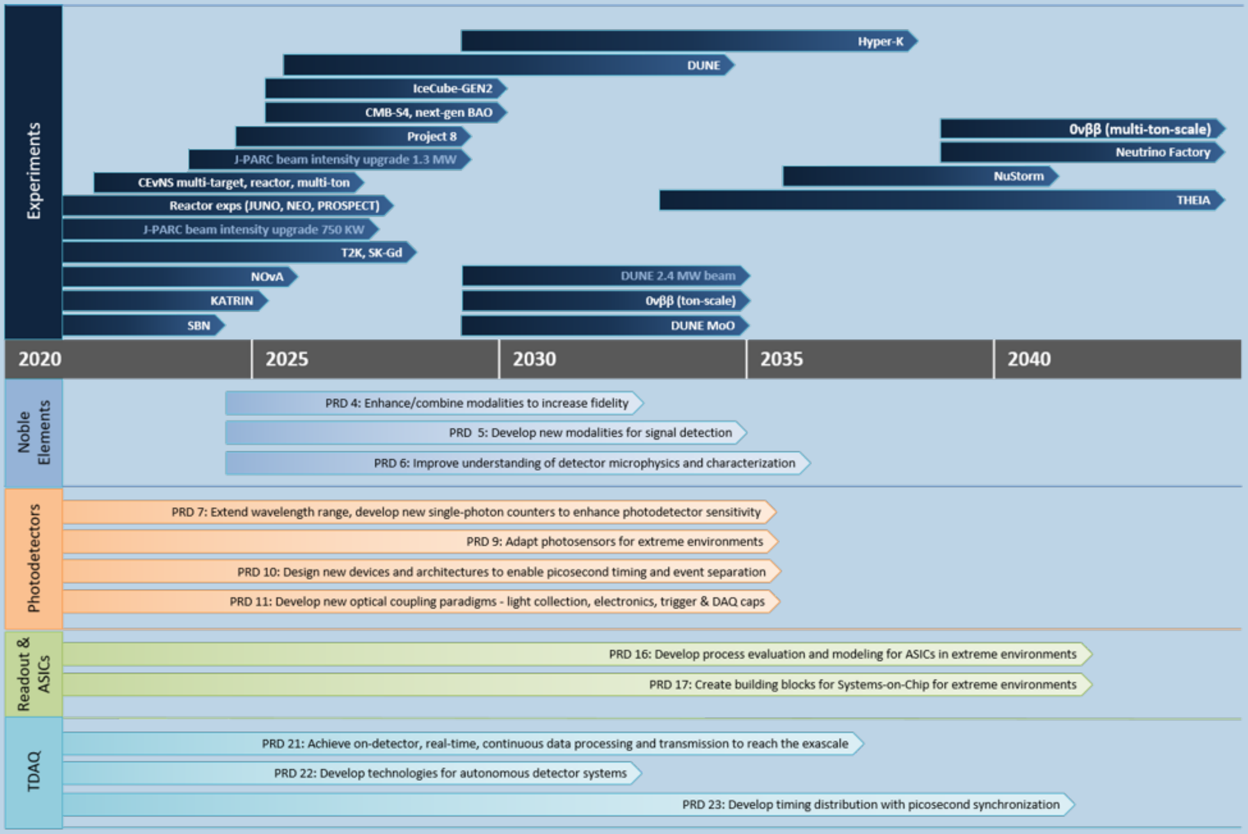

Figure II: Timeline of neutrino experiments.

Novel and improved technologies will not only bring higher precision and broader reach to the search for new physics, but will also expand the range over which we can observe neutrinos: we will extend the energy regime, observe new kinds of neutrino sources, and measure previously undetectably faint fluxes. Higher resolution, lower thresholds, and ultra-high sensitivity will require advances over a wide range of detection capabilities, including but not necessarily limited to new modalities for signal detection in noble elements.

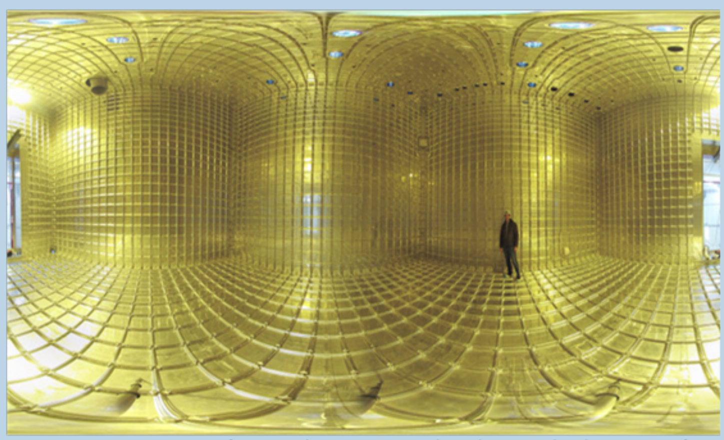

Figure III: Panoramic view from inside ProtoDUNE, the 1-kton single-phase DUNE far detector prototype, operated at CERN.

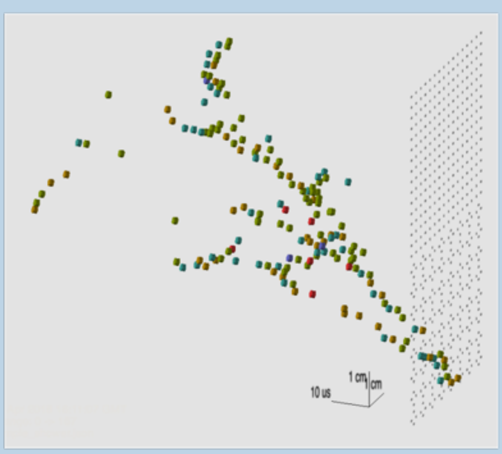

Figure IV: Pixelated charge readout example. The small colored cubes in this 3D visualization represent reconstructed energy loss along the tracks of charged particles produced by neutrinos in a liquid argon TPC.

Observation of neutrino CP violation, resolution of the mass ordering, and precision measurements of the parameters driving three-flavor oscillations are the main targets of the upcoming generation of neutrino oscillation experiments. The measured parameter values are input to theoretical models of neutrino mass and mixing. Furthermore, precision tests of this three-flavor paradigm, including unitarity tests, may uncover discrepancies with expectations that would be evidence for new physics.

The next generation of accelerator experiments (DUNE, Hyper-K) will precisely measure the oscillations of neutrinos with energies in the $\sim$0.5 to few-GeV range. Comparison with measurements of reactor, solar, and atmospheric neutrinos will yield percent-level tests of the three-flavor model. Effects of new physics, such as non-standard interactions or sterile neutrino states, would appear as tensions between these measurements made using neutrinos of different initial flavor and energy regimes and the three-flavor oscillation model.

Current technologies that can be feasibly deployed at the required 10 to 100 kton scales are liquid argon time-projection chambers (LArTPCs), water Cherenkov detectors, and scintillator detectors. Gadolinium-doped and scintillator-doped water represent interesting new directions for large neutrino detectors. Enhancements in the granularity and fidelity of these detectors translate to improved precision in the neutrino sector and will extend the reach for new and unexpected phenomena. For LArTPCs, unambiguous 3D charge readout at the mm scale and high-efficiency light detection are key targets for detector development. Doping of large liquid detectors opens new possibilities for observables, such as neutron multiplicity or scintillation calorimetry. Such new detector-material technologies coupled with enhanced photosensors with fast timing and/or photon wavelength sensitivity would maintain Cherenkov tracking performance in a scintillating detector [29]. Novel ideas [30] may deliver a combination of the fast timing and calorimetry of scintillator detectors with the spatial granularity of tracking detectors. Understanding of flavor-time structure of a beam source via improved timing [31] may also result in extended reach. Although it is not easy to quantify precisely, foreseen improvements in current detector performances (factors of a few in light yield, photosensor performance, resolution, etc.) would yield modest improvements in oscillation parameter precision for the upcoming generation of experiments. Transformative advances in the science will require innovative source-detector combinations, for which some examples are discussed below.

Existing oscillation results are dominated by measurements with electron- and muon-flavor neutrinos, while parameters derived from tau neutrinos are only weakly constrained [32]. Tau neutrino measurements require advances in detector technology substantially beyond the state-of-the-art. In particular, developing detectors with extremely high spatial granularity (e.g., 0.1 mm) is a path to observe the sub-mm track produced by a tau lepton before it decays. While this granularity has been demonstrated [33], delivering this performance in real-time in a $\mathcal{O}(100$ kton) detector requires novel developments.

Looking further into the future of oscillation physics, the need for new neutrino sources must not be neglected. While sources are not the focus of this study, their realization will place new demands on detectors. Neutrino factories and high-power stopped-pion or beam radioisotope sources are potential tools to reach sub-percent precision in neutrino physics.

Despite the power of oscillation measurements, these measurements are insensitive to some basic neutrino properties. In particular, we do not yet know the absolute masses of the neutrinos. Measurements searching for the direct kinematic signature of the neutrino mass limit it to less than $\sim$1 eV, and the sensitivities of ongoing experiments are expected to reach $\sim$0.1 eV in the near future [34]. Measurements of the large-scale structure of the Universe and weak gravitational lensing of the cosmic microwave background limit the sum of the neutrino masses to less than the eV scale, albeit indirectly [35, 36].

We also do not know the mechanism by which neutrinos obtain their very small masses. The most prevalent mass models lead to the extraordinary conclusion that neutrinos may be Majorana particles, i.e., their own antiparticles. Understanding the Majorana vs. Dirac nature of the neutrino is essential not only for neutrino mass models, but also for understanding the matter-antimatter asymmetry of the Universe. Searches for lepton number violation in neutrinoless double-beta decay (NLDBD) or related processes are the most sensitive probe of the Majorana nature of neutrinos. The most sensitive measurements of such processes have half-life limits greater than $\sim 10^{26}$ years, constraining the effective lepton-number-violating neutrino mass to be less than $\mathcal{O}(0.1$ eV). Detector requirements for next-generation NLDBD experiments are excellent energy resolution near the two-neutrino beta decay endpoint, ultra-low background, and scalability to large masses (ton scale or greater) of enriched isotopes. Ability to explicitly tag the DBD final state would be transformative.

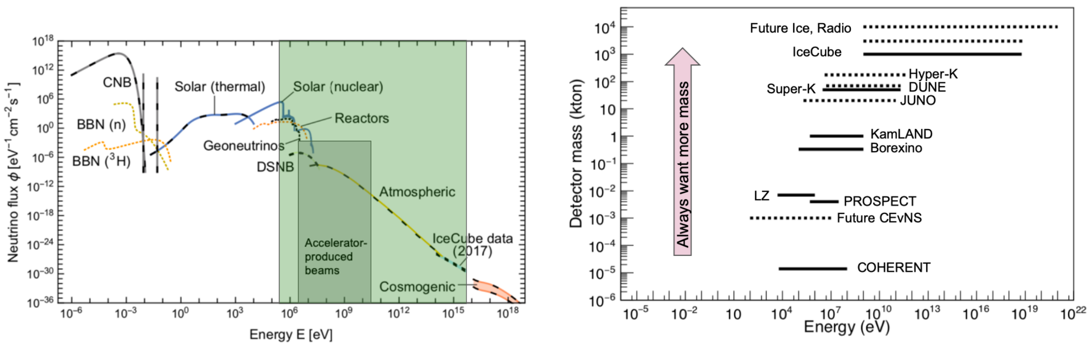

Figure 9: Left: "Grand Unified Neutrino Spectrum" on Earth showing natural neutrinos (and reactor neutrinos). Figure courtesy of authors of [38]. Accelerator-produced neutrinos occupy the few to few tens of GeV regime, shaded in dark green. Light green shaded region: energy regime over which neutrinos have been detected directly. Right: Neutrino detector mass vs. approximate range of sensitivity to energy deposition (note that below charged-current (CC) threshold, deposited energies in neutrino interactions can be much smaller than neutrino energies). Solid lines: existing detectors. Dashed lines: future detectors.

3.2.3 Expanding regimes of neutrino measurements

Neutrinos serve as probes of particle physics and astrophysics over 25 orders of magnitude in energy–see Figure 9. At the present time, we have detected neutrinos in the range from approximately half an MeV [37] up to $\mathcal{O}(10)$ PeV. The challenge of expanding the regimes of neutrino measurements includes not only expanding the range of energies accessible to us for neutrino detection, but also accessing new, possibly low-intensity, sources of neutrinos within that range. We describe here several case studies for expanding neutrino measurement regimes. These do not come close to exhausting the possibilities.

Measure neutrinos at macroscopic energies from cosmic distances: This decade has seen the discovery of $\mathcal{O}(100)$ astrophysical neutrinos with energies from 100 TeV to $\mathcal{O}(10)$ PeV [39]. These are the most energetic neutrinos ever measured, and have traveled the furthest distances of any observed. They have enabled a unique measurement of the neutrino-nucleon cross section at center-of-mass energies well exceeding previous measurements, up to hundreds of GeV. Astrophysical neutrinos should be observable up to macroscopic energies ($\sim 10^{19}$ eV), enabling measurements of the neutrino-nucleon cross sections at 100 TeV, sensitive tests of fundamental physics such as Lorentz invariance, and exotic oscillations scenarios over cosmic baselines. The P5 report points out that ultra-high energy neutrinos are of clear significance for particle physics due to their ability to probe weak interactions at energies inaccessible with colliders. Expanding astrophysical measurements to higher energies requires sensitivity to fluxes of order one neutrino/km^2 every ten years.

Radio techniques are the most promising path for the detection of ultra-high energy neutrinos [40], via radio Cherenkov emission in pure ice, geomagnetic emission from tau-neutrino-induced air showers, or a novel radar technique under development [41]. These techniques require fast ($>$ few GHz), low-power digitization with the capability to make complex trigger decisions to achieve lower thresholds than currently possible. Multi-channel digitizers capable of operating at $\ll 1$ W will allow for an autonomously powered array of the size and performance necessary to collect the sample of order $\sim$100 ultra-high energy neutrinos that is necessary for precision measurements of unique fundamental physics.

Measure supernova burst neutrinos in all three flavors in real time: Supernova 1987A with only a couple of dozen events observed in a few kton-scale detectors nevertheless generated hundreds of particle physics papers on topics ranging from neutrino absolute mass to axion properties [42, 43]. The next core-collapse supernova in the Milky Way will yield up to five orders of magnitude more events in next-generation neutrino detectors [44], which will be transformative for our knowledge. The extreme environment of a core-collapse supernova is the only way to access such processes as neutrino-neutrino interactions [45]. The information content is in the flavor, energy and time structure of the neutrino burst flux. The experimental challenge is to unfold the true neutrino fluxes from the observed events. The events are small in energy deposition (few to few tens of MeV) and spatial extent (few to few tens of cm), and present specific reconstruction and background challenges. Precision detector resolution, better photodetection, and background reduction are needed. As a specific example, a physics target currently inaccessible in very large (multi-kton scale) argon and scintillator detectors is the neutral-current "glow" from coherent elastic neutrino-nucleus scatters (CEvNS) [46], which would give a measurement of the *total* neutrino flux in all flavors. This would allow better astrophysical modeling (and therefore particle physics constraints), better constraints on BSM physics related to understanding of total energy release, and tracking of supernova burst flavor content as a function of time. In argon, the excess CEvNS events would result in a diffuse glow of $\sim 10^3$ photons emitted per ton over $\sim$10 seconds (with corresponding excess ionization charge). Enhanced photodetection (improved efficiency and reduced dark noise) and radiological background reduction are required to make this measurement.

Solar neutrinos: Neutrinos from solar fusion processes [47]— proton-proton (pp), carbon-nitron-oxygen (CNO), Beryllium-7, Boron-8, Helium-3+p (hep) – occupy an energy regime ranging from sub-MeV to $\sim$ 15 MeV. There is a minor ($< 3\,\sigma$) tension in measurements of Δm^2_{12} between reactor and solar neutrino experiments. Boron-8 neutrinos have been well measured by neutrino-electron scattering, but the potential exists to measure them with improved event-by-event energy resolution through ν_e charged-current (CC) interactions in argon [48], for which $\sim 10^2$ events per day above $\sim$5 MeV are expected in 40 kton. Such a measurement could resolve the existing tension (or point to new physics) and also improve our knowledge of solar physics. The requirement for this measurement is a reduction of backgrounds by a factor of 100-1000. As for supernova physics, improved spatial and energy resolution as well as improved real-time DAQ and triggering for signal selection in the presence of high background rates at low-energy threshold are needed. Previously inaccessible components of the solar flux, e.g., CNO and hep, are interesting targets as well.

Sub-MeV neutrinos— below CC threshold: Going to lower energies, we reach nearly unexplored territory. The pp solar flux, below 1 MeV, has been measured in real time by Borexino [37] (and radiochemically), but in the presence of high backgrounds. At even lower energies, one finds neutrinos produced by thermal processes in the Sun. Also interesting are the low-energy tails of reactor neutrinos or artificial radioactive sources. In this regime, we are below charged-current (CC) threshold for production of $e^\pm$ on nuclei. The inverse beta decay threshold is 1.8 MeV for interactions of $\bar{\nu}_e$ on free protons; a few nuclei have lower CC thresholds, but there are few available targets for which large mass is feasible. New ideas are needed.

Ideas relevant for sub-MeV dark matter are relevant for low-energy neutrinos as well. Indeed the "neutrino floor," where neutrinos dominate background for WIMPs, constitutes a signal as well. This technological regime has challenges similar in nature to those for dark matter, but requirements for detection of low-energy natural neutrinos as a signal are even more stringent (high-flux artificial sources may be easier). Practical ideas for very low-energy neutrino detection are few. Possibilities include elastic scattering on electrons, protons and nuclei, for which there is no physics threshold, but for which cross sections (typically scaling as E_ν^2) are tiny; therefore target mass scalability is a primary issue. Cross sections are higher for heavier targets, and CEvNS in particular takes advantage of the coherent N^2 cross-section scaling. However, the maximum recoil energy scales as $\sim 2E_\nu^2/M$, so observable energy is much smaller for targets with higher mass M. In all cases, backgrounds are a significant issue, and their nature is often poorly known. For thermal solar flux measurement ($\sim$10 keV neutrinos), kton or greater detector masses with $<$ meV recoil thresholds would be needed, which may not be realistic; for $\sim$100 keV natural neutrinos, $\sim$eV thresholds and ton-scale detectors would be needed. High-flux radioactive sources (e.g., ^{51}Cr [49]) may be more promising for BSM searches via very low-energy neutrino detection. Directional detection of neutrino-induced recoiling particles is another desirable feature, for signal vs. background discrimination as well as sensitivity to kinematics associated with BSM interactions.

Cosmic neutrino background (CνB): At the very lowest energies, the relic Big Bang neutrinos pervade the Universe. Detection of these would have tremendous impact on cosmology, and could possibly give insight into the Majorana vs. Dirac nature of the neutrino. The requirements for detection are dauntingly stringent. The only plausible detection idea is capture by beta decaying nuclei, which would lead to a small bump at the end of the spectrum (nominally tritium). This measurement requires $<$10 meV energy resolution at the endpoint, with a kg-scale source with less than 10 meV distortion at the endpoint [50, 51].

3.2.4 Direct searches for new physics in neutrino experiments

Our third category of neutrino experimental approaches is direct searches for new physics using neutrino experiment technology [52]. In some cases, the new physics resides in the neutrino sector itself, and in other cases, it happens that neutrino detector technology is suitable for searches for new physics in other sectors. This category is extremely diverse, and Technical Requirements are often hard to quantify, so again we focus here are a few selected, non-prioritized, examples.

Neutrino magnetic moment: In many extensions of the Standard Model (SM), neutrinos acquire nontrivial electromagnetic properties that allow for direct electromagnetic interactions of neutrinos. The most established and sensitive method for the experimental investigation of neutrino electromagnetic properties is provided by measurements of neutrino-electron scattering at low energies in solar, accelerator and reactor experiments. Measurements of neutrino-nucleus recoils (CEvNS) also have sensitivity to the neutrino magnetic moment [53]. Although current experimental sensitivity on neutrino magnetic moments [54] ($\sim 3\times10^{-11}\mu_B$) is many orders of magnitude above the SM prediction ($< 10^{-19}\mu_B$), new physics could result in much larger magnetic moments than that prediction. Detectors of 100 kg or greater scale coupled with intense neutrino sources (e.g., reactors or radioactive sources) with very low recoil energy threshold (∼10 eV), detection could potentially push the limits on transition magnetic moments of Majorana neutrinos down by an order of magnitude.

New signatures and new particle searches at accelerators and reactors: At accelerators, searches for signatures of new physics ranging from extra dimensions to light dark matter are enabled by the combination of high-intensity proton beams (and corresponding high-intensity neutrino beams) for neutrino precision measurements with large mass detectors with precise tracking and energy measurement, good timing resolution and low energy thresholds. Accelerator neutrino data offer unique opportunities to look for new physics in the neutrino sector and beyond (e.g. effects of BSM physics on neutrino oscillation, sterile neutrino oscillation). In addition, the proximity to the beam target makes near detectors well suited for the exploration of new states (light dark matter, heavy neutrinos, millicharged particles, etc.) produced in the beam target. Reactor experiments also offer excellent opportunities for sterile neutrino and new physics searches. Detectors similar to those of existing programs (e.g., the LArTPC detectors of the Short-Baseline Neutrino (SBN) program at Fermilab [55, 56], CEvNS detectors at the Spallation Neutron Source [57], and Lithium-loaded scintillator-based PROSPECT at the Oak Ridge nuclear research reactor HFIR [58]) can also search for BSM physics, and detector enhancements will extend the reach of these types of experiments.

Examples of new states that can be produced in the beam target and decay or interact inside the neutrino detector are heavy sterile neutrinos, dark neutrinos and light dark matter. Typical signatures of these events consist of $\nu l^+ l^-$ with energies in the range from ten to hundreds of MeV. Trident events can be produced from SM neutrinos or from light dark-sector particles, and both would lead to similar signatures in the neutrino detector. Excellent spatial resolution, energy and time resolution, particle identification and light yield are required to efficiently identify and reconstruct these topologies. Improvements in the resolution can be achieved by reducing the detector's pixel size and concurrently reducing the electronic noise in the TPC, also allowing the reduction of the energy threshold. Magnetizing the detector would improve the capability to reconstruct the individual leptons in the event.

Neutrino experiments can also probe the existence of millicharged particles (mCPs), particles with fractional electric charge $Q_\chi = \epsilon \cdot e$, a simple extension of the SM. When traveling through matter, mCPs will lose energy by atomic excitation and ionization like any charged particle but with ionization and excitation rates reduced by ϵ^2. Therefore, the mCP ionization track is undetectable except when knock-on electrons, energetic enough to themselves produce a visible signal, are emitted. The distribution of electron recoil energies, T, falls like $1/T^2$, and low-energy thresholds are therefore key to detect these "δ-rays" produced by mCPs. Since the neutrino detectors have different sizes and cosmic-ray backgrounds, signal-to-noise optimization is needed for each of them. A clean way to look for mCPs, by looking for multiple low-energy deposition hits in events aligned with the beam target, has been demonstrated [59, 60]. Further background rejection in the detection of mCPs could be achieved with a detector capable of identifying the "faint" mCP ionization tracks. A kton-scale detector with high granularity and capability to achieve per-channel signal over background >10 above 100 keV would be able to provide strong constraints on mCPs in unexplored parameter regions.

3.2.5 Neutrinos: Preparing for Discovery

Neutrino physics has yielded a bountiful harvest of knowledge over the past few decades, and neutrinos still hold great promise as windows into new physics. The goals of the next generation of neutrino experiments are to:

- Push the three-flavor paradigm into the regime of high-precision measurements of all parameters.
- Explore unknown territory in neutrino energy range, types of neutrino sources, and faint source intensities.
- Hunt for evidence of new particles and phenomena in the neutrino sector, and in other sectors using neutrino detectors.

Table 3 summarizes Technical Requirements for physics progress in these directions. These examples are, however, barely scratching the surface of possibilities, and we expect detector enhancements to extend the physics reach in both depth and breadth.

Science	**Measurement**	**Technical Requirement (TR)**	**PRD**
Neutrino mixing matrix unitarity	Measure tau neutrino appearance with high efficiency/purity	TR 2.1: Resolve short tracks (0.1 mm at 10 GeV) in 10 kton detectors	**4,6,10, 11,16,21,22, 23,25,26**
Measure neutrinos at macroscopic energies from cosmic distances for BSM searches	Sensitivity to neutrino fluxes 1/km^2/decade at low energy threshold	TR 2.2: Low power ($\ll$ 1 W) digitizers sampling at >3 GHz, triggering at $\mathcal{O}(1)$S/N	**16,17**
Resolve solar/ reactor Δm^2_{12} tension	Measure solar ^{8}B, hep and neutrino regeneration in the Earth with S/B>1 above a few MeV	TR 2.3: Radiogenic background reduction by a factor of 100-1000 in argon TR 2.4: <1 cm spatial, TR 2.5: < 10% energy resolution at kton scale	**4,6,21,22, 23,24,25,26**
Measure all flavor components of a supernova burst in real time	Flavor tagging with >90% efficiency, 5-50 MeV; measure CEvNS glow/buzz in large LAr or scintillator	TR 2.3, 2.4, 2.5 TR 2.6: Photodetector efficiency improvement by factor of 10 TR 2.7: Photosensor dark noise reduction by factor of 100	**4,6,7,9,10, 11,16,21,22 23,24,25,26**
BSM physics with sub-MeV (or sub-keV) neutrinos (geoneutrinos, pp neutrinos, solar thermal neutrinos, artificial radioactive sources)	Sensitivity to very low energy nuclear or electronic recoils in real time	TR 2.8: 10 eV nuclear recoil threshold at multi-ton to kton scale TR 2.9 Few degree recoil directionality	**5,6,7,9,11, 12,14,24,25,26**
Cosmic relic neutrino background, test of cosmological models	Measure cosmic relic neutrino capture on nuclei	TR 2.10: 10 meV energy resolution at beta endpoint, $\mathcal{O}$(1 kg) source with TR 2.11: <10 meV energy loss distortion at endpoint	**12,14,26**

Table 3: Technical Requirements to enable example neutrino physics topics and map to Priority Research Directions.

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3.3 Dark Matter

3.3.1 Science Impact

It is remarkable that, despite the enormous progress in particle physics over the last century, we understand only about one-sixth of the total particles that compose matter in the Universe. The remaining 5/6th are still to be discovered dark matter particles, presumed to be passing through Earth at a speed similar to that of Earth's orbiting the Galaxy. The importance of this problem has been recognized in numerous DOE reports and studies including the 2014 P5 report that identified the search for dark matter particles as one of the five priority Science Drivers for the HEP program.

There are many well motivated ideas of what the dark matter might be. The most popular ones include Weakly Interacting Massive Particles (WIMPs) [61], gravitinos [62], axions [63–65] or other light bosons, sterile neutrinos [66–68], asymmetric dark matter [69], dark glueballs [70], strongly interacting massive particles [71], and hidden sector dark matter [72–78]. These candidates span many orders of magnitude in mass (see Figure 10), and, of course, it is entirely possible that the dark matter could be composed of more than one type of particle. The mass of the dark matter particle is unknown, and in principle could be anywhere between 10^{-22} eV and 10^{19} GeV.

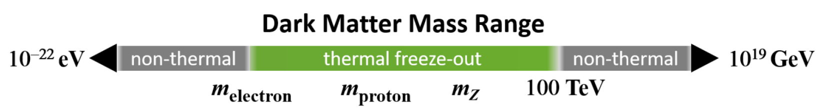

Figure 10: Mass range of theoretical dark matter candidates (from [79]). "Thermal" dark matter is in thermal equilibrium with ordinary matter in the early Universe.

Although multiple astronomical observations give abundant evidence for the gravitational interactions of dark matter at a variety of length and time scales, no other interactions of dark matter have been conclusively detected. As such, it is imperative that several different approaches be pursued. There are four known experimental approaches to search for dark matter: (1) direct detection of interactions of dark matter in terrestrial detectors, (2) detection of signatures of dark matter production by particle accelerators, (3) indirect detection of signatures of annihilations and decays of dark matter from astrophysical sources, and (4) detection of astrophysical evidence of non-gravitational interactions.

The search for dark matter interactions is a multi-pronged world-wide effort involving underground experiments, particle accelerators, and both space-based and ground-based experiments. The U.S. effort is supported by multiple funding agencies including the DOE, other federal agencies, and several private foundations. The foundation of the U.S. dark matter program is the current Generation-2 (G2) dark matter experiments ADMX [80], LZ [81] and SuperCDMS [82]. Additionally, the DESI [83], VRO-LSST [84] and CMB-S4 [85] cosmic surveys have science goals that include probing the microphysics of dark matter through its impact on small-scale structure formation. However, the frontier in dark matter research continues to evolve and in order to maintain U.S. leadership, investment is needed in R&D to develop technologies needed to achieve the scientific goals of the next two decades. We expect broad impact on searches for multiple types of dark matter from a significant number of PRDs in this report.

3.3.2 Sensitivity approaching the neutrino floor to interaction of galactic dark matter particles (1 GeV - 100 TeV)

WIMPs are a favored theoretical class of dark matter particles because there is a simple model for their thermal production in the early Universe. WIMPs would interact with Standard Model particles through the exchange of a Z or Higgs boson, a pair of W bosons, or undiscovered bosons with similar mass, such as the squarks predicted by supersymmetry. The interaction cross-section of the thermally-produced WIMP is model dependent and extends many orders of magnitude, with WIMP masses ranging from the 1 GeV to 100 TeV scale. Significant supersymmetric WIMP parameter space can be tested by future experiments. The cross-section sensitivity to heavier dark matter particles scales linearly with the dark matter mass, producing the same recoil spectrum, independent of dark matter particle mass in the limit where dark matter mass becomes much greater than that of the target nucleus. These experiments therefore have much higher mass

Dark Matter

The composition of dark matter is one of the most mysterious puzzles in particle physics and astrophysics. These ghost-like particles make up approximately 85% of the matter in the universe, but only rarely interact with ordinary matter. As such, dark matter particles surround us and pass through our bodies essentially unimpeded. Scientists became aware of dark matter over 80 years ago by studying its gravitational effects on galaxies, and the evidence is now overwhelming that dark matter is a new kind of

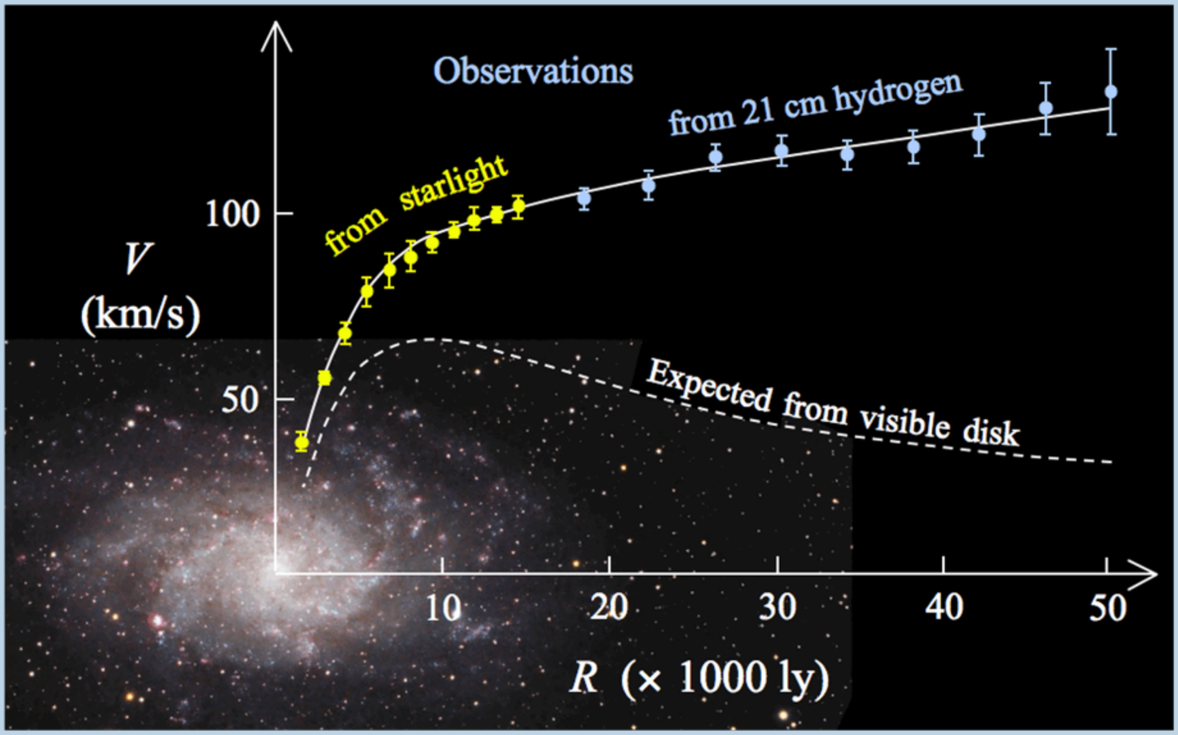

Figure I: Galaxy M33 illustrating how a gravitation force, in addition to that from the visible stars, is needed to explain the speed of stars at the outer edge of this galaxy. Creative Commons Attribution 3.0 Unported. Asher Yahalom, 2019. The Effect of Retardation on Galactic Rotation Curves. Journal of Physics: Conference Series. 1239. 012006. 10.1088/1742-6596/1239/1/012006.

particle that has never been detected in the laboratory. A dark matter halo encompasses our own galaxy, the Milky Way, providing gravitational force that prevents the stars at the edge from flying into outer space. Experiments over the past several

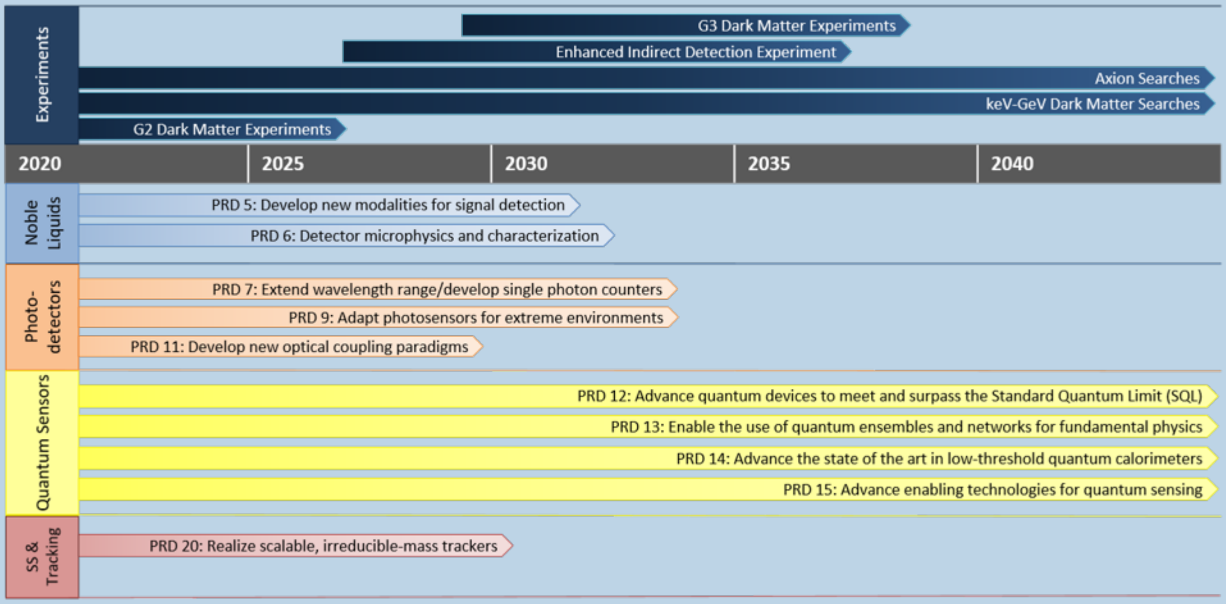

Figure II: Dark Matter Timeline

decades have used increasingly sophisticated techniques to unravel the mysteries behind these enigmatic particles.

Dozens of experiments world wide employ a diverse toolkit of technologies to discover the nature of dark matter. Some of these techniques make use of crystals equipped with state-of-the-art sensors, noble liquids such as argon and xenon, or resonant cavities in an attempt to detect the interactions of dark matter. Other techniques use ground based and space based telescopes to detect particles made in the decay or collision of dark matter particles in galaxies. The timeline for dark matter experiments is illustrated in Figure II.

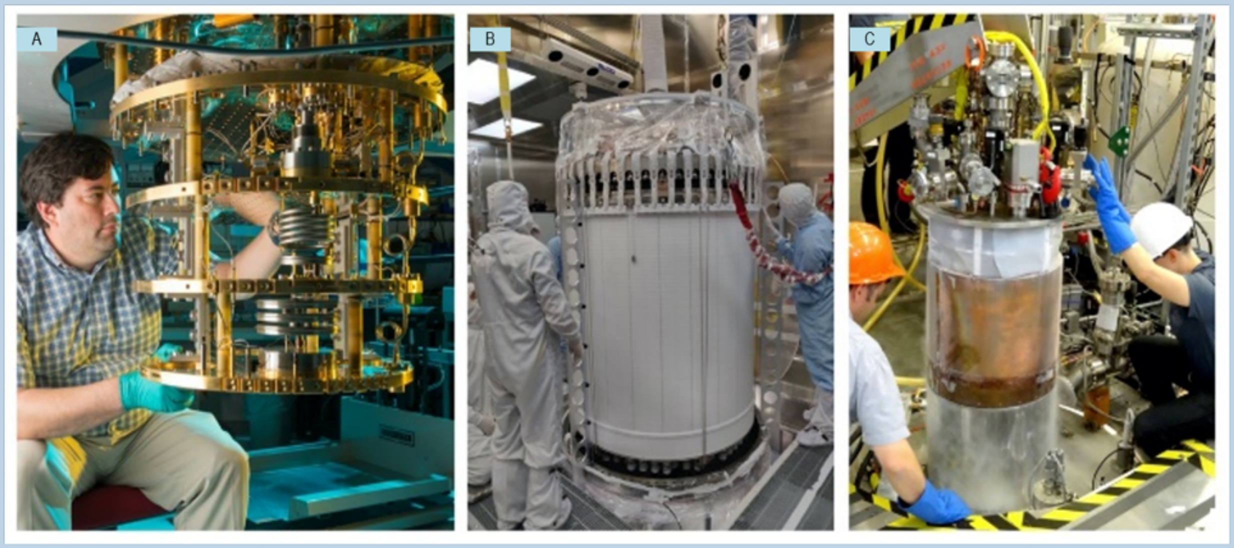

Figure III: The current generation 2 (G2) dark matter experiments include (A) SuperCDMS, (B) LZ, and (C) ADMX. Image credit: Fermilab.

Presently running and future experiments are shown along with their starting times and durations. The current generation 2 (G2) dark matter experiments include ADMX, LZ, and SuperCDMS, depicted in Figure III. The next generation (G3) experiments will build upon the technology of these existing experiments. In addition, there are a large variety of novel detectors currently under development to search for dark matter with masses much smaller than a proton.

Advances in detection technologies are needed in many directions. As an example, one thrust involves development of quantum sensors that enable measurements to surpass the standard quantum limit in order to extend the reach of experiments searching for axions. Figure IV illustrates one such development in quantum sensors. Another thrust involves developing solutions and techniques for reducing backgrounds, including those intrinsic in the materials used to construct the experiments and external backgrounds such as solar neutrinos. A full list of the Priority Research Directions for each technology area needed to expend the mass range in which we can search for dark matter is outlined in Figure II.

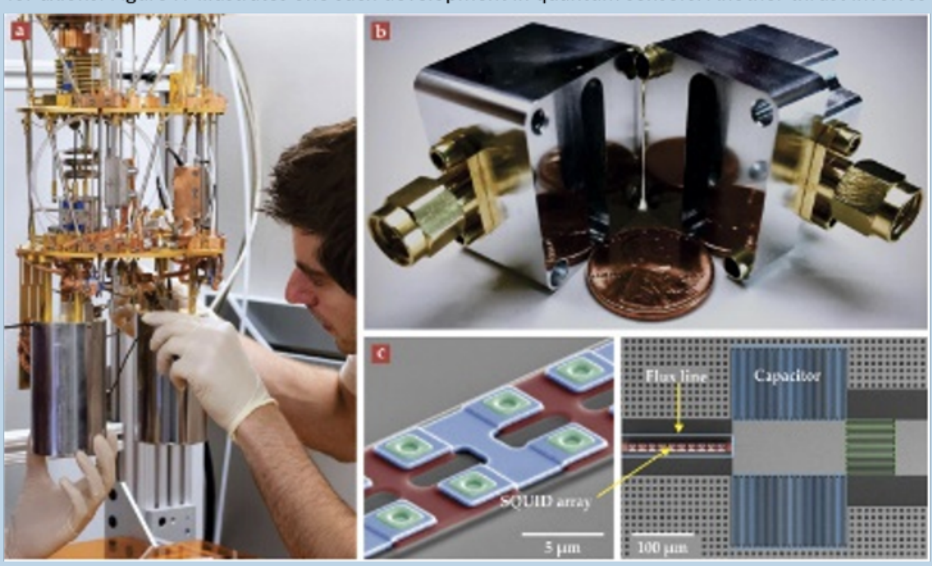

Figure IV: Experimental prototypes. (a) Researchers assemble the two Josephson parametric amplifiers in this squeezed-state receiver for the HAYSTAC experiment. (b) The 7.1 GHz aluminum cavity for the squeezed-state receiver is split open. (c) This microphotograph shows a Josephson parametric amplifier composed of an array of superconducting quantum interference devices (SQUIDs). (Photographs courtesy of Dan Palken.) Published in: Karl van Bibber; Konrad Lehnert; Aaron Chou; *Physics Today* **72,** 48-55 (2019), DOI: 10.1063/PT.3.4227 Copyright © 2019 American Institute of Physics reach than current collider-based experiments, extending up to and beyond the thermal dark matter mass limit of ∼100 TeV, above which the annihilation cross-section of thermally-produced dark matter becomes too small, leading to an over-abundance of dark matter in the Universe.

The current portfolio of direct detection experiments is focused on extending the sensitivity to the scattering of WIMPs on nuclei and the scattering of low-mass dark matter candidates on electrons. Leading these efforts are the DOE funded G2 experiments LZ and SuperCDMS, as well as competing international experiments. These experiments will have searched the spin-independent nucleon-WIMP coupling parameter space to within an order of magnitude of the neutrino floor (the space where solar, atmospheric and astrophysical neutrino interactions become a dominant background) by 2025. In addition, the LZ experiment and PICO, a dedicated spin-dependent dark matter search experiment in Canada, will also have excluded significant parameter space for spin-dependent interactions. There are also ongoing efforts to push sensitivity beyond the neutrino floor using directional detectors. There are also dedicated searches to understand the origin of the annual modulation of event rate observed by DAMA/LIBRA.

The goal of the next generation dark matter experiments (G3) is to explore the dark matter parameter space to the neutrino floor for WIMPs with mass 1 GeV to 100 TeV, as recommended in the P5 report. Relevant PRDs include 5, 6, 7, 9, 11, 24, 25, and 26 (see Table 4). Experiments with sensitivity down to the neutrino floor for masses above 10 GeV will likely be based on two-phase xenon, solid xenon, two-phase or single-phase argon, or bubble chamber detectors. Between 1 and 10 GeV there is a larger variety of proposed targets, including cryogenic and non-cryogenic semiconductors, gaseous detectors, crystalline scintillators, bubble chambers, supercooled water, hydrogen-doped liquid xenon, and xenon and argon detectors with charge-only readout. For all of these proposed G3 experiments, a major challenge is achieving sufficiently low background levels while scaling to large detector masses and maintaining a low energy threshold.

Science	**Measurement**	**Technical Requirement (TR)**	**PRD**
Test for dark matter particles with mass >1 GeV	Search for nuclear recoils arising from scattering of >1 GeV dark matter with normal matter via spin-independent and spin-dependent couplings to nucleons	**Mass 1 - 10 GeV** TR 3.1(SI),TR 3.7(SD): Background rate < coherent scattering rate of solar neutrinos TR 3.2(SI), TR 3.8(SD): Target mass ∼100 kg TR 3.3(SI), TR 3.9(SD): Energy Threshold: ∼100 eV	**5**, **6**, **24**, **25**
		Mass > 10 GeV TR 3.4(SI), TR 3.10(SD): Background rate < coherent scattering rate of atmospheric neutrinos TR 3.5(SI), TR 3.11(SD): Target mass ∼100 tonnes TR 3.6(SI), TR 3.12(SD): Energy Threshold: ∼10 keV	**6**, **7**, **9**, **11**, **25**, **26**

Table 4: Technical Requirements to enable dark matter direct detection experiments to reach the neutrino floor, and map to Priority Research Directions. SI denotes Spin-independent, SD denotes Spin-dependent.

3.3.3 Detection of sub-GeV galactic dark matter particles (1 meV – 1 GeV)

As indicated in Section 3.3.2, a great efforts have gone into searching for the canonical WIMP. However, there has been no evidence of its existence from direct searches and no evidence of physics beyond the Standard Model at the LHC. Theoretical advances in the last decade have indicated that there exists a large number of reasonable dark matter candidates with lower masses, many in the meV-GeV range. Several dark matter candidates naturally lie in this mass range, including asymmetric dark matter, strongly interacting massive particles, and hidden sector dark matter. The motivation for sub-GeV dark matter is described in

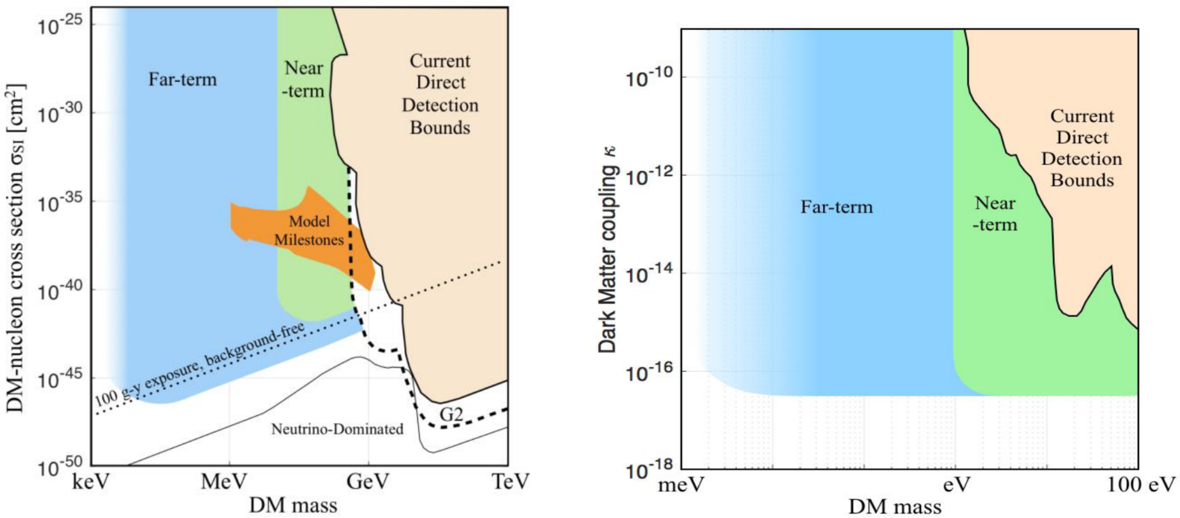

Figure 11: Left: Parameter space for galactic dark matter (DM) scattering off nuclei that can be probed with advanced detectors with demonstrated technologies (green region) and additional R&D (blue region). The G2 direct detection program probes a complementary higher mass region (dashed line) that extends below the constraints from existing direct detection experiments (peach region). Neutrinos begin to dominate the rate below the solid black line. A modest exposure of 100 g-yr can probe extremely low cross sections as long as the detector has the requisite energy sensitivity and sufficiently low backgrounds (dotted line). The orange region (labelled "Model Milestones") presents an example in which dark matter attains the observed relic abundance from its thermal contact with the Standard Model particles. Right: Parameter space for galactic dark-photon dark matter being absorbed by electrons or other excitations that can be probed with advanced detectors with demonstrated technologies (green region) and additional R&D (blue region). Existing constraints from past direct detection experiments are shown in peach. From [79].

a 2019 Basic Research Needs study [79] and references therein, which also describes the many technologies proposed to test these models. Briefly, experiments may search for nuclear recoil (NR), electron recoil (ER), and/or absorption events due to interactions with dark matter. Proposed dark matter interaction targets include semiconductors, two-phase xenon and argon detectors, superfluid helium, molecular gases, crystals, and superconductors. There is strong motivation to search for direct interactions of thermally-produced dark matter particles down to a dark matter mass of a few keV, below which structure formation at small length scales would be suppressed more than is allowed by astrophysical observations. Models of non-thermally produced matter models extend down to much lower masses. Current and projected limits for dark matter NR, ER, and absorption interactions are shown in Figure 11 and Figure 12. Relevant PRDs include 5, 6, 11, 14, 24, and 25 (see Table 5).

Semiconductor-based approaches include cryogenic silicon and germanium as used in SuperCDMS, silicon CCDs as in DAMIC and SENSEI, and doped silicon or germanium crystals with intrinsic charge amplification. Challenges largely derive from internal backgrounds due to tritium and ^{32}Si, external backgrounds from Compton scattering of gamma rays, instrumental backgrounds from charge leakage, and energy thresholds limited to the eV energy scale, below which no ionization signal is produced.

Two-phase xenon and argon detectors are able to search for sub-GeV dark matter particles in charge-only mode, in which a prompt scintillation signal is not required and therefore the detector is not operated as a time projection chamber. Backgrounds due to delayed charge release off of impurities, electrons emitted by metallic grids, and Compton scattering of gamma rays limit the sensitivity. Again, thresholds are limited to the eV scale by the need for ionization to be produced.

A number of other target materials are being proposed, with energy thresholds below the eV scale and resulting sensitivity to lower-mass dark matter particles. These materials include superfluid helium, molecular gases, and crystals. Depending on the target, there are a range of possible quanta that might be

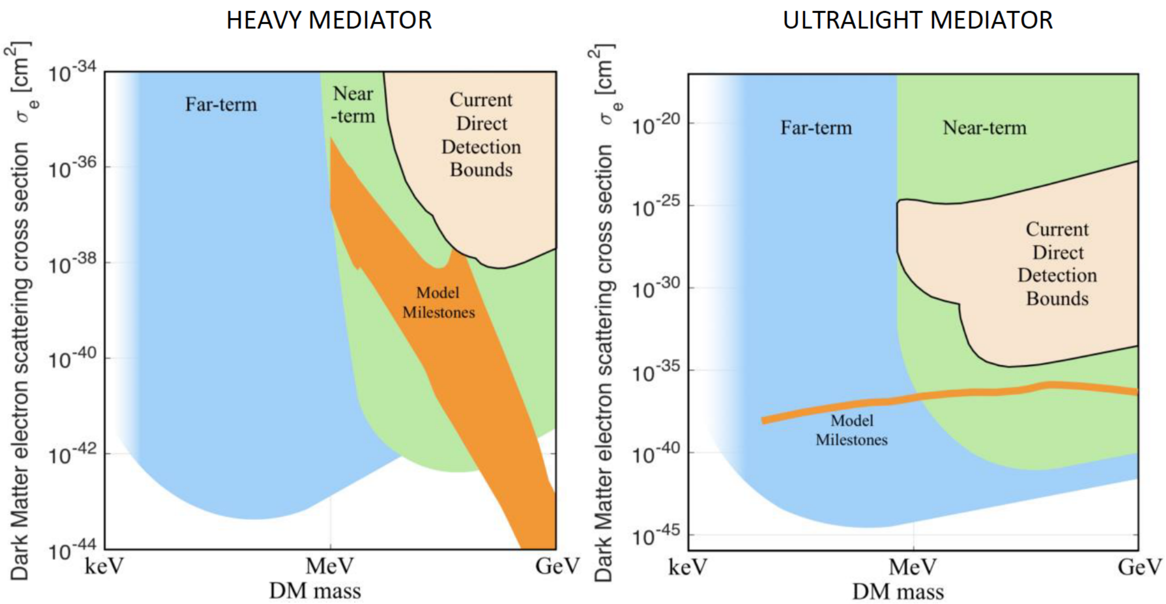

Figure 12: Parameter space for galactic dark matter scattering off electrons, which can be probed by advanced detectors with demonstrated technologies (green region) and additional R&D (blue region), for a mediator with a mass that is heavy (left) or ultralight (right). Constraints from existing direct detection experiments are shown in peach. The orange regions (labelled "Model Milestones") present a range of model examples in which dark matter attains the observed relic abundance from its thermal contact with Standard Model particles (regions are as in the "US Cosmic Visions Dark Matter" report [86]). In the right plot, the upper green region is currently unconstrained, assuming the dark matter is a subdominant component. From [79].

detected, including photons, phonons, rotons, and evaporated He atoms. There is also a range of detection technologies that could be used to sense these quanta, including transition edge sensors (TESs), microwave kinetic induction devices (MKIDs), and superconducting nanowire single photon detectors (SNSPDs).

3.3.4 Detection of galactic dark matter waves ($10^{-22} - 10^{-1}$ eV)

If dark matter is composed of very light bosons, it will have wave-like properties. This strongly affects the search strategy, which may take advantage of the coherence of the oscillating dark matter field over long temporal and spatial scales.

The QCD axion is generally accepted to be the best motivated of the light boson dark matter candidates, because its existence would also solve the strong CP problem [87–89]. Since axions naturally arise in many frameworks for beyond Standard Model physics, searches for axions would be well motivated even if the dark matter problem did not exist [90, 91]. Astrophysical constraints allow the QCD axion to have a mass between approximately 10^{-12} eV and 10^{-1} eV. There is also a simple linear relationship between the QCD axion coupling strength and its mass. These restrictions set clear experimental goals for the next generation experiments, shown in Table 6. In the relatively near term, by 2030, it is expected that the basic technology will be demonstrated by searching for QCD axion dark matter across a total of 3 mass decades between 1 peV to 100 μeV. As explained below, such a wide range necessitates different technical approaches that will probe different mass ranges. In the longer term, by 2040, the technology will have matured to the point that searches will proceed more quickly, enabling coverage of the entire region between 1 peV and 100 meV (11 mass decades).

Additionally, recent theoretical progress has revealed that a broader range of ultralight particles similar to axions can be excellent dark matter candidates. Bosonic light DM fields can be as light as 10^{-22} eV (deBroglie wavelength comparable to the size of dwarf galaxies) and can also range to higher mass scales than allowed by astrophysical constraints on couplings of the QCD axion since the coupling strength of

Science	Measurement	Technical Requirement (TR)	PRD
Test for meV–GeV mass dark matter particles	Search for scattering or absorption of meV–GeV dark matter via coupling to nucleons	**Near Term:** TR 3.13 Threshold ∼1 eV TR 3.14 Target Mass ∼1 kg with negligible background **Long Term:** TR 3.15 Threshold ∼1 meV TR 3.16 Target Mass ∼100 kg with negligible background	**5**, **6**, **11**, **14**, **24**, **25**, **26** **5**, **6**, **14**, **25**, **26**
Test for meV–GeV mass dark matter particles	Search for scattering of meV–GeV dark matter with normal matter via coupling to electrons	**Near Term:** TR 3.17 Threshold ∼1 eV TR 3.18 Target Mass ∼1 kg with negligible background **Long Term:** TR 3.19 Threshold ∼1 meV TR 3.20 Target Mass ∼100 kg with negligible background	**5**, **6**, **11**, **14**, **24**, **25**, **26** **6**, **14**, **25**, **26**

Table 5: Technical Requirements for experiments designed to detect meV-GeV scale dark matter, and map to Priority Research Directions. In the long term, either target mass of 100 kg (with negligible background and ∼1 eV threshold) or a threshold of 1 meV would allow substantial new dark matter parameter space to be tested. Ideally, both of these technical goals would be attained.

generic bosonic dark matter is not as well constrained theoretically as the QCD axion. Covering the more than 20 orders of magnitude in allowed mass range for wave-like dark matter will require a combination of many diverse experimental approaches. Future experiments will have to rapidly search large regions of mass-coupling parameter space to be justifiable.

Figure 13 shows a cartoon illustration of the different regions to be probed by wave-like dark matter searches. There is significant overlap in the couplings and mass ranges that can be covered by the various techniques. If an experiment were to discover a dark matter signal at a specific mass and coupling, it would set an immediate target for other experiments to provide confirmation. In addition, measuring the different couplings of wave-like dark matter with different particles, for example with photons vs. nuclei, would elucidate the nature of the particle and the new physics it entails.

Quantum instruments capable of detecting strains in space-time and/or on material objects, variations in energy levels of quantum systems and/or fundamental constants, differential accelerations, spin torques, and small electromagnetic fields are well-suited to contribute to the search for wave-like dark matter. Examples of detection techniques include atomic clocks, atomic interferometers, magnetic-resonance-based sensors, optical cavities, resonant-mass detectors, microwave cavities, single-photon detectors, superconducting resonators, superconducting quantum interference devices (SQUIDs), quantum amplifiers, and opto-mechanical sensors. PRD 12, 13, and 15 are especially germane to the efforts described in this section (see Table 7).

QCD axion dark matter searches The QCD axion has a coupling to photons that results in small modifications to Maxwell's equations in the presence of axion dark matter. The local dark matter axion density can be represented by an oscillating classical scalar field weakly coupled to the conventional E and B fields. This coupling is the basis for signal generation in the majority of proposed axion search experiments.

The best established axion search technique and the only one so far to have demonstrated sensitivity to QCD axions is the "axion haloscope" proposed by Pierre Sikivie in 1983 [92]. In these experiments, the small

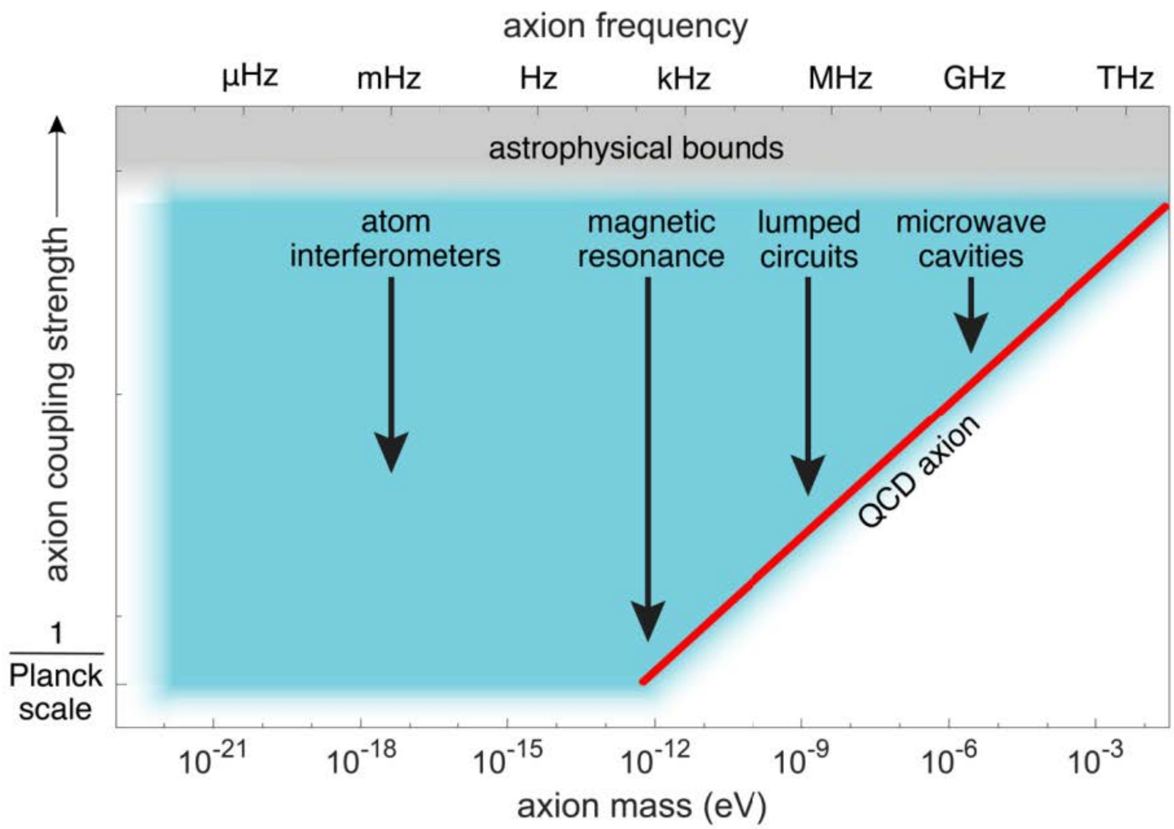

Figure 13: Cartoon figure roughly representing the parameter space for ultralight dark matter and the expected reach of various detection methods. The parameter space for general wave-like dark matter is shown by region shaded in blue. The highest priority target, the QCD axion, is shown by the red line. Current bounds set by astrophysical constraints are shown approximately by the region in gray. Wavelike dark matter with masses below $\sim 10^{-22}$ eV are inconsistent with structure formation. Figure from [79].

oscillating electric field produced by the coupling of the axion to a strong imposed magnetic field drives a high-quality factor (Q) resonant cavity. The most important parameters are the magnetic field strength, the cavity volume and the noise temperature of the amplifier used to read out the cavity. To compare amplifier noise performance between devices operating at different frequency, the noise may be expressed as a ratio between the measured device noise power and the power corresponding to the Standard Quantum Limit (SQL) of noise for photons of a given frequency, $\eta = P_{noise}/P_{SQL}$. As described in the Quantum Sensors section of this report (Section 4.4), the SQL applies whenever a conventional amplifier that allows simultaneous measurements of the amplitude and phase of the electromagnetic field is used to read out the detector. For this type of device (e.g. a transistor or a DC SQUID), $\eta > 1$. Haloscope experiments have a figure-of-merit $QV^2B^4\eta^{-2}$ proportional to the scan speed at a given level of coupling sensitivity, with V the cavity volume, B the magnetic field, and Q the quality factor of the resonator. Historically, experiments have operated at noise levels above the SQL. For example, the ADMX-G2 experiment operated in 2017-2018 with $\eta \sim 10$, achieving sensitivity to QCD axions between 2.7 and 3.3 μeV [80, 93]. Unfortunately, there appears to be only a relatively narrow mass window in which a definitive QCD axion search is possible with $\eta > 1$. Future experiments will need to achieve noise below the SQL in order to probe the much wider mass range allowed by astrophysical constraints. Techniques such as vacuum squeezing (see Section 4.4; initially demonstrated by the HAYSTAC experiment [94]) and photon counting [95] must be developed. This is an exciting example of how research in Quantum Sensors may dramatically effect the prospects for discoveries in particle physics over the coming decades.

For QCD axion dark matter with masses above approximately 100 μeV, the resonant cavity technique becomes very difficult to implement, since resonant structures coupling efficiently to the axion have dimensions of order the Compton wavelength $\lambda = h/m_a c$ and therefore have volume and signal power decreasing as $1/m_a^3$. There is a need for new types of tunable, large volume (i.e. many times λ^3) resonators at high frequency (> 1 GHz). A number of promising schemes have been proposed relying on insertion of adjustable dielectric structures into open linear cavities [96, 97]. Alternatively, non-resonant axion antennas have been proposed [98], with the advantage that no frequency tuning is required. In this case, there is a need for designs that can be scaled efficiently to large size to boost signal power and for sensors combining the lowest possible noise with broadband frequency response.

For axion masses much below 1 μeV, the construction of resonant cavities becomes impractical due to the large physical size. However, a similar type of experiment may be performed using a "lumped element" approach where the self-inductance and capacitance of the cavity are replaced by discrete inductors and capacitors forming an LC circuit [99, 100]. This technique has recently been demonstrated in toroidal [101, 102] and solenoidal [103] configurations. The DMRadio-1m^3 Consortium is developing such an experiment to search the 100 neV to 1 μeV mass range.

For the lumped element approach, the scan rate is proportional to $QV^{10/3}B^4T^{-1}\eta^{-1}$, where T is the physical temperature of the resonator circuit and Q is its quality factor. Comparing the figures-of-merit for the resonant cavity and lumped element approaches, one can see that they are quite similar and this implies significant overlap in the R&D requirements for these two approaches. For this study, we include Technical Requirements so that lumped element experiments can discover or exclude the QCD axion in the 1 neV to 1 μeV mass range in Table 6.

Though the lumped element approach can be usefully employed to search for general wave-like dark matter below 1 neV, it is very difficult to achieve the required coupling sensitivity to discover the QCD axion through its electromagnetic coupling. In this mass range, experiments searching for the coupling of QCD axions to nuclear spins appear to be more promising, where the axion field may induce an oscillating nuclear electric dipole moment or appear as a fictitious, oscillating magnetic field. In either case, a small oscillating torque on an ensemble of polarized nuclear spins can be detected using magnetic resonance techniques, as proposed by the CASPEr Collaboration [104]. This may enable a search with sensitivity to the QCD axion at masses as low as 1 peV. The fundamental limit to this approach is spin projection quantum noise and if an experiment can achieve this limit, it would be sensitive to the QCD axion. However, this approach is limited by the thermal spin polarization (P), spin coherence time (τ), number of nuclei (N), and the quantum sensor readout, which provide guidance for the requirements listed in Table 6.

Axion-Like Particle, Fifth Force, and "Light Shining Through Walls" Experiments Below 1 peV the coupling of the QCD axion to normal matter becomes extremely small and difficult to detect. However, the same theoretical constructs that predict QCD axions can also yield other wave-like dark matter candidates down to 10^{-22} eV with potentially stronger couplings than QCD axions. (Wave-like dark matter with masses below $\sim 10^{-22}$ eV are inconsistent with structure formation.) Atomic interferometers, opto-mechanical sensors, and torsion pendulums can be used to search this mass range for a variety of signatures such as strains in space-time and/or on material objects, variations in energy levels of quantum systems and/or fundamental constants, differential accelerations, spin torques, and small electromagnetic fields. Given the wide variety of experimental approaches and unexplored parameter space, a generic technical requirement is that development of future technologies should focus on those able to exclude many decades of mass and couplings all at once. It is reasonable to expect that 15 square decades in the mass-coupling parameter space can be probed in the coming decade and 30 square decades in the coming two decades.

Another category of experiment does not seek to directly detect dark matter particles from our galactic halo, but instead probes the existence of new forces mediated by scalar or vector bosons that might also be the dark matter. The new force can be either spin-dependent or scalar or spin-scalar, implying a large parameter space to search with diverse methods. For example, the ARIADNE experiment [105] uses magnetic resonance techniques to search for spin-dependent fifth forces due to axion exchange between nuclei and can potentially cover the QCD axion mass range between 10 μeV and 10 meV in the next $\sim$ 20 years. To achieve this requires improvements in polarization fraction (P), spin-density (n), relaxation time (τ), and sample volume (V) in terms of axion wavelengths (λ_a), which drives the Technical Requirements listed in Table 7.

It is also possible that a new boson may mediate coupling between the electromagnetic field modes of separated resonant cavities [106, 107]. Experiments to search for hidden photons, axions, and axion-like particles have been carried out at microwave and visible light frequencies. Such "light shining through walls" searches depend strongly on the cavity quality factor, motivating relevant technical requirements. A new generation of such experiments may be enabled by recent progress in improving the quality factor of RF cavities for accelerator applications.

The European-led IAXO experiment is a large effort that will search for axions and axion-like particles produced in the Sun over a wide mass range [108]. It will be the only experiment sensitive to QCD axions at the highest allowed mass range of approximately 100 meV. One challenge of this experiment is the development of custom X-ray optics.

Generally, fifth force and light shining through walls experiments also benefit from the same types of technologies needed for QCD axion searches, including resonator improvements, lower noise amplifiers, photon counters in new regions of the electromagnetic spectrum, and techniques to evade the SQL.

Science	**Measurement**	**Technical Requirement (TR)**	**PRD**
Test for peV–neV QCD axion dark matter	Search for peV–neV QCD axion dark matter via axion-nucleon coupling with nuclear magnetic resonance	**Near Term:** TR 3.21 $P \geq 0.05$ TR 3.23 $N\tau = 10^{24}$ sec.	**12, 13, 15**
		Long Term: TR 3.22 $P \geq 0.3$ TR 3.24 $N\tau = 10^{25}$ sec.	**12, 13, 15**
Test for neV–μeV QCD axion dark matter	Search for neV–μeV QCD axion dark matter using axion-photon conversion in lumped-element electromagnetic resonators	**Near Term:** TR 3.25 $Q_L \geq 10^6$ GeV TR 3.27 $\eta \leq 20$ TR 3.29 $BV \geq 4\,\mathrm{T}\cdot\mathrm{m}^3$	**12, 15**
		Long Term: TR 3.26 $Q_L \geq 10^8$ TR 3.28 $\eta \leq 0.1$ TR 3.30 $BV \geq 10\,\mathrm{T}\cdot\mathrm{m}^3$	**12, 15**
Test for μeV–meV QCD axion dark matter	Search for μeV–meV QCD axion dark matter using axion-photon conversion in cavity electromagnetic resonators	**Near Term:** TR 3.31 $Q_C \geq 10^5$ TR 3.33 $\eta \leq 1$ TR 3.35 $B \geq 10\,\mathrm{T}$, $V \geq 100l$	**12, 15**
		Long Term: TR 3.32 $Q_C \geq 10^6$ TR 3.34 $\eta \leq 10^{-6}$ TR 3.36 $B \geq 30\,\mathrm{T}$, $V \geq 1l$	**12, 15**

Table 6: Technical Requirements and map to Priority Research Directions for experimental parameters (polarization fraction P, number of nuclei N, spin coherence time τ, sample volume V, noise temperature ratio η, magnetic field B, and resonator quality factor Q_C or Q_L) for experiments to detect or exclude QCD axion dark matter in the 1 peV to 100 μeV range.

3.3.5 Detection of dark matter particle annihilations and decays

If the dark matter particle has mass above the TeV scale, indirect detection techniques, where the gamma rays, antiprotons, positrons, neutrinos, and other particles that are produced in the annihilations or decays of dark matter particles are detected, may be the most feasible discovery tool. A primary candidate for indirect detection searches is the WIMP with masses in the GeV to TeV range. In addition, recent theoretical models motivate dark matter with mass up to the PeV range and with stronger interactions, decaying dark

Science	Measurement	Technical Requirement (TR)	PRD
Search for 10 μeV–10 meV QCD axions and ALPs (not necessarily dark matter)	Test for fifth forces via nuclear magnetic resonance	**Near Term:** TR 3.37 $P \geq 0.5$ TR 3.39 $n\tau = 10^{24}\,\text{sec.cm}^{-3}$ TR 3.41 $V = 10^3\,\lambda_a$	**12, 13, 15**
		Long Term: TR 3.38 $P \geq 0.7$ TR 3.40 $n\tau = 10^{27}\,\text{sec.cm}^{-3}$ TR 3.42 $V = 10^4\,\lambda_a$	**12, 13, 15**
Search for hidden photons (not necessarily dark matter) 10^{-12} eV - 10^{-4} eV	"Light shining through walls" experiments with electromagnetic resonators	**Near Term:** TR 3.43 $Q \geq 10^{11}$	**12, 15**
		Long Term: TR 3.44 $Q \geq 10^{13}$	**12, 15**

Table 7: Technical Requirements and map to Priority Research Directions for non-dark-matter-based searches for the QCD axion, ALPs, and hidden photons via fifth-force and "light shining through walls" experiments in terms of polarization fraction P, spin-density n, relaxation time τ, sample volume V, and resonator quality factor Q.

matter [109–116], and hidden sector candidates [117, 118]. Dark matter more massive than the TeV scale can be difficult to access by collider searches and their low number density make direct searches for them challenging. However, it is possible to search for the products of dark matter annihilations from high density dark matter regions within and beyond our galaxy. In addition, an instrument with a large field of view and extended viewing time could also look for extended emission from the decay of dark matter particles in galactic halos.

The abundance of dark matter in the early Universe is set by the dark matter self-annihilation cross section in many theoretical models. In these models, a stable particle with a thermally averaged annihilation cross section of $\langle\sigma v\rangle \simeq 2.2\times10^{-26}\,\text{cm}^3/\text{s}$ is predicted to freeze out of thermal equilibrium with an abundance equal to the measured cosmological density of dark matter [119–121]. The dark matter is predicted to annihilate with a similar cross section in the modern Universe in a variety of theoretical models. This provides an important benchmark for indirect dark matter searches. Early-Universe thermal production of dark matter requires the dark matter particle mass to be less than about 200 TeV. The current generation of gamma ray, neutrino, and cosmic ray searches for dark matter annihilation products are sensitive to dark matter with this cross section for masses up to the order of the weak scale. Moving forward, the goal of these searches is to cover the entire mass range up to 200 TeV.

The current portfolio of indirect detection experiments is focused on extending the sensitivity of the annihilation of thermal WIMP dark matter from a variety of sources including the galactic center and dwarf galaxies. Leading these efforts are the space/balloon-based instruments Fermi Gamma Ray Space Telescope, AMS-02, and GAPS and the ground-based telescopes HESS, MAGIC, VERITAS, HAWC and IceCube. The space/balloon-based telescopes are most sensitive to dark matter candidates with mass below ∼TeV, while the ground-based telescopes are most sensitive to dark matter candidates with mass above ∼TeV. These experiments will have sensitivity to many theoretical models with a thermally averaged annihilation cross section of $\langle\sigma v\rangle \simeq 2.2\times10^{-26}\,\text{cm}^3/\text{s}$ by 2025. In addition, the data from these experiments have been used to put constraints on models of dark matter decay from a variety of sources.

Space/balloon-based telescopes are based on particle trackers and will benefit specifically from PRD 20, which seeks to advance this type of detector. Most ground-based telescopes work by imaging high-energy photons through the Cherenkov radiation from secondary charged particles that are produced when the photon hits the atmosphere, while water-Cherenkov-based experiments detect the charged particles when they reach the ground via Cherenkov emission as they pass through water tanks. The challenge for the next generation of ground-based experiments is to develop cheap photodetectors with sufficient quantum efficiency to cover a large enough area to maintain sensitivity of the entire dark matter mass range up to 200 TeV/c^2 for dark matter with a thermally averaged annihilation cross section of $\langle \sigma v \rangle \simeq 2.2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$. As such, several of the PRDs relating to photodetectors will have a significant impact on ground-based telescopes, as listed in Table 8. PRD 26 will benefit both types of experiments given the scale-ups in experiment size that must go hand-in-hand with improved detection technology.

Science	**Measurement**	**Technical Requirement (TR)**	**PRD**
Test for <1 TeV dark matter that annihilates or decays	Search for annihilation or decay products (gamma rays, antimatter) with space-based or balloon-based experiments	TR 3.45 Area ∼30 m^2 str with all sky sensitivity TR 3.46 angular resolution ∼few arcminutes	**26** **20**
Test for 1–200 TeV dark matter that annihilates or decays	Search for dark matter annihilation or decay products with ground-based experiments	TR 3.47 Area ∼221,000 m^2 with varying fill factors & wide field of view TR 3.48 SiPM QE > 40-50% in UV/optical TR 3.49 SiPM dark rate <1 KHz/mm^2 at 5° C TR 3.50 SiPM dynamic range from 1 PE to 100 PE / mm^2 TR 3.51 timing < 0.5 nsec TR 3.52 factor ∼3 increase in scintillating light yield (1 PE for 6 MeV)	**11, 26** **7** **7** **7** **7** **11**

Table 8: Technical Requirements and map to Priority Research Directions for indirect detection experiments.

3.3.6 Dark matter physics in other HEP sub-fields

In addition to the models and techniques described above, other sub-fields across HEP are making significant contributions to constraining dark matter models and may enable detection of its interaction with Standard Model particles.

In thermal "dark sector" models, there are particles that interact with both the dark matter as well as the Standard Model. This dark sector may manifest as a force carrier that mediates interactions between the dark matter and Standard Model particles. In some models, dark sector particles may decay to a combination of Standard Model and dark sector particles. In other models, the dark sector includes excited states that decay into Standard Model particles or a combination of Standard Model particles and dark matter. Particle accelerators like the LHC and SPS can be used to search this space; work in this area is described in Section 3.5.5, in Physics of the Unknown.

Missing momentum and beam-dump experiments are another primary tool for searching this space. In general, such experiments search for deviations from Standard Model predictions due to production of dark matter particles. Missing momentum experiments use detectors operating in a lepton beam, identifying dark matter particles via the kinematics of visible particles recoiling from dark matter production events through a force mediated with a dark photon. Operating these experiments in a continuous-wave electron beam offers a path to achieving at least 1000-fold enhanced sensitivity to certain hypothesized dark matter interactions over existing capabilities. These experiments have significant potential for detecting dark matter in the keV to GeV range. DOE facilities providing such beams include LCLS-II and CEBAF. HPS is one such experiment, currently in operation at CEBAF. LDMX is one proposed missing momentum experiment, which would take place at LCLS-II.

Beam-dump experiments use detectors placed downstream from an existing electron or proton beam-dump. Capable of a factor of at least 10-fold increased sensitivity to certain hypothesized dark matter interactions over existing capabilities, these experiments search for dark matter particles produced in the beam dump which then scatter in a sensitive detector. In the event of a discovery, these experiments offer the unique ability to measure additional properties of the dark matter particle. The U.S. has multiple facilities that can be exploited to realize a beam-dump experiment including CEBAF or LCLS-II, Booster/Main Injector, SNS or LANSCE.

Cosmological measurements and studies of structure formation in the early Universe are another powerful method of constraining dark matter models. Instruments used to study dark energy and inflation can also be used to probe the microphysics of dark matter through its impact on the formation of small-scale structures. Details of these programs can be found in Section 3.4, Cosmic Acceleration: Dark Energy and Inflation.

3.3.7 Dark Matter: Preparing for Discovery

Tremendous advances in technology have lead to significant progress in excluding large areas of dark matter parameter space. However, despite this progress, the constituents of dark matter remain unknown. We outlined an ambitious physics program along four major thrusts:

- Searching for WIMP dark matter towards the neutrino floor
- Searching for particle dark matter with low masses
- Searching for wave-like dark matter
- Searching for the annihilation or decay products of dark matter interactions

R&D into new technologies is required in order to achieve the science program outlined here. With adequate support, each of these programs has the potential to lead to a major discovery in the coming decades.

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3.4 Cosmic Acceleration: Dark Energy and Inflation

3.4.1 Introduction

Cosmological measurements are a powerful window into particle physics and our cosmic origins. The discovery of the cosmic microwave background (CMB) in 1965 validated the hot big bang cosmological model, and subsequent measurements of CMB anisotropies point towards an epoch of accelerated expansion during the first instants of our Universe. In the late 1990s, measurements of the expansion history using Type Ia supernova (SNe Ia) provided the first evidence for cosmic acceleration [122, 123] at late times. Cosmic acceleration in the early and late Universe corresponds to new physics that is not captured by Standard Model particles and interactions.

Over the past three decades, scientists have studied the physics of late (dark energy) and early (inflation) cosmic acceleration using a combination of space-based and ground-based experiments, where space-based facilities benefit from being above the atmosphere and ground-based facilities can deploy instruments with very large collecting areas. The ground-based program has taken a staged approach through a series of increasingly complex and sensitive cosmology experiments. The ground-based experiments DES, HSC, and Stage III CMB experiments are operating or have completed operations and are analyzing data. Ground-based experiments in the construction or planning stages include the US-led Dark Energy Spectroscopic Instrument (DESI) [83], the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) [84] and CMB-S4 projects [85], and the Japanese-led PFS.

Where these current cosmic surveys primarily probe the very early or very late Universe, next-generation surveys will seek to measure the entire Universe at a variety of scales. They will characterize the distribution of matter using 1) the largest volumes possible to optimize cosmological measurement precision, 2) a large range of spatial scales for sensitivity to a full suite of cosmological parameters, and 3) the broadest possible range in redshift to fully measure the evolution of the cosmos. Below we motivate next generation ground-based cosmic surveys in more detail and describe the new instrumentation required to implement this exciting program.

3.4.2 Next generation cosmic surveys

Following the completion of DESI, LSST, and the upcoming CMB-S4 surveys, there are two primary goals for a next generation cosmic survey program.

- **Fully sample the late-time accelerating epoch to advance our understanding of dark energy** This goal requires an optical-infrared spectroscopic galaxy survey out to redshifts of $z < 1.5$ and spanning scales smaller than 100 Mpc. Fully sampling this volume corresponds to measuring 500M individual galaxy spectra each with resolving power of 3000.

- **Distinguish between single-field and multi-field inflationary models.** This goal complements current experiments measuring the energy scale of inflation (e.g. via CMB polarization). Non-Gaussianity, generically parameterized by f_{NL}, is sensitive to the number of fields active in inflation and measuring f_{NL} down to ~ 1 would distinguish between multi-field and single-field inflationary models. This objective is best achieved through multiple survey techniques that exploit the large volume accessible at high redshifts and corresponds to measuring the integrated flux from $O(1\text{B})$ galaxies out to $z \sim 6$.

The science impact from an ambitious program of next generation cosmic surveys in the 2030-2040 timeframe is broad and profound, extending beyond the topics of dark energy and inflation. These surveys will also sharpen our understanding by constraining the neutrino mass scale, probing the microphysics of dark matter through its impact on the formation of small-scale structures, and unveiling new degrees of freedom produced at high energies in the early Universe.

Below, we outline the scientific potential provided by cosmic surveys addressing the two goals discussed above. There are two clear regimes of discovery space. The first is at low redshifts, where the Universe transitions from a decelerating regime governed by matter to an accelerating regime governed by an unexplained physical mechanism (dark energy). The second regime is at high redshifts where the large volume allows precise tests of inflation, neutrino mass, early Universe physics, and non-standard models of dark energy

Cosmic Acceleration: Dark Energy and Inflation

Cosmological surveys measure how the entire universe grows over time (see Figure I), and uniquely explore the fundamental physics underlying two eras of cosmic acceleration: an early acceleration epoch explained by the physics of inflation, and a period of late cosmic acceleration driven by Dark Energy. Neither are explained by our current standard model of particles and interactions, and cosmological surveys are the only measurements that can study them.

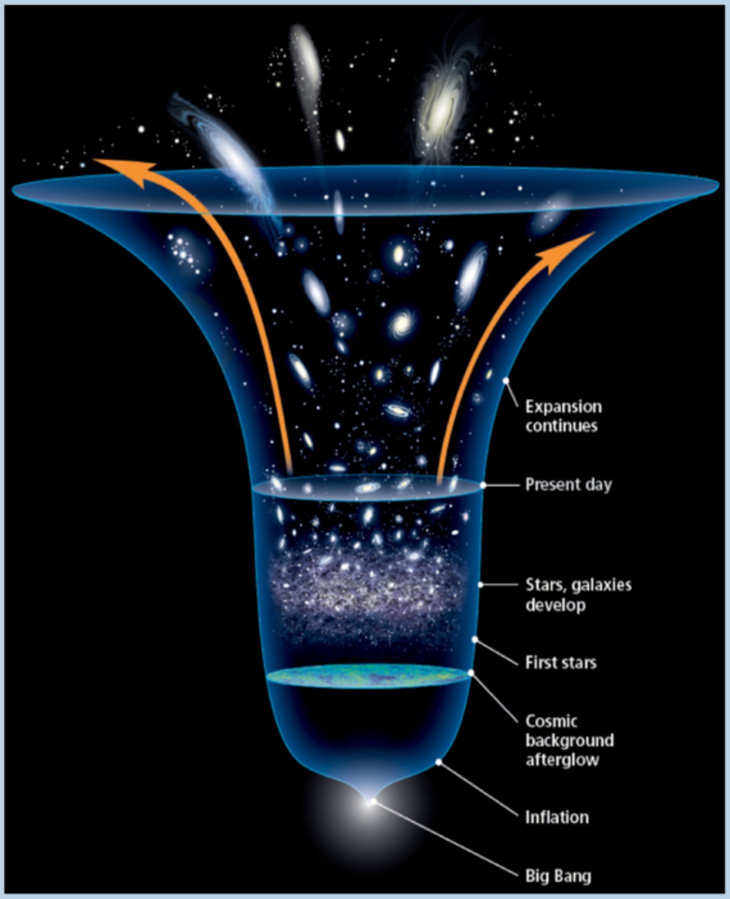
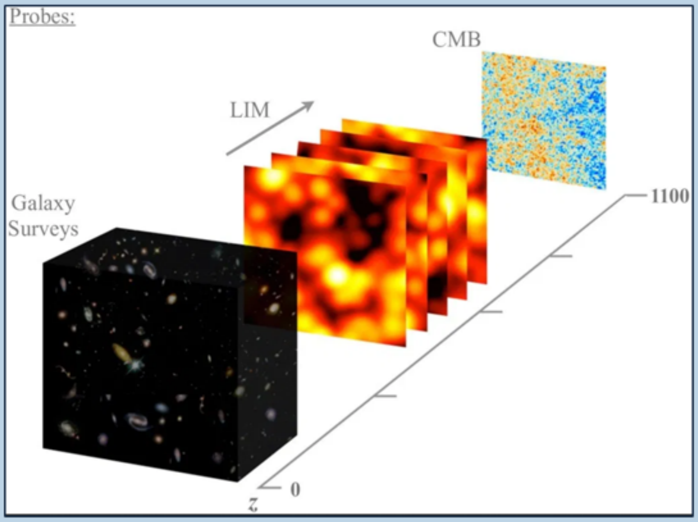


Figure I: The origin and evolution of our Universe. Image credit: Roen Kelly.

Over the past three decades, research into late (dark energy) and early (inflation) cosmic acceleration used a series of increasingly complex and sensitive cosmological surveys. The current generation of experiments are DESI and LSST, which study dark energy, and CMB-S4, which studies inflation. The combination of these three surveys will anchor our understanding of the universe at both early and late times, but still only provides access to a tiny fraction of the available Universe. The next generation of cosmic survey facilities aim to fully survey the evolution of the universe as it grows from these early instants into what we observe today. These new facilities include: a facility for an optical/infrared spectroscopic galaxy survey, and facilities for line intensity mapping surveys (LIM), one focused on the 21-cm line and one at mm-wavelengths.

Figure II shows the sensitivity of each type of survey. The results will provide new tests of the intersection of cosmology and particle physics, including insight into the physics of early and late cosmic acceleration.

These three new facilities require new photodetector, quantum sensor, and TDAQ technologies to vastly increase the sensitivity and survey speed over existing cameras. For the optical/near infrared survey, increased sensitivity will come from new detectors that can detect light at longer wavelengths than the traditional silicon CCDs, as well as increases in the number of spectroscopic targets with reduced spacing between the fibers that measure the flux from each source.



For the 21-cm facility, the primary technological challenges come from synchronizing the timing of each radio dish to better than one pico-second, at spacings of more than one kilometer apart. The mm-wave facility requires development and scaling of new on-chip, mm-wave detector and readout technologies with a few hundred channels per pixel. Figure III shows a single-chip spectrometer prototype that could be developed for mm- wave intensity mapping.

Figure II: Different surveys access different regions of the history of the universe: Galaxy surveys probe the recent history and CMB surveys probe the physics of the very early universe. Line Intensity Mapping (LIM) surveys can access the uncharted regions between galaxy surveys and CMB surveys. Credit http://arxiv.org/abs/1903.04496

Figure IV shows anticipated progress of cosmic surveys: For galaxy surveys, after DESI and LSST the next step in exploring the properties of Dark Energy will require a massive spectroscopic survey, reaching longer wavelengths than currently possible, and a huge increase in the number of measured spectra. The CMB detector technology has a potential application for intensity mapping at mm wavelengths, if a high enough density of detectors can be achieved. A prototype experiment should be developed after the completion of the current Stage 3 CMB experiments to demonstrate the feasibility of a future large mm-wave survey in the 2030's. Intensity mapping of the 21cm line is also a promising way to study the uncharted regions between the CMB and galaxy surveys. The main technical challenge, picosecond timing synchronization, is an area of active progress and early R&D could enable an experiment start by the end of the decade.

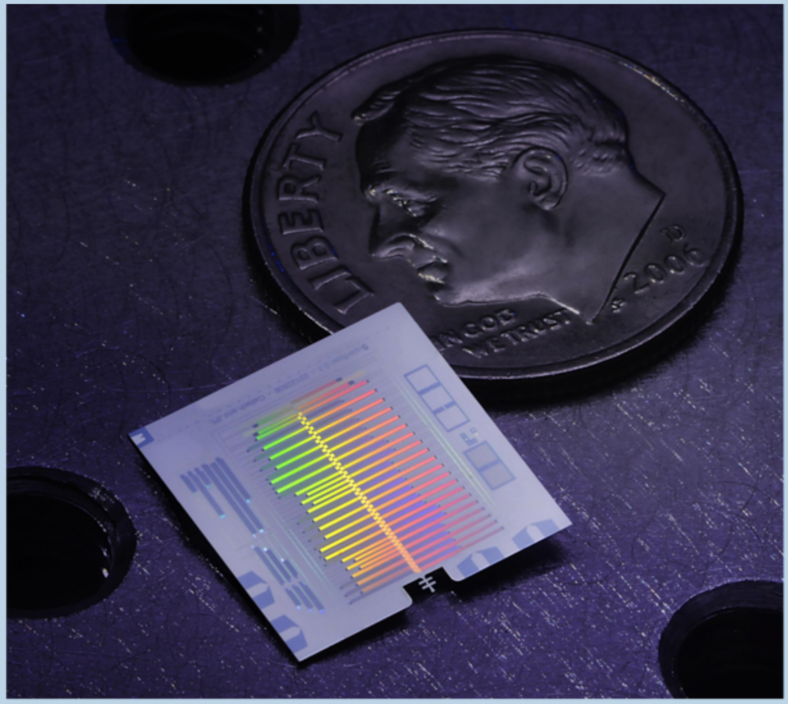


Figure III: A prototype single-chip spectrometer operating in the millimeter-wave regime. Image credit: JPL/NASA.

These facilities, enabled by the new technology discussed above, will measure the distribution of mass in the universe as it evolved from early to late times, strengthening the connection to the early universe results from CMB experiments. They will collect spectra of billions of galaxies over an expanded wavelength range, increasing the precision and sensitivity of probes of late time physics. Together these facilities address the most fundamental questions in cosmology.

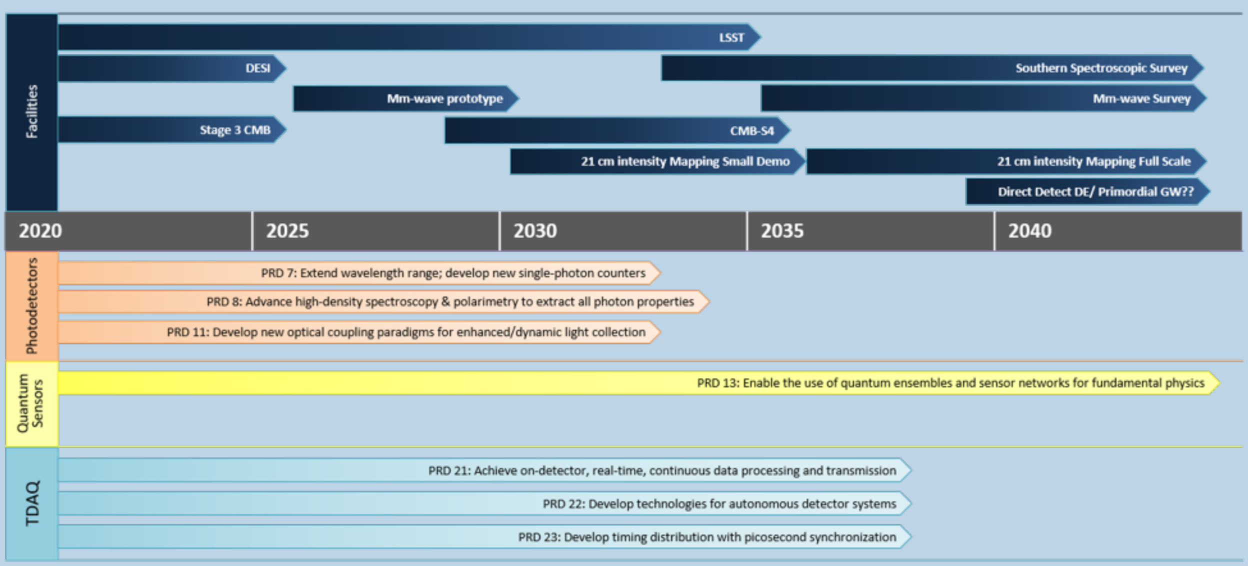


Figure IV: Dark Energy and Inflation Timeline (e.g. early Dark Energy). The discovery space for these survey programs is presented in Figure 14, and the timeline is found in the Cosmic Acceleration sidebar.

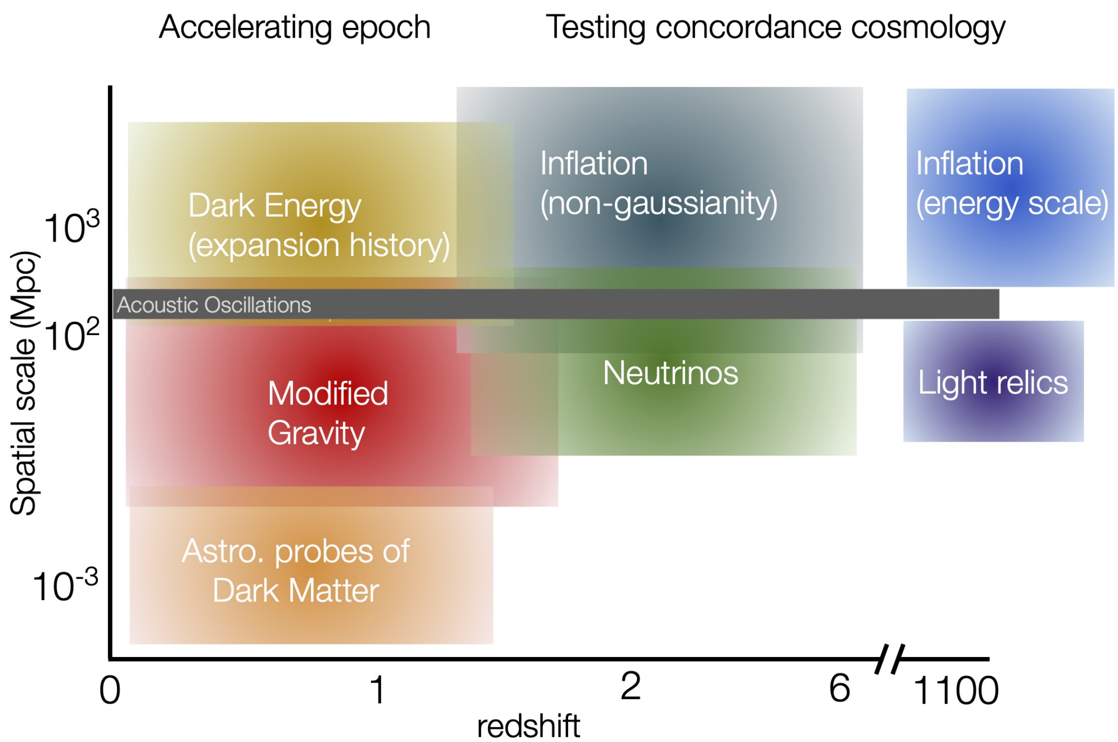


Figure 14: Key cosmological Science Drivers as a function of redshift (x-axis) and scale of clustering (y-axis).

3.4.3 Next-generation cosmic survey requirements

The above two primary science goals, understanding dark energy and inflation, define at a high level the structure of a next-generation cosmic survey program in the 2030-2040 timeframe. This survey program has two components: one focused on fully sampling the low redshift ($z < 1.5$) Universe when late-time cosmic acceleration is dominant, and one focused on sampling much more densely the Universe out to $z \sim 6$. The science impact from these next-generation cosmic surveys extends well beyond the topics of dark energy and inflation: they will also probe the microphysics of dark matter, constrain the neutrino mass scale, and test for early Dark Energy, and search for new degrees of freedom produced at high energies in the early Universe.

Extract all available information about dark energy by fully sampling the late-time accelerating epoch. Dark energy becomes dominant at late times, $z < 1.5$, the last 9 billion years. The ability to constrain dark energy is limited by the statistical power of surveys in this epoch. The baryon acoustic oscillation (BAO), weak lensing, and SN Ia measurements from current experiments will lead to major advances in understanding the time-evolving nature of dark energy. However, there will be a vast reservoir of information on the cosmic expansion history remaining to be tapped through spectroscopic observations of clustering at small scales and lower redshifts (lower left corner of Figure 14). Fully extracting the available information requires fully sampling scales smaller than 100 Mpc for $z < 1.5$. Such sampling requires an optical-infrared spectroscopic galaxy survey with resolving power of 3000 measuring 500M individual galaxy spectra, an order of magnitude larger sample than expected from near-term surveys. Three-point statistics, forward modeling of the density field, and advanced modeling of the galaxy-halo connection will make it possible to extract information from next-generation measurements of structure growth on these small, nonlinear scales. Combining our ability to exploit the physics at these small scales with unprecedented sensitivity, these measurements will deepen our understanding of dark energy and potentially show whether General Relativity must be modified to explain late-time cosmic acceleration [124].

Beyond cosmic acceleration, survey data on the smallest-scale structures (dwarf galaxies, streams, and other galactic substructures) will enable tests of dark matter particle mass, self-interactions, coupling to the Standard Model, and time evolution [125].

Distinguish between single-field and multi-field inflationary models by exploiting the large survey volume available at $z > 1.5$. Experiments are currently being planned or proposed to measure, or set stringent upper limits on, the energy scale of inflation (ground-based: CMB-S4; space-based: Inflation Probe). The other crucial aspect of inflation that needs to be understood is whether it involves a single or multiple fields. With this information, the shape of the corresponding potential(s) can be determined from the data. Non-Gaussianity in the distribution of matter in galaxy clustering over the largest scales, generally parameterized by f_{NL}, is sensitive to the number of fields, with $f_{NL} \approx 1$ dividing single- and multi-field inflation. This objective is best achieved through surveys at 21 cm and mm wavelengths, which provide access to the large volume available at high redshifts prior to the Epoch of Reionization [126], making use of the $O(1\text{B})$ galaxies out to $z \sim 6$ (top central region of Figure 14). The resulting factor of 100 increase in sample size relative to current surveys will yield an order of magnitude improvement in precision over the best limits available today ($\sigma_{f_{NL}} \sim 5$ [127]).

In parallel, exploration of clustering at $z > 1.5$ at smaller scales (bottom central region of Figure 14) will lead to vast improvements on the precision of the BAO distance scale and structure growth measurements. These measurements will open a new frontier in measuring the neutrino mass scale, testing for early Dark Energy, and searching for new degrees of freedom in the early Universe [128].

3.4.4 Science-driven technology R&D

To achieve unprecedented constraints on fundamental physics from future cosmology measurements, we require surveys of the cosmos at a variety of scales that will be enabled by immediate R&D to develop instrumentation across three different techniques: Optical/IR spectroscopy, 21-cm intensity mapping, and mm-wave intensity mapping (see Table 9). Intensity mapping is a survey technique that uses low spatial resolution instruments with high sensitivity to measure the emission from all objects along the line of sight. For sufficiently narrow detection bands, the spatial map is dominated by line-emission coming from galaxies within a narrow slice in redshift. Observations over a broad range of detection bands provide a spatial-spectral data cube that measures the distribution of a biased tracer of the three-dimensional dark matter density field.

Optical-infrared spectroscopic cosmic surveys

The key enabling technologies for the Stage-IV VRO-LSST and DESI surveys are large-format Silicon CCDs [84] [129]; for DESI these are hosted by three-channel spectrographs and robotic positioners [130] that place fiber optics into the light path of spectroscopic targets. DESI will obtain spectra at $z < 1.5$ at typical densities of 1500 galaxies per square degree. Clustering at higher redshifts will be explored through quasar spectra, primarily through absorption at $z > 2$ due to the Lyman-alpha transition in neutral hydrogen. Even with Lyman-alpha forest observations, DESI will be shot-noise limited on all scales at $z > 1.5$.

A next generation galaxy survey is motivated in part by the pursuit of dark energy science and models of modified gravity with measurements of the structure growth rate at $z < 1.5$. To incorporate advanced models that optimally constrain the structure growth rate on Mpc scales, a sampling of the density field of at least 20,000 galaxies per square degree is required. Such a sample will enable modeling of astrophysical nuisance parameters and allow significant strides in modeling the dynamic nature of dark energy or modified gravity. Over a 14,000 square degree footprint, a next generation program would produce 280 million spectra, corresponding to 7% of the LSST gold sample.

Precision measurements of clustering at redshifts $z > 1.5$ further motivate a next generation galaxy survey. Massive spectroscopic samples at these redshifts would advance modeling of non-concordance dark energy, curvature, inflation, and neutrino physics. These objectives are best pursued with Lyman-alpha emitting and Lyman-break galaxies that are plentiful over the redshift interval 1.5<z<4. A sample of 10,000 galaxies

Science Goal	Measurement	Technical Requirement (TR)	PRD
Fully sample the epoch of late-time cosmic acceleration	500M Galaxy spectra (R$\sim$3000) to z<4	For Optical/IR spectroscopy TR 4.1: Sensitivity at wavelengths beyond the 1eV Silicon cutoff. TR 4.2: Ten-fold increase in multiplexing relative to current experiments	**7, 11, 26**
Distinguish between single vs. multi-field inflation by measuring f_{NL} down to 1	Multiple Intensity mapping surveys to measure flux from 2.9B galaxies to z<6	For 21-cm Intensity Mapping: TR 4.3: Pico-second timing synchronization across $\sim$km TR 4.4: Direct digitization and real-time calibration	**21, 22, 23, 26**
		For mm-wave Intensity Mapping: TR 4.5: On-chip mm spectrometers with R>200 TR 4.6: Fabrication and readout of 1M detectors	**7, 8, 26**

Table 9: Science goals for next generation cosmic survey program along with survey techniques and technical requirements.

per square degree at magnitudes over a 14,000 square degree area can be identified with LSST imaging, leading to a density that is two orders of magnitude larger than the quasar density of DESI. These high redshift galaxies also illuminate the foreground neutral hydrogen that produces the Lyman-alpha forest, thus allowing continuous sampling of the low bias and low contrast density field. A program of this scale would contain most of the cosmological information from the linear regime from 1.5<z<4. Over a 14,000 square degree footprint, a next generation program of this scope would produce 140 million spectra, corresponding to about 3% of the LSST gold sample.

A next generation optical/IR spectroscopic survey during the 2030–2040 timeframe would characterize 10% of the LSST galaxy sample (including both the high density survey and Lyman-alpha survey described above). Such a survey would span more than 12 billion years of cosmic history and significantly advance all of the cosmological Science Drivers found in Figure 14. Reaching this number density for a spectroscopic survey requires an order of magnitude increase in multiplexing capability relative to DESI, a 10–12 meter class telescope to observe faint targets, and infrared detectors for robust redshift estimation that is unreliable or impossible with Silicon CCDs. The two key technologies for a next generation galaxy survey are therefore infrared detectors and massive increases in multiplexing capabilities. The requirements for these two technologies are as follows:

- **Infrared detectors**: As demonstrated in Figure 15, the effective band-gap around 1 eV limits Silicon CCDs to galaxy redshifts at $z < 1.6$. At higher redshifts, singly-ionized oxygen ([OII]), the primary spectroscopic feature used to determine redshift, is moved out of the bandpasses accessible by Silicon. Infrared detectors would enable robust redshift measurements over $1 < z < 1.5$ (middle panel of Figure 15) with multiple lines and new redshift estimates over $1.5 < z < 2.0$ (bottom panel of Figure 15) both of which are impossible with Silicon. Infrared detectors covering the near-IR transmission band to 1.35 microns also allow robust redshift estimation through [OII] emission to validate Lyman-alpha detections at redshifts $2 < z < 2.6$. Infrared detectors covering the next atmospheric transmission window out to 1.8 microns would provide sensitivity to [OII] emission to nearly $z = 4$. Cost-effective infrared detectors pursued under PRD 7 are required with quantum efficiency and noise performance comparable to Silicon CCDs. Facilities are needed for fabrication, assembly, and testing of these detectors. Hundreds of infrared detectors will need to meet specifications for quantum efficiency, readnoise, and uniformity requiring scalability beyond current experiments as indicated by PRD 26.
- **Increased multiplexing**: An order of magnitude increase in the density of spectroscopic targets is required for a next generation survey. This density can be obtained with sampling of the focal plane at a 5–6 mm pitch or smaller. New instrumentation requires real-time target placement with high

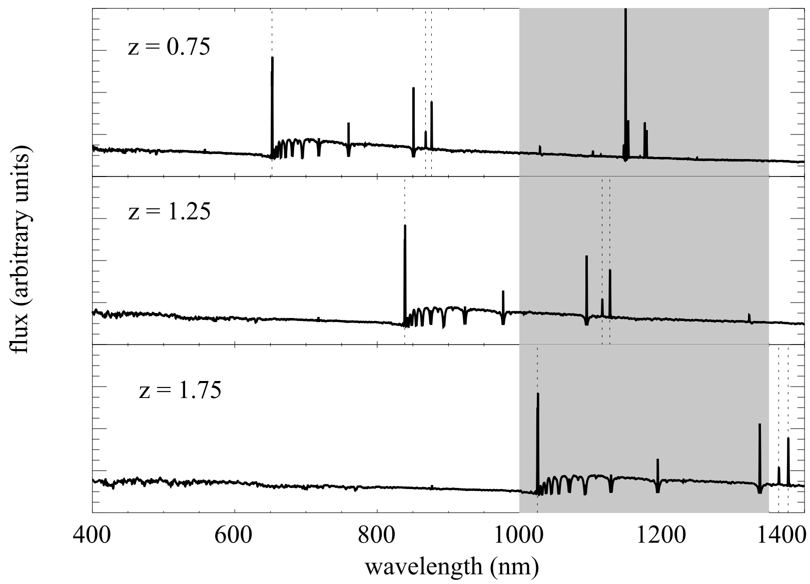


Figure 15: Spectra of emission line galaxies at redshifts $z = 0.75$ (top panel), $z = 1.25$ (middle panel), and $z = 1.75$ (bottom panel). The location of [OII] and [OIII] emission lines is identified by the dashed lines. The coverage at redder wavelengths enabled by infrared detectors is shown in the shaded region, demonstrating new access to spectral features that are invisible to Silicon.

accuracy across the whole focal plane. Heat dissipation must be sufficient to prevent degradation in telescope dome seeing following focal plane reconfigurations. The light path must be controlled for each spectrum to provide imaging stability for sky subtraction. Several conceptual designs of robotic fiber positioners exist and can be explored as a possible technology under PRD 11. Reconfiguration of the focal plane using micromirrors, microshutters, or another form of advanced robotics could allow even larger increases in survey speeds for multi-object spectroscopy.

21-cm (1420 MHz) intensity mapping cosmic surveys

21cm experiments form essentially spectroscopic surveys across enormous survey areas, combining compact radio arrays with developments in modern digital technology in the radio band. The first 21cm radio telescopes sensitive enough to form spatially unresolved maps of large scale structure to measure the expansion history at redshift $1 < z < 2$ are expected to produce their first results in the 2020–2025 timeframe [131]. The CHIME experiment and others are driving the field in demonstrating the technology and analysis techniques required for cosmological results for key dark energy science goals [132]. These current 21cm experiments probe intermediate redshift ranges that have overlap with optical surveys, but because neutral hydrogen is ubiquitous in the Universe, higher redshift surveys are not inherently more difficult than their lower redshift counterparts. As a result, next generation arrays can be designed for redshifts up to $z \sim 6$ where the neutral hydrogen line naturally remains visible at redshifts beyond traditional optical surveys. Above redshift $z = 6$ (< 200 MHz), the signal becomes dominated by astrophysical effects. Overlap with optical surveys increases below redshift $z = 2.5$ (> 400 MHz) and could be used to round out the surveys to cosmic variance limits. The resulting science possible from high redshift 21cm measurements of large scale structure live in redshift range $0 < z < 6$, and at scales 10^{-3} 1 Mpc, naturally probing non-Gaussianity, non-concordance Dark Energy, and neutrinos.

To achieve a redshift $0 < z < 6$ next generation survey of large scale structure with a 21cm interferometer requires a compact array of 1000+ radio dishes, outfitted with radio receivers, a timing network, digital and/or GPU-based correlators, the ability to remove bright foregrounds that swamp the cosmological signal of interest, and a compute infrastructure to handle the 200+PB of observational data and even more for simulations [133]. Today, signals are amplified at the foci of the receiver, but transported by long analog links to the central processing location. This leads to differential temperature dependence in phases and gain from individual elements. Digitization of the analog signals at the focus of each telescope would allow transformative improvements in complex gain stability and enable rigorous real-time feedback required for co-adding. This may also allow direct correlation with calibration signals deployed on calibration drones, digital shaping of the bandpass of the instrument to remove frequency dependence and hence aid in removing foregrounds, and measurement of cross-talk between dishes. To directly digitize and down-sample the resulting data rates at low cost and power (PRD 26) we require:

- **Picosecond clock distribution** Distributing a clock signal from a central location to each dish suffers from drifting phase dependencies. As a result, precision clock distribution techniques that actively monitor delays and maintain pico-second synchronization across the full size of the interferometer ($>$ km) [134] must be deployed. (PRD 23)
- **Real time calibration** A full N^2 correlation of 1000+ interferometric elements across a wide bandwidth would result in data rates exceeding 1000s of PB/day. This can be reduced to as low as 100 Tb/day or about 200 PB total by co-adding across elements that have the same physical spacing between antennas. Such co-addition can be done efficiently using spatial FFT correlation [135], which decreases the data rate and also the computation, storage and power since it scales algorithmically as $N \log N$ rather than N^2. This processing will therefore be required for next generation experiments. However, signals from individual antennas must be phase- and gain-calibrated across the band in real time at the native digitization rate, prior to correlation. (PRD 21, PRD 22)

Mm-wave intensity mapping cosmic surveys

The third cosmic survey technique is an intensity mapping cosmic survey using the signal from rotational CO transitions and the [CII] fine structure lines. This approach, like the 21-cm technique, is sensitive to both non-Gaussianity from inflation and high redshift cosmology through measurements of the BAO distance scale. Cross-correlation between 21-cm and mm-wave measurements would yield results that are robust to astrophysical assumptions (e.g. foregrounds, star-formation uncertainties).

At high redshifts, the CO/[CII] lines are shifted to mm wavelengths, frequencies that are difficult to detect using traditional technologies. Existing mm-wave spectroscopic techniques (e.g. grating spectrometers, Fourier transform and etalon instruments, and submm mixers) cannot easily scale to the optical throughput and bandwidths required for a cosmological survey. The best approach is an integrated field unit (IFU), an instrument that combines both spectrographic and imaging capabilities. Realizing IFUs at mm wavelengths requires developing and scaling new mm-wave detector technologies. These technologies are being pursued in the astronomy community using detectors similar to those in CMB experiments. Instruments in progress, including TIME (CO/CII), AIM-CO (CO), COMAP (CO) and TIM (CII) (see [136, 137] for reviews) will make the first proof-of-concept measurements of these lines. Near-future projects planned for CCAT-Prime and the South Pole Telescope will deploy larger integral field unit (IFU) spectrometers to carry out initial cosmological measurements and will serve as pathfinders for a next generation cosmic survey.

Within the HEP and Astronomy communities, the development of large arrays of superconducting detectors (such as used for CMB) provides the technical foundation for advancing this new probe of cosmology. Key Technical Requirements are:

- **On-chip mm-wave spectrometers with a few hundred channels per pixel, each with a resolving power of a few hundred** PRD 7 and PRD 8 will advance new technologies with compact on-chip spectrometers at mm wavelengths.
- **Fabricating and reading out large arrays (∼1M channels) of these on-chip spectrometers.** Expanding the on-chip spectrometer technology to the pixel density required for a survey-class instrument will require significant improvements in fabrication yield, testing and readout requirements that are addressed by PRD 26. There is substantial overlap between the mm-wave spectrometer technology and current state-of-the-art CMB detectors and the facilities and expertise used for executing CMB-S4 provide a solid technical basis for carrying out the needed R&D for a mm-wave next generation cosmic survey.

3.4.5 Cosmic Accelertation: Dark Energy and Inflation: Preparing for Discovery

From imaging our primordial Universe to the discovery that the current expansion of space-time is accelerating, measurements of our cosmos have transformed our understanding of fundamental science and high energy physics. The next generation cosmic surveys program will

- Drive cosmological measurements to new spatial and temporal scales
- Explore the properties of inflation, dark energy, and dark matter
- Study neutrino physics in a context complementing terrestrial techniques
- Test our concordance cosmological model in new regimes

Developing new instrumentation is critical to the success of these programs. New CCD-like photodetectors with photon sensitivity into the near-IR along with high density robotic fiber positioners will enable a next generation optical/infrared cosmic survey. Developing large data-volume distributed networks with autonomous operation, picosecond synchronization, and real-time data processing will enable a 21-cm intensity mapping cosmic survey. Large arrays of compact mm-wave on-chip spectrometers capable of simultaneous imaging and spectroscopy will enable mm-wave intensity mapping cosmic surveys.

The rich program of cosmological studies planned for the next few decades is based on our current understanding of the formation and evolution of the Universe. We must also prepare for potential discoveries along the way that will inform post-2050 era experiments. Research into new techniques could provide new methods for measuring cosmic observables. For example, advances with quantum measurements (e.g. PRD 13) could enable the direct detection of primordial inflationary gravitational waves or even dark energy. A new window into the Universe could be opened through measurements of the cosmic neutrino background (CNB) and its anisotropy. Imaging the CNB would provide a snap-shot of the Universe as it was one second after the Big Bang: the energy of the neutrinos corresponds to the total distance traveled, providing a redshift-dependent surface of last scattering and potentially a detection of the seeds of structure formation at the co-moving locations of current structures.

The launch of current cosmic surveys (DESI, LSST, CMB-S4) makes this BRN report especially timely. A strong investment into new detectors and instrumentation is foundational for developing the required technology needed for the next generation cosmology program and beyond.

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3.5 Explore the Unknown

3.5.1 Science Impact

The Standard Model of particle physics and general relativity describe the known Universe over a vast range of scales, allowing accurate calculations at distances as small as 10^{-18} m and as large as 10 billion light years. However, there are major known shortcomings. These include experimental facts that are not described, such as the existence of dark matter and the presence of matter but not antimatter in the Universe. There are also theoretical shortcomings, such as the unexplained tiny numbers (e.g., the ratio between the electroweak and Planck scales, the amount of dark energy in the Universe, and the QCD theta angle) that must be put into the theory by hand. These are not minor gaps in our knowledge. They involve some of the most basic features of the world around us. We can parametrize our Universe, but we still do not understand much of it. Making progress requires an open-minded search for clues. The importance of this line of inquiry was called-out in the 2014 P5 report, which included ”Explore the unknown: new particles, interactions, and physical principles” as one of the five Science Drivers.

Our aim here is to identify Technical Requirements for the broad-based explorations that might reveal the first steps on our path to extending the Standard Model. A data-driven approach, in which we test precise Standard Model predictions looking for discrepancies, has historically paved the way to important discoveries in particle physics. High-precision measurements can provide the first indications of new physics at energy scales that are beyond the reach of direct searches, as illustrated in Figure 16. They provide an important complementary approach to energy frontier searches: although our first hint of new physics might come from these measurements, we will need direct collider production of new particles to fully understand the origin of the effects. In this section we will discuss four categories of experiments covering heavy flavor, lepton flavor violation, electric dipole moments and the dark sector. The general strategy is to identify

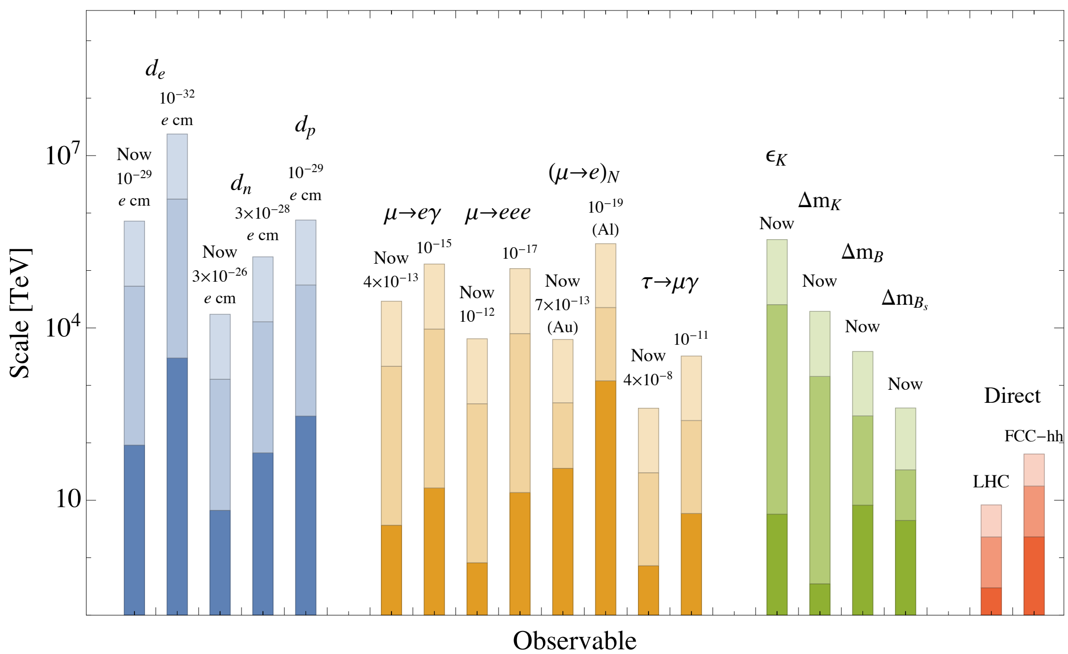


Figure 16: Energy reach of various (current and future) indirect precision tests of physics beyond the Standard Model (electric dipole moments, lepton flavor violating decays, and neutral hadron mixing), compared to direct searches. For the indirect probes, the shaded regions make various assumptions about the strength of the coupling of the probe, the larger the coupling assumed the higher the mass that is probed if no observation is made. For direct searches, the shaded regions make assumptions about the production cross section, the larger the cross section assumed the higher the mass that is probed if no observation is made. Figure produced by Matthew Reece (Harvard University) for this report. Technical details may be found in Reference[138]

Physics of the Unknown

A diverse set of experiments, comprising precision measurements and searches for rare decays, aim to "Explore the Unknown". Dedicated experiments use heavy flavor, rare muon and kaon decays, and electric dipole moments (EDMs) to search for phenomena that are very unlikely to happen in the Standard Model but are precisely calculable, and hence are promising places for even small, subtle effects of new physics to become visible. The future reach of these experiments depends on a strong research and development program in detector technology.

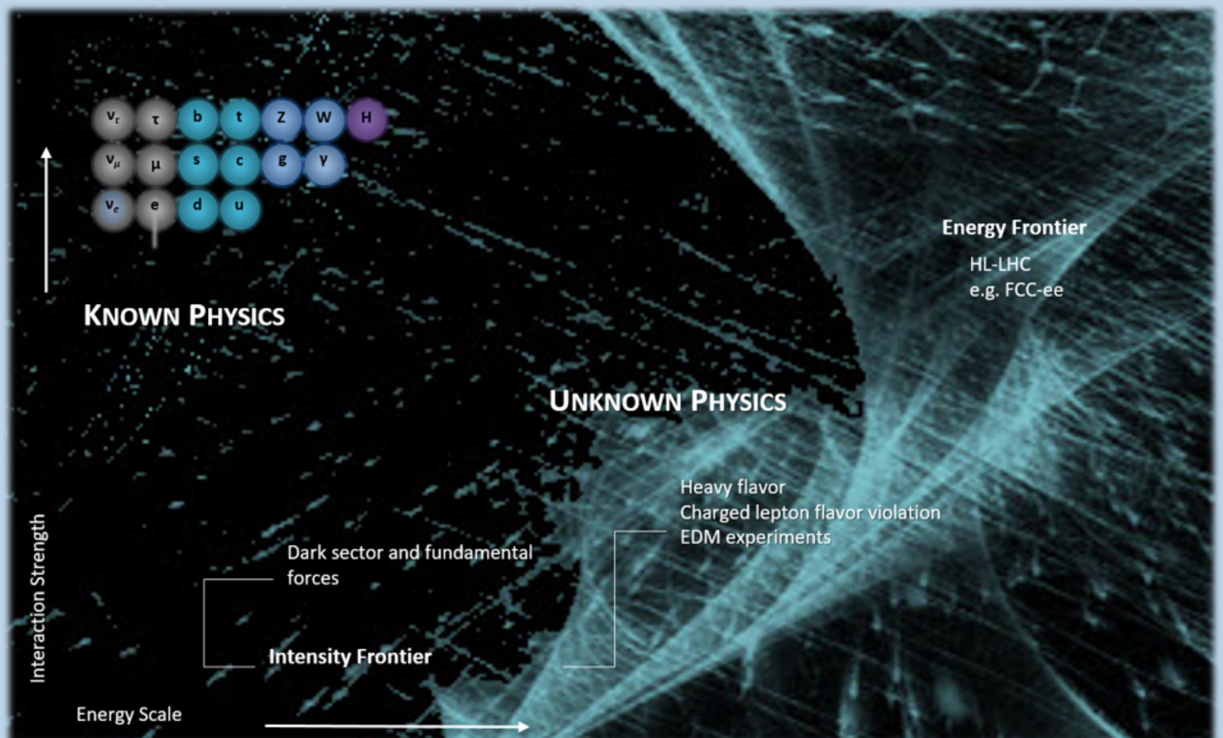


Figure I: New physics could evade discovery because it lies beyond the energy reach of our experiments (upper right), or because it interacts weakly with the matter around us (lower left). To Explore the Unknown, we must search for feeble interactions or indirect, low-energy manifestations of high-energy physics. Dark sector, flavor, and CP-violation searches offer such new discovery opportunities, which complement energy-frontier colliders.

Future upgrades to heavy flavor experiments are particularly reliant on the development of improved timing and position resolution for identifying particles and associating them with the correct vertex to untangle the signals from backgrounds. The high statistics needed result in high radiation environments in which future detectors must successfully operate. The challenge will be to achieve simultaneously precise timing, high granularity, high-rate readout and radiation hardness with cost-effective detectors.

A diagram of the proposed LHCb Upgrade II detector, central to the future of the heavy flavor experimental program, is shown in Figure II. This Upgrade will allow the full flavor-physics opportunities at the HL-LHC to

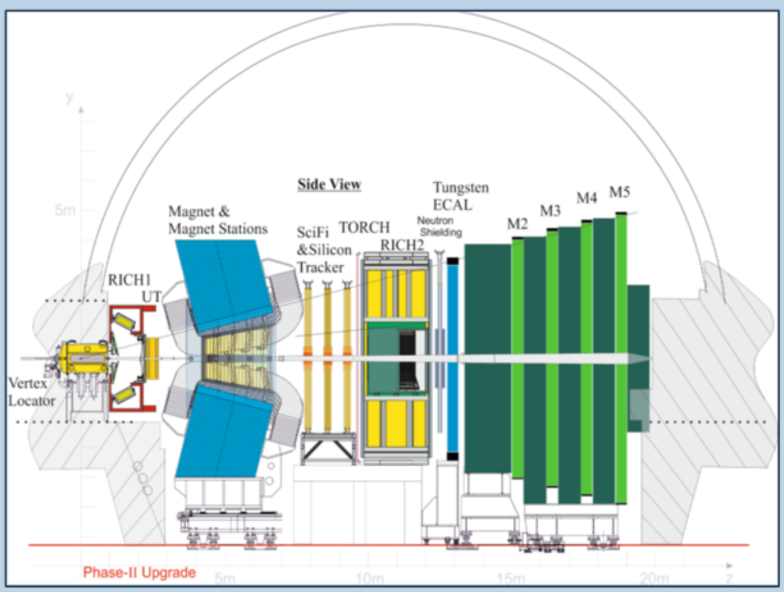


Figure II: A schematic side-view of the proposed LHCb Upgrade II detector, currently planned to begin operation in the early 2030s.

be realized, and open up other topics that can be studied with a forward spectrometer. It will build on the strengths of the current LHCb experiment and Upgrade I and will operate at a luminosity up to ten times that of the Upgrade I detector. The new physics mass scale probed, for fixed couplings, will almost double compared with the pre-HL-LHC era.

A timeline for the heavy flavor physics program, along with the corresponding technological developments needed, is shown in Figure III.

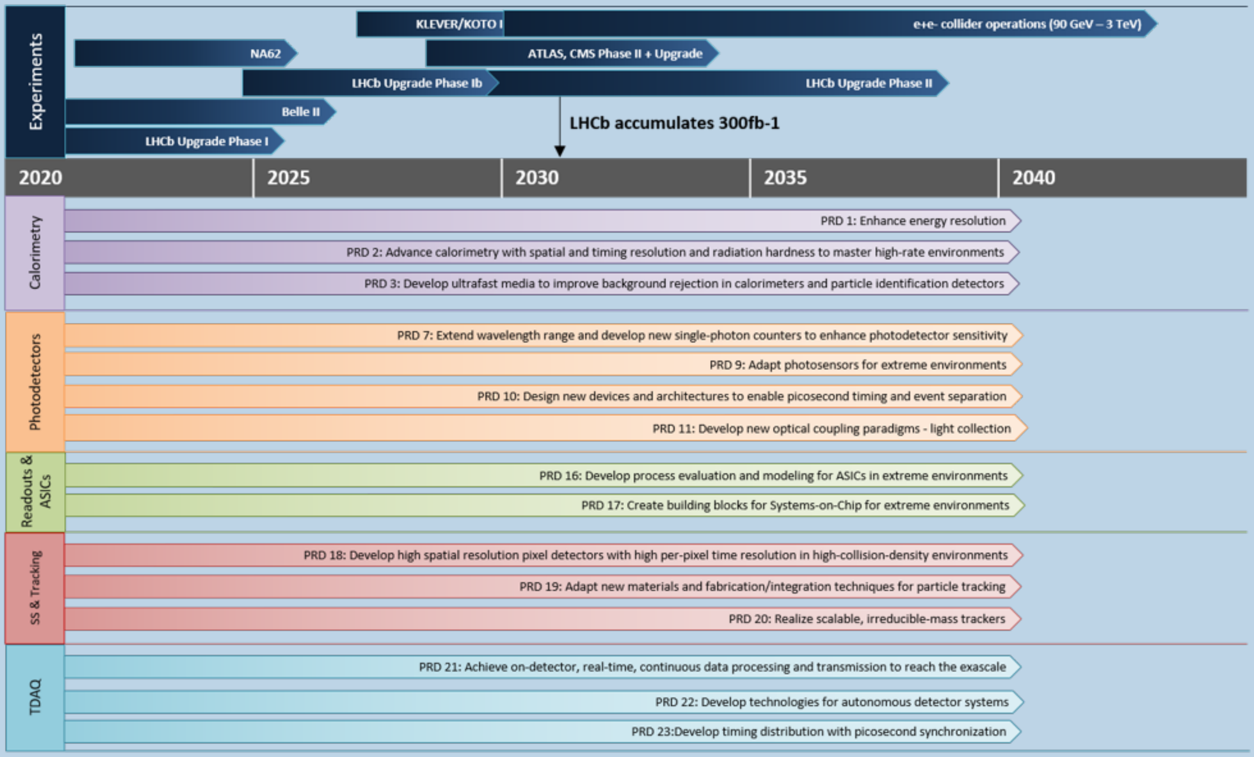


Figure III: Flavor physics timeline. The arrows that extend until the 2040s indicate instrumentation PRDs that will enable the flavor physics program at proposed future e+e- colliders at the energy frontier such as the FCC-ee, CEPC, ILC and CLIC.

An experimental program in rare muon and kaon decays will also require substantial development of improved and cost-effective detectors. In this case the precise momentum measurements needed to separate signals from backgrounds necessitate low-mass, high resolution tracking detectors and calorimeters able to withstand high fluences. The timeline envisioned for future muon experiments is shown in Figure IV.

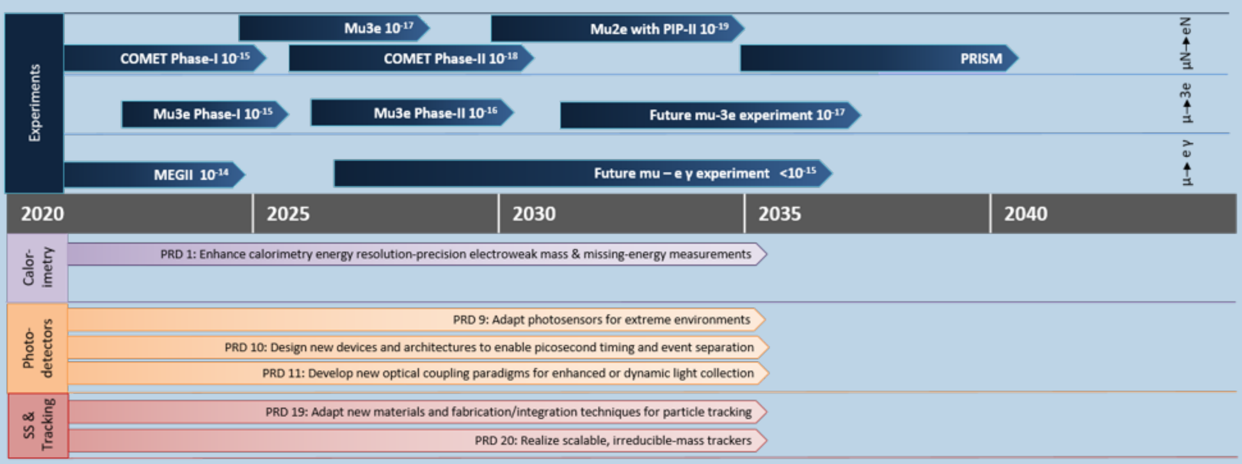


Figure IV: Rare Muon Experiments Timeline

Future measurements of the EDMs of particles will provide access to searches for new physics at energy scales that are inaccessible with the direct searches being carried out at the energy frontier. These experiments will require laser cooling and trapping of molecules beyond what is currently achievable, with long coherence times and large numbers of particles. Robust, turnkey systems for laser locking, tuning and linewidth narrowing will be required, as will the improved characterization of the target atoms, molecules and nuclei. Figure V shows a schematic of the planned Advanced ACME experiment, which will have an order of magnitude improved sensitivity to the electron EDM compared to current constraints.

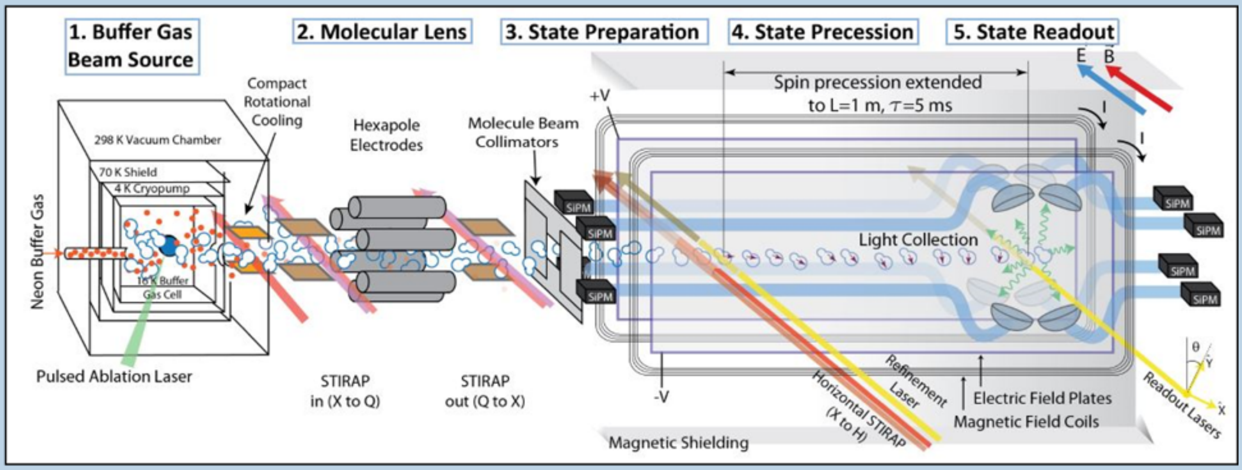


Figure V: Schematic of the planned Advanced ACME experiment. The current ACME experiment is housed at Harvard University

While tremendous progress has been made exploring the universe and discovering our "known physics", there is much that remains unknown. Experiments using heavy flavor decays, searching for charged lepton flavor violation, and searching for EDMs enable us to explore this territory. A timeline for possible future EDM experiments is provided in Figure VI.

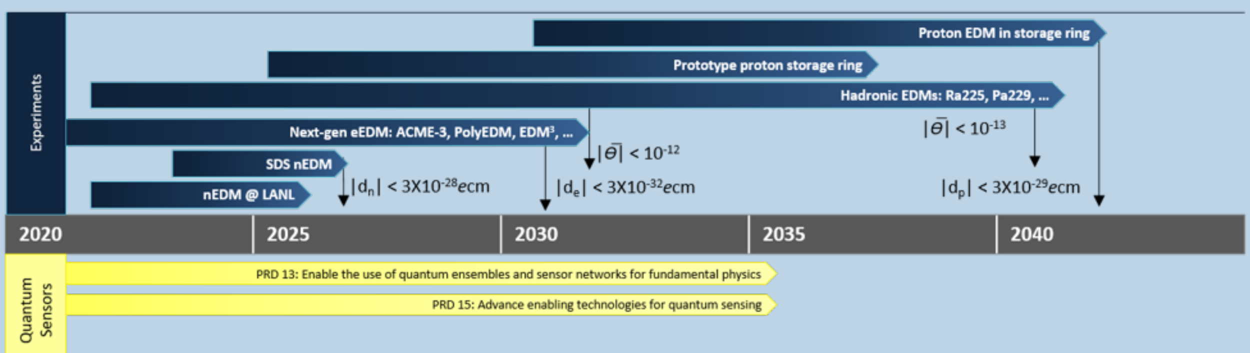


Figure VI: EDM Experiments Timeline, where d_n refers to the EDM of the neutron, d_p refers to the EDM of the proton, d_e refers to EDM of the electron, and theta is the strong CP phase.

phenomena that are very unlikely to happen in the Standard Model but are precisely calculable, and hence are promising places for even small, subtle effects of new physics to become visible. Searches for new forces or new fundamental particles in the dark sector are also outlined.

3.5.2 Heavy flavor

The Standard Model has many approximate symmetries that suppress the rates of various processes, or require that two processes happen at the same rate to very good approximation. For example, the Standard Model predicts charged lepton flavor universality, which relates the rates of processes involving electrons, muons, and taus, to very high accuracy. This can be tested in decays of heavy flavors, and is a topic of great current interest due to anomalies in data from the LHCb experiment [139–141] and B-factories [142–144]. The continued exploration of the unknown with heavy flavor is being pursued with the Upgrade I of the LHCb detector, currently under construction, which will start to take data in 2021 and with the Belle II experiment, which has recently started to take data at the SuperKEKB collider. The Upgrade II of the LHCb detector [145], currently planned to begin operation in the early 2030s, and which is still awaiting approval, will enable a wide range of flavor observables to be determined with unprecedented precision during the HL-LHC program. Some initial considerations are also being given to a possible, future SuperKEKB accelerator upgrade extending beyond the existing program and increasing the design luminosity by a factor of five. The ATLAS and CMS experiments will also continue to contribute to flavor physics, notably in B decays to final states containing muons throughout the foreseen HL-LHC program. Other rare flavor-changing processes arise in kaon decays, such as $K \to \pi\nu\bar{\nu}$ (searched for by KOTO in the case of K_L^0 and NA62 in the case of K^+). These searches have in common that even a modest number of convincingly detected events beyond the precisely predicted expectation could overturn the Standard Model. For the charged kaon mode, feasibility studies are underway to improve the precision with higher beam intensities, while for the neutral mode the KOTO-II experiment [146, 147] as well as the KLEVER [148] project at CERN are being discussed.

In the long-term, collecting data at the Z^0 center-of-mass at future colliders such as FCC-ee will provide an excellent opportunity to study heavy flavor in a relatively clean environment. An experiment at FCC-ee could accumulate $\sim 10^{12}\, Z \to b\bar{b}$ events [20]. The advantage of FCC-ee relative to a hadron collider is the clean environment and knowledge of the center-of-mass frame. This combination will make it particularly powerful for studying and setting constraints on channels with neutral particles or neutrinos in the final state. For instance, decays proceeding via $b \to s\tau\tau$ transitions can be measured with high precision, providing access to new observables sensitive to physics beyond the Standard Model through, e.g., angular analyses. At FCC-hh, a very large number of heavy flavor hadrons will be produced, allowing measurements of ultra-rare processes. Requirements to perform flavor physics at FCC-hh are similar to those relevant for the Higgs and the Energy Frontier (e.g. radiation hardness, high granularity, and fast timing in both tracking and calorimeters). However, the need to access lower lepton momenta could be challenging, placing harder constraints on the triggering and data-acquisition system.

In the high-occupancy environment where future flavor physics experiments will operate, event reconstruction will be very challenging. Given the large number of hits, the number of possible combinations will become so high that it will be extremely difficult to identify tracks. Therefore, in addition to spatial resolution, the need for precise timing information, where timing is associated with each track point, thus allowing 4D tracking, will become more and more pressing. The challenge in tracking detectors will be to achieve simultaneously precise timing, high granularity, high-rate readout and radiation hardness.

A few tens of ps timing resolution has been identified as essential for the Upgrade II of the LHCb detector, which will have to cope with luminosities ten times larger than those of the Upgrade I currently under preparation. The use of precision timing of 10 to 30 ps in multiple detectors will be essential to not degrade performance and to maintain a broad flavor physics program. These detectors include the silicon vertex detector, which must provide high-granularity spatial information in close proximity to the interaction region, in a high radiation environment (with a yearly, highly non-uniform fluence of up to $10^{16}\,\mathrm{n_{eq}/cm^2}$); the RICH detector, downstream of the spectrometer magnet; the TORCH (Time Of internally Reflected CHerenkov light) detector, a large area time-of-flight detector for particle identification; and calorimeter systems. Precise timing information will allow charged tracks and photons to be associated to the primary vertex from which they originate, thereby drastically suppressing combinatorial background and saving CPU resources in track reconstruction.

Following in the footsteps of Belle, Belle II, which is the first "super-B factory" experiment, is designed to record an unprecedented data sample of 50 ab^{-1} with a better or comparable performance to that of the previous Belle experiment or BaBar at SLAC. Ideas are being explored for a possible upgraded experiment, "Belle III", based on technologies that could be relevant on the time scale of more than ten years. The concept of a vertex detector based on thin pixel sensors with exquisite space-time resolution has been put forward to meet the vertexing requirements while addressing the occupancy and reducing the data to disk and storage costs. The timing requirements for Belle III are similar, but generally less stringent, than those discussed for the LHCb Upgrade II.

A few tens of ps hit time resolution is essential for rare kaon decay experiments such as NA62. The tracking rate in the Gigatracker, a set of three innovative silicon pixel detectors measuring the arrival time and position of the incoming beam particles, is what is currently limiting the sensitivity of the experiment. Assuming, for example, that a ten-fold increase in the amount of primary protons delivered from the SPS could be provided, the time resolution in the Gigatracker would need to decrease from the current $\sim$120 ps per station to less than 50 ps, while the pixel sizes would need to be reduced by a factor of two, down to $\sim 150 \times 150\ \mu\text{m}^2$.

Particle identification is of paramount importance for flavor physics experiments. System redundancy is key to achieve good particle identification in a high-occupancy environment, as demonstrated by the LHCb experiment. High-granularity electromagnetic calorimeters for electron, photon and π^0 identification and RICH detectors for hadron identification utilizing new radiation-hard and low-noise photodetectors with higher granularity will allow precision measurements of a variety of decay channels. These capabilities are essential for many key measurements in flavor physics, e.g., to constrain the CKM matrix parameters and probe lepton flavor universality. A TORCH detector is under consideration for the LHCb Upgrade II to extend charged-particle identification capabilities over the momentum range 2–10 GeV/c. Development of radiation hard and fast photosensors will be necessary to achieve the goal of a time resolution of 15 ps per incident charged particle.

For the LHCb Upgrade II the innermost modules of the electromagnetic calorimeter will be exposed to a total dose of over 200 Mrad/300 fb^{-1}, so radiation hardness will be essential. At the same time, a granularity of typically 2×2 cm^2 in the innermost region will be necessary to resolve overlapping showers. Fast calorimeters with good granularity and timing capabilities would also be critical for the next-generation KLEVER and KOTO-II experiments.

To cope with the very large amount of data that future experiments will collect, it will be essential to store only information important for offline analysis. The LHCb Upgrade II is expected to produce up to 400-500 Tb/sec of data, which will have to be processed in real time and reduced by at least four to five orders of magnitude before being recorded. Development of radiation-hard, high-rate optical links, with tight constraints of low power consumption and low mass, will also be required. A paradigm change is ongoing, not dissimilar to when we started to store only digitized information, giving up on the analog information offline. These paradigm changes will require a sophisticated online processing and analysis of events and will profit from the ongoing revolution in deep learning. Future trigger algorithms will have to be flexible enough not to lose potentially interesting or even anomalous events, which are poorly characterized, while at the same time dealing with large background and elaborating all information from high-granularity and fast detectors. Tools such as automatic calibration and almost-online automatic data-quality control will be needed to ensure a robust system. The ATLAS and CMS heavy-flavor program in the HL-LHC era will need access to low transverse momentum di-muon and di-electron events, which will require stringent online selection through trigger-level analysis. Similar future experiments at higher-energy hadron colliders will have even more stringent trigger processing requirements.

The technical requirements, which inspire a variety of Priority Research Directions to enable the heavy flavor physics program, are outlined in Table 10.

3.5.3 Charged lepton flavor violation

The Standard Model predicts that the rates of flavor-changing processes for charged particles are vanishingly small, whereas many extensions to the Standard Model provide enhancements to these rates. Charged Lepton Flavor Violation (CLFV) is therefore a deep and unique probe of new physics. The rate of CLFV depends on the nature of the underlying physics, which can be explored with a diverse program using various rare

Science	Timescale	Technical Requirement (TR)	PRD
	medium term	TR 5.1: Timing resolution at the level of $10-30$ ps per hit in the silicon-pixel vertex detectors and $10-30$ ps per track for both PID detectors (RICH, TORCH) and electromagnetic calorimeters	**2**, **10**, **18**
Search for new physics though rare flavor interactions	medium term	TR 5.2: Development of radiation-hard, fast and cost-effective photosensors for TORCH and RICH detectors and tracking systems with optical readout	**9**, **11**
	medium term	TR 5.3: Development of the next generation ASICS to extract the large data rate (and possibly pre-process it) out of inner pixel layer detectors in a very challenging radiation environment	**16**, **17**
	medium term	TR 5.4: Radiation-hard silicon pixel detectors (fluences of 5×10^{16} $\mathrm{n_{eq}/cm^2}$)	**18**, **20**
Tests of the CKM quark mixing matrix description	medium term	TR 5.5: Cost-effective electromagnetic calorimeter with granularity of typically 2×2 cm^2, resolution of $\frac{\sigma(E)}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 1\%$ and timing resolution of a few tens of ps; total radiation dose of $\sim 200\,\mathrm{Mrad}$	**1**
	medium term	TR 5.6: Real-time processing of large amount of data (400-500 Tb/sec) and development of radiation-hard, high-rate optical links, with tight constraints of low-power consumption and low mass	**16**, **17**, **21**, **22**
	long term	TR 5.7: Fast-timing resolution at the level of 1 ps per track for $\pi/K/p$ separation up to 50 GeV	**3**, **10**
	long term	TR 5.8: Further ASICS development to extract and pre-process on detector the large data rate of inner layers detectors in an extreme radiation environment	**16**, **17**
Studies of Lepton Flavor Universality	long term	TR 5.9: Radiation-hard, ultra-fast silicon pixel detectors (fluences of 10^{18} $\mathrm{n_{eq}/cm^2}$)	**18**, **19**, **20**
	long term	TR 5.10: Very high granularity calorimeters preserving an energy resolution of $\frac{\sigma(E)}{E} \sim \frac{10\%}{\sqrt{E}}$	**1**, **2**, **7**, **9**
	long term	TR 5.11: Real-time processing of large amount of data (1Exabytes/sec) and development of radiation-hard, high-rate optical links, with tight constraints of low-power consumption and low mass	**16**, **17**, **21**, **22**, **23**

Table 10: Technical Requirements to enable the physics program of heavy flavor and the map to Priority Research Directions. The "medium-term" timescale refers to experiments that will begin operation in the late 2020s and early 2030s. The "long-term" timescale refers to experiments that will begin operation in the 2040s and beyond.

decay modes of in muons, taus, kaons and B-mesons. These experiments require extremely high statistics of particle decays in order to reach their desired level of sensitivity and extend their sensitivity reach to higher energy scales. The Technical Requirements and corresponding PRDs to enable the charged lepton flavor violation physics program are outlined in Table 11.

Example experiments with muons that will take data over the upcoming several years include MEG II [149], COMET [150], Mu2e [151], and Mu3e [152]. Sensitivity to the signal process at MEG II ($\mu^+ \to e^+\gamma$) requires measuring the photon energy, positron momentum, and their relative angle and timing with excellent resolution. The CLFV signal at Mu2e and COMET ($\mu N \to eN$) is an electron with an energy near the rest mass of the muon, characteristic of neutrinoless $\mu \to e$ conversion in the field of the nucleus. Separating this signal from backgrounds due to cosmic rays and other Standard Model processes requires excellent momentum resolution from a low-mass tracking detector. The Mu3e experiment requires excellent momentum, position and timing information in order to achieve the desired 10^{-16} branching-ratio sensitivity to $\mu^+ \to e^+e^-e^+$ This current generation of experiments is projected to deliver orders of magnitude better sensitivity than current limits.

Substantial improvements in our experimental techniques would enable the study of signals seen in current experiments or extend our reach to new physics even further. Mu2e II, COMET Phase II and Mu3e Phase II are foreseen to begin running either late in 2020 or early in 2030, either exploring signals or continuing the search with heightened sensitivities. These experiments are already challenging in their current incarnations due to the extremely intense beams of muons that are required, leading to a busy detector environment, and the level of control of backgrounds that is needed to reach the desired sensitivities. The future experiments are even more aggressive. They would benefit from massless trackers with timing information and low-cost calorimeters that can withstand high doses of radiation and provide excellent vertex assignment.

Additionally, new opportunities could be opened up, enabling targeted searches for $\tau \to e\gamma$, $\tau \to \mu\mu\mu$ and other less constrained processes that are, in some cases, even better motivated by Standard Model extensions. A large number of taus will be needed to go beyond the limit that will be established by the Belle II and Belle III experiments. A fixed-target experiment utilizing a high-energy, high-intensity proton beam is a promising option. Such an experiment will require very precise tracking close to the interaction point (or to the target) with excellent timing capabilities to suppress combinatorial background, and allow for a very clean analysis environment. However, in general, these needs are in conflict with radiation hardness requirements, which will also be key for such an experiment, requiring future R&D. FCC-ee could also enable 3rd generation CLFV searches, such as $\tau \to e\gamma$, provided the detectors are up to the challenge. Sufficient energy resolution and pointing capabilities in the calorimeter would enable the photon and electron to be associated with a common vertex.

The Technical Requirements and corresponding Priority Research Directions to enable the CLFV physics program are outlined in Table 11.

Science	**Timescale**	**Technical Requirement (TR)**	**PRD**
Medium term: extend reach of CLFV searches	medium-term	TR 5.12: Low-cost calorimeters with $< \frac{10\%}{\sqrt{E}}$ energy resolution $<$ 500 ps timing, able to withstand a dose of $\sim$1 Mrad.	**1**
	medium-term	TR 5.13: 20 ps track-level timing in a low-mass tracker with excellent momentum resolution	**19**
Long term: probe CLFV with 3rd generation	long-term	TR 5.14: Transparent tracker with excellent resolution	**19**, **20**
	long-term	TR 5.15: Calorimeter with $< \frac{10\%}{\sqrt{E}}$ energy resolution and excellent pointing capabilities and timing resolution	**1**, **9**, **10**, **11**

Table 11: Technical Requirements to enable the physics program of Charged Lepton Flavor Violation (CLFV) and the map to Priority Research Directions. The "medium-term" timescale refers to experiments that will begin operation in the late 2020s and early 2030s. The "long-term" timescale refers to experiments that will begin operation in the 2040s and beyond.

3.5.4 EDM experiments

The charge conjugation parity symmetry, CP, is another approximate symmetry of Standard Model processes that may be badly violated by new physics. In the Standard Model, CP violation appears through a phase in flavor-changing processes. Quantum sensor measurements of flavor-conserving, CP-violating physics, such as electric dipole moments (EDM) of fundamental particles, which are predicted to be tiny, have the potential to provide a powerful window on energy scales that greatly exceed what can be probed directly at the LHC [153]. We know that there must be new CP-violating physics beyond the Standard Model, at some energy, in order to explain the matter/antimatter asymmetry of our Universe. EDMs could also shed light on one of the last unmeasured parameters of the Standard Model, the strong CP phase $\bar{\theta}$, which contributes to the EDM and is puzzlingly small – the current bound on the neutron EDM implies that $\bar{\theta} \lesssim 10^{-10}$. The current overall best bound is on the electron EDM. It is obtained by the ACME experiment by using a cryogenic molecular beam and is already probing some types of physics at mass scales above the reach of the LHC. New quantum sensor technology enabling more precise measurements of both nuclear- and electron-spin-dependent interactions can extend the reach of EDM searches to even higher energy scales. Strikingly, next generation experiments could provide access to the PeV scale [154].

The reach of an EDM experiment depends upon the following parameters: the effective electric field that is being used to probe the dipole moment, which can be a very large field inside a molecule, the coherence time over which the experiment is performed, and the total number of independent measurements. The measurement uncertainty can be estimated as [155]

$$\delta d_e \approx \frac{\hbar}{2\mathcal{E}_{\text{eff}}\tau\sqrt{N_{\text{obs}}}}. \tag{1}$$

At the ACME II experiment, the bound is obtained by using a cryogenic molecular beam of the heavy polar thorium-oxide molecule, ThO [156]. This has a large effective electric field $\mathcal{E}_{\text{eff}} \approx 8 \times 10^{10}\,\text{V/cm}$. ACME II's coherence time (how long it takes the beam to pass through the apparatus) is $\tau \approx 1\,\text{ms}$, and roughly 10^7 molecules per second are measured over a total running time of order a day. This led to a statistical sensitivity around $4 \times 10^{-30} e\,\text{cm}$ [155, 156]. Future experiments should aim to substantially increase any of $\mathcal{E}_{\text{eff}}$, τ, or the number of molecules analyzed in order to go orders of magnitude beyond ACME II.

One of the primary ways to improve the sensitivity of molecular EDM experiments is to increase τ, and possibly, N_{obs} also by trapping molecules using laser cooling [154]. In the case of diatomic molecules like ThO, there is a basic incompatibility between the "parity doublet" structure that provides control over systematics in EDM experiments and the electronic structure that allows laser cooling. Moving to polyatomic molecules resolves this problem; essentially, one part of the molecule is the target for laser cooling and another part of the molecule provides the EDM sensitivity. A candidate molecule that can allow sensitivity to PeV-scale new physics is YbOH. While the atomic physics community has extensive experience with laser cooling and trapping of atoms, the technology is less developed for molecules. Development of this technology will allow *quantum control* of molecules, enabling sensitivity to very high-mass physics beyond the Standard Model. Other proposed technologies, both to probe the electron EDM and to probe hadronic EDMs with atoms or molecules, have similar aims. An even more ambitious proposal, the EDM^3 experiment, aims to use a solid-state system to improve the bound by more than four orders of magnitude [157].

Given the recent rapid progress in atomic and molecular probes of EDMs, we can make estimates of the rate of future progress. We expect that the bound on the electron EDM will reach $10^{-32} e\,\text{cm}$, probing 1-loop PeV-scale new physics, within 10 years, with further orders of magnitude improvement possible in the following decade with a dedicated effort. We expect that bounds on hadronic EDMs, obtained with diamagnetic atoms like ^{225}Ra or ^{229}Pa, will tighten constraints on $\bar{\theta}$ by two orders of magnitude in the next ten years and a further order of magnitude in the following decade, if there is sufficient funding support.

Apart from approaches based on atomic and molecular physics experiments, other EDM experiments have been proposed. Examples include neutron EDM experiments at Los Alamos National Laboratory and the Spallation Neutron Source at Oak Ridge National Laboratory, which will reach a precision of $3 \times 10^{-28} e\,\text{cm}$ within the next decade [158]. Improvements in this area could arise from a dedicated ultracold neutron source. Another set of experiments uses charged particles in storage rings, aiming to probe proton and deuteron EDMs. Tests at the COSY facility have demonstrated that systematics can be controlled, but further progress will require the construction of a dedicated storage ring [159], which could potentially begin operating in the late 2020s or early 2030s to reach a precision of $10^{-29} e\,\text{cm}$ by 2040.

In the long run, understanding any positive EDM signal will require measuring multiple systems. Any EDM experiment is sensitive to multiple effects beyond the Standard Model. Only by performing measurements of several different particles or molecules, which probe different linear combinations of these effects, can the signal be interpreted. This may eventually provide a strong impetus to improve neutron EDM and storage ring EDM experiments, but in the short term, the molecular approach is poised to make the most rapid progress, with relatively modest investments. Quantum control of molecules will have other applications beyond EDM searches.

The Technical Requirements and corresponding Priority Research Directions to enable the electron dipole moment physics program are outlined in Table 12.

Science	Technical Requirement (TR)	PRD
Search for new physics using electric dipole moments	TR 5.16: Controlled preparation of many coherent particles. Laser cooling and trapping of molecules is a concrete path forward. Coherence times $\tau \gtrsim 1\,\mathrm{s}$ or total numbers of particles $N \gg 10^{12}$ would represent an advance.	**13**
	TR 5.17: Robust, turnkey systems for laser locking, tuning, and linewidth narrowing (keeping many narrow-band lasers on target) and for tunable, narrow band <1 MHz, ~200-400 nm light generation.	**15**
	TR 5.18: Characterization of target atoms, molecules and nuclei. This includes low energy, high resolution nuclear spectroscopy (e.g., for ^{229}Pa) and spectroscopy of molecules containing heavy atoms.	**15**

Table 12: Technical Requirements for electric dipole moments and the map to Priority Research Directions.

3.5.5 Dark sectors and fundamental forces

An interesting class of experiments that explore the unknown are searches for particles in dark or secluded sectors, which interact only very weakly with the Standard Model [160]. Searches for new, very weakly interacting fundamental forces also fall in this category. One example is the search for a dark photon, a hypothetical massive spin-1 particle with couplings to Standard Model particles that are proportional to, but smaller than, their electric charge. Any process involving a dark photon has an intrinsic background from off-shell ordinary photons. However, again, a high-precision measurement can make a discovery by finding a narrow peak above the Standard Model background. This is a good example of a collider search for the unknown that requires very high luminosity and precision, rather than high energy. Dark photons can also be searched for at much lower masses through resonant experiments. Other light bosons (scalar fields like dilatons or moduli, or spin-1 fields like a Z') are also interesting targets. If the values of such light, bosonic fields vary over time and space, they can give rise to apparent spatio-temporal variations of fundamental constants, such as the fine-structure constant or the electron-to-proton mass ratio. Such variations can be searched for with high-precision experiments.

Dark sectors can be searched for either at dedicated experiments or at existing collider experiments. Recently, several dedicated experiments have been proposed at the CERN accelerator complex. FASER-II [161], MATHUSLA [162] and Codex-B [163] are proposals for experiments at LHC that look for displaced vertices coming from the pp interaction, while SHiP [164] would operate at the SPS. These experiments are relatively far away from the interaction point and therefore they do not have a radiation hardness requirement, but in order to achieve best sensitivity, they in general require large area detectors with good timing capabilities (in particular SHiP and MATHUSLA). In MATHUSLA-like experiments, the cost of SiPM photo detectors is one of the limiting factors. Dark sector searches are also carried out at ATLAS, CMS, and LHCb in complementary regions of parameter space, and will continue at other future colliders like FCC-ee and FCC-hh.

Another key set of searches are those for the QCD axion or more general axion-like particles (ALPs), as discussed in more detail in Section 3.3.4. The QCD axion solves the Strong CP problem by dynamically relaxing $\bar{\theta}$ to zero [165]. Although it may be most easily detected if it constitutes dark matter and exists in great abundance around us, it is also important to search for this particle if it is *not* the majority of dark matter. This can be done through searches for spin-dependent fundamental forces [166], or by "light shining through walls" experiments in which a photon converts to an axion, propagates through a barrier, and converts back to a photon. A natural target for such searches are given by the classic KSVZ and DFSZ models of the QCD axion, which predict a linear relationship between the axion's coupling to photons and its mass. Section 3.3.4 provides a summary of these types of non-dark-matter-based searches and Table 7 lists corresponding technical requirements. More generally, very light bosonic fields could generate subtle energy perturbations that could be detected with precision quantum sensors such as atomic clocks, atomic interferometers, atomic magnetometers, micro- and nano-resonators, high-Q cavities, and other such instruments. To search for such exotic interactions, it is necessary to push the precision frontier of quantum sensors to maximize the sensitivity to a range of different types of energy perturbations.

Finally, we remark that gravitational waves have the capability to be messengers of heavy or dark sector physics from the primordial Universe. Many nonlinear dynamical processes, from (p)reheating after inflation [167] to dark-sector phase transitions, could potentially produce a stochastic gravitational wave background. For cosmological applications, frequencies in the mid-band between LISA and LIGO, as well as the high-frequency regime from kHz to GHz, can be interesting, with energy fraction per logarithmic frequency $\Omega_{\rm gw} \sim 10^{-9}$ (equivalently, strain $h \sim 3 \times 10^{-23}\,(1~{\rm Hz}/f)$) an interesting target [167]. Astrophysical backgrounds are absent at these high frequencies, but new technologies must be developed for their detection [168].

The Technical Requirements and corresponding Priority Research Directions to enable the dark sector and fundamental forces physics program are outlined in Table 13.

Science	Technical Requirement (TR)	PRD
Search for dark sectors that interact weakly with ordinary matter	TR 5.19: Low-cost / fast-timing photosensors for experiments such as MATHUSLA and SHiP.	**7**
	Quantum sensor technology developments for precision searches for new exotic interactions ("fifth" forces) and non-dark-matter-based searches for the axion and ALPs. The QCD axion generically provides a quantitative target for axion searches. Spin-based QCD axion searches are addressed by TR 3.37-3.42. "Light shining through walls" searches for ALPs using cavity resonators are addressed by TR 3.43-3.44. TR 5.20: More generally, technology developments for non-dark-matter-based searches for ALPs or fifth forces should have the potential to cover many square decades in mass-coupling parameter space.	**12**, **13**, **15**
	TR 5.21: Develop technologies to enable searches for spatio-temporal variations of fundamental constants that have the potential to cover many decades of relevant parameter spaces.	**12**, **13**
	TR 5.22: Develop quantum sensor technology to expand the frequency range of searches for gravitational waves in the mid-band between LISA and LIGO and in the high frequency band above LIGO, extending as high as GHz and to achieve sensitivity to strains of $h \sim 3 \times 10^{-23}\,(1~{\rm Hz}/f)$.	**13**, **15**

Table 13: Technical Requirements mapped to the Priority Research Directions for dark sectors and fundamental forces.

3.5.6 Explore the Unknown: Preparing for Discovery

In the current physics context, where we have many unsolved mysteries but lack clear evidence of the scale of new physics, it is crucial to maintain a broad and diverse research program that explores the unknown.

We have outlined a physics program along four major lines that has the potential to pave the way to a transformative next step in our understanding of the Universe:

- Precision measurements in heavy flavor decays
- Searching for charged lepton flavor violation in rare decays of muons and kaons
- Tests of CP violation through electric dipole moment searches
- Probes of the dark sector and hunts for new fundamental forces

The experiments outlined here have the potential to indicate the scale of new physics and provide insight into its nature. A vibrant research and development program to create new detector technologies is necessary in order to realize this potential, and to inspire new ideas for experiments that have not yet been imagined.

4 Technologies in Support of HEP

Particle physicists seek to measure as precisely as possible the position, time, momentum, energy and identity of particles. Progress in the field has only been possible by developing specialised instrumentation to achieve this. The instrumentation technologies that have been developed have often found use far beyond particle physics. To achieve the physics goals of Section 3 requires the development of new instrumentation to meet the Technical Requirements. The instrumentation can be classified into seven broad technologies these are Calorimetry, Noble Elements, Photodetectors, Quantum Sensors, Readout and ASICs, Solid State, and Trigger and DAQ. This section presents for each of these technologies the principles of operation, the current state of the art, the Priority Research Directions and associated research Thrusts, actionable Research Plans, the facilities needed to enact them, and the connections to other fields (see Figure 17). It is likely the technologies described here will continue the tradition of instrumentation developed for HEP having impact far beyond particle physics.

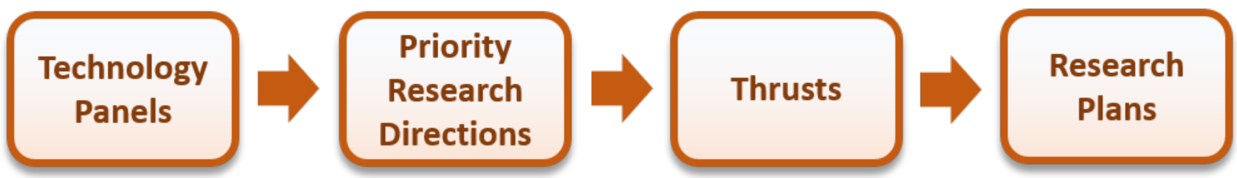


Figure 17: The Technology Panels develop Priority Research Directions to meet the Technical Requirements of the Physics Panels. For each PRD, a set of Thrusts and actionable Research Plans are described.

4.1 Calorimetry

4.1.1 Introduction

Calorimeters are devices used to measure the energy of particles. They are traditionally divided into two distinct sections, the electromagnetic section (EM), at the front, to measure the energy carried by electrons and photons, and the hadronic, to measure the energy deposited by such particles as protons and charged pions. The particle's energy is estimated by summing up the energy depositions of the cascade of particles produced as a primary particle is stopped in the calorimeter. For particles with high energies this requires a significant depth of material, over 1 m of steel for 1 TeV particles.

The technology of calorimetry is divided into two distinct types. One of the types is a sampling calorimeter constructed with an active medium, like silicon or plastic scintillator, sandwiched between layers of dense material such as steel or tungsten. Thus, the cascade or shower of particles is 'sampled' in the active medium, yielding an estimate of the primary particle's energy. Another type is the total absorption calorimeter where the active medium is also the dense, absorbing material. The former has generally a lower cost and a lower precision, and the latter type has better resolution and higher cost. The total absorption technique is typically only used for EM calorimeters.

For total absorption EM calorimeters, scintillating crystals (CsI, BGO, LYSO) or heavy glasses, like lead-glass, are used. Several high energy physics experiments (e.g., BaF, Crystal Ball, CLEO, CUSB, L3, CMS) have utilized this technology achieving excellent resolutions over a wide range of energies. An example is the CMS EM calorimeter (ECAL), whose barrel detector, shown in Figure 18, will be operating for the whole lifetime of the High Luminosity LHC (HL-LHC) after the upgrade of its front-end electronics. This technology has since been adopted by the medical imaging industry where it is used extensively in positron-emission tomography.

Sampling calorimeters can be constructed using different active media. One type uses liquid argon, which is a cryogenic liquid, where the ionization by particles in the liquid argon is used to measure the energy. Liquid argon is intrinsically stable and radiation-hard and for this reason it is used in the ATLAS detector. Another type, known as imaging or high granularity calorimeters, uses planes of wafer-scale silicon detectors interleaved with tungsten. Sampling calorimeters, where low-cost plastic scintillator is the active medium, have been used since the mid-1980s, and are currently in use as the hadronic calorimeters for both ATLAS

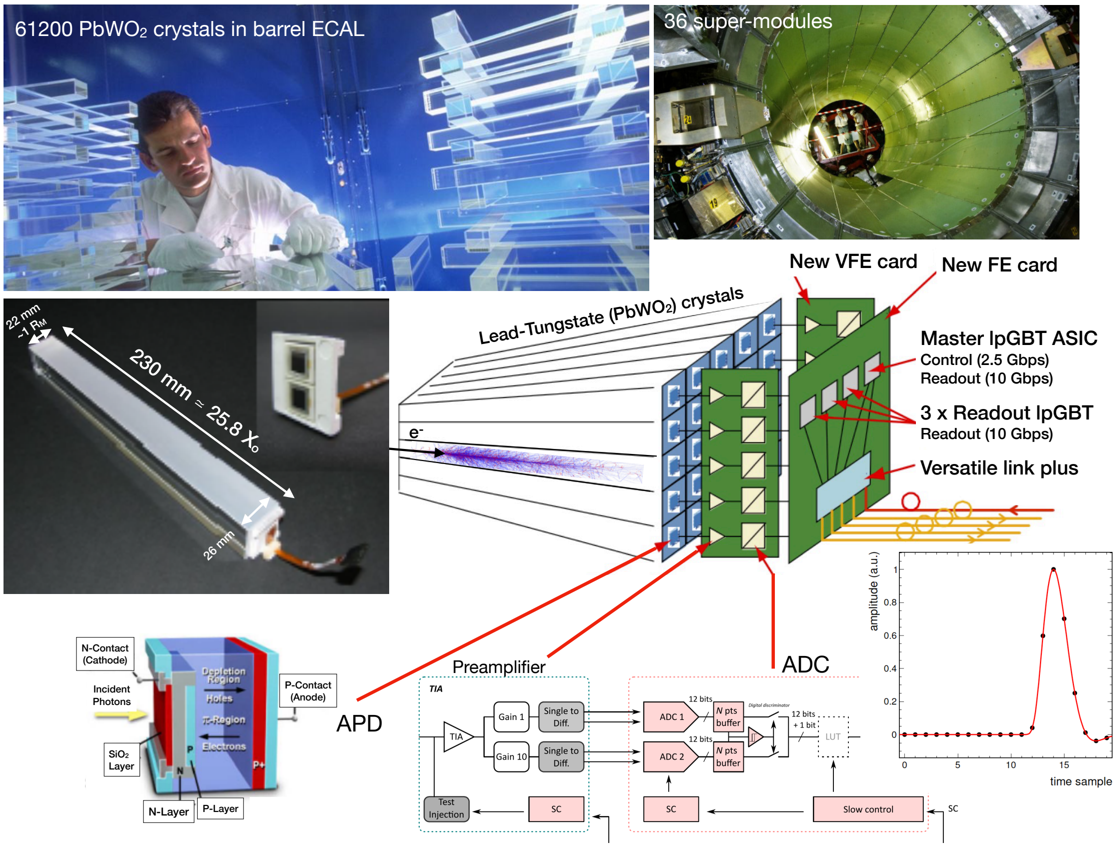


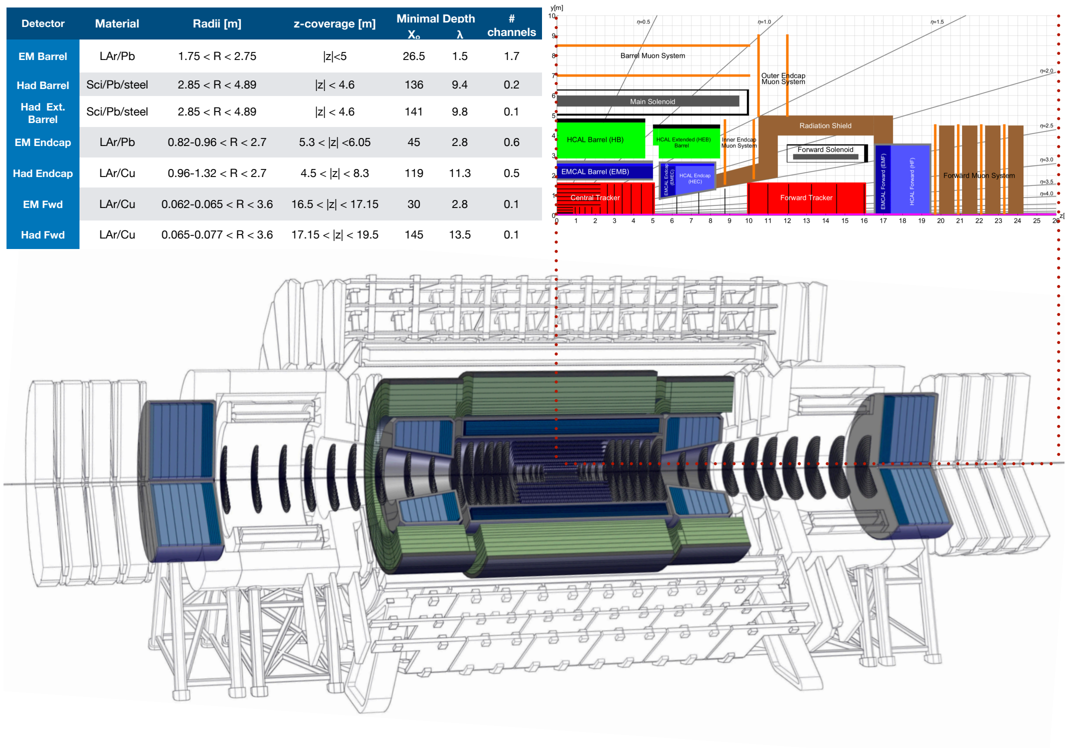
Figure 18: The CMS ECAL represents the state-of-the-art of large-scale total absorption EM calorimeters. The barrel detector is made of 61,200 lead-tungstate ($PbWO_2$) crystals assembled in 36 super-modules (pictures from CERN [169]). Scintillation light, produced by showering electrons and photons in the crystals, is detected by avalanche photo-diodes, whose output current is amplified, shaped and digitized at a very high frequency sampling rate, before being transmitted to the next stages of the CMS trigger and readout systems. For the HL-LHC upgrades, the front-end electronics of the CMS barrel ECAL will be upgraded to optimize performance of the detector in the presence of the increased pile-up conditions and radiation levels

and CMS. A fourth type, known as 'Dual Readout' measures both scintillation light and Cherenkov radiation (light emitted as a relativistic particle slows down to the speed of light in the material) to track fluctuations in hadronic showers to improve the jet energy resolution. This type of calorimeter has yet to be employed in a running experiment but has shown promise in simulations and recent test beam measurements.

One major paradigm shift that has occurred in the world of calorimetry is the way in which the information from the tracker and the calorimeter are treated together, rather than as separate measurements. This use of data from the two sources is known as “particle flow” and has helped to improve the performance of the detectors at the LHC. Any planned detector system is now designed with particle flow in mind. Imaging calorimetry should allow detailed reconstruction of individual showers. Timing information, though yet to be employed in any large-scale calorimeter, has shown considerable promise in the mitigation of pileup at hadron colliders.

In future collider experiments, both at electron-positron colliders and proton-proton colliders, the calorimeters will need to be large massive devices, weighing hundreds of tons.

While the future for major new collider projects around the world is uncertain, the discussion here is based on the possible road map for future machines described in the sidebar ”Higgs and the Energy Frontier” in Section 3.1. In this scenario, sometime after 2030, an electron-positron collider will come online. This will be followed by a hadron-hadron (hh) collider that will start operation sometime after 2040. We emphasize



Detector	Material	Radii [m]	z-coverage [m]	Minimal Depth X_0	Minimal Depth λ	# channels
EM Barrel	LAr/Pb	1.75 < R < 2.75	|z|<5	26.5	1.5	1.7
Had Barrel	Sci/Pb/steel	2.85 < R < 4.89	|z| < 4.6	136	9.4	0.2
Had Ext. Barrel	Sci/Pb/steel	2.85 < R < 4.89	|z| < 4.6	141	9.8	0.1
EM Endcap	LAr/Pb	0.82-0.96 < R < 2.7	5.3 < |z| <6.05	45	2.8	0.6
Had Endcap	LAr/Cu	0.96-1.32 < R < 2.7	4.5 < |z| < 8.3	119	11.3	0.5
EM Fwd	LAr/Cu	0.062-0.065 < R < 3.6	16.5 < |z| < 17.15	30	2.8	0.1
Had Fwd	LAr/Cu	0.065-0.077 < R < 3.6	17.15 < |z| < 19.5	145	13.5	0.1

Figure 19: Calorimetry of the reference FCC-hh detector. The system consists of a central and extended barrel, two endcaps, and two forward calorimeters. Dimensions are summarized in the top left table. The central barrels and the endcaps detectors are immersed in the 4 T magnetic field of the main solenoid [170].

that for a new technology to be considered for a future collider detector, the research and development needs to be in an advanced state before the start of construction, which typically is eight to ten years before operation of the machine begins. The timeline for the R&D needed in this scenario is also shown in the sidebar afore mentioned.

The most exigent requirements for future calorimeters at high energy colliders are those for calorimeters at a proton-proton collider like the FCC-hh. While this machine is not expected to come into operation in twenty or more years, it sets the context and the needs for research and development for future experiments. The environment at the FCC-hh will be similar to that of the planned HL-LHC, but with beam energies an order of magnitude higher and the number of interactions of particles in a bunch crossing will be around 1,000. The radiation levels will be much higher due to both the increased beam currents and the increase in energy, with levels in excess of 10^{18} neutrons/cm^2, approaching those experienced in nuclear reactors. In this harsh environment, the calorimeters will need to measure with high precision the energy of electromagnetic particles (photons and electrons) and of jets of strongly interacting particles. In Figure 19 a possible calorimeter for the FCC-hh is shown. The active media is the naturally radiation-tolerant liquid argon, and it has very fine segmentation, to manage the pile up of $1,000$ events per bunch crossing.

Apart from collider experiments, calorimeters are used extensively to provide precise energy measurements to identify extremely rare processes, or to eliminate unwanted backgrounds. Examples of these are the searches for the decay of a muon to an electron and a photon [170], the measurement of the anomalous magnetic moment of the muon [171], and the Fermilab muon to electron experiment [172]. The general needs of these calorimeters are their high precision at energies much lower than those at colliders, and their ability to distinguish events separated by a short time interval ($<$ 1ns). Calorimeters are also used in space-borne detectors, like the Fermi satellite. These calorimeters are required to be low mass and stable over long periods.

We have identified three Priority Research Directions where progress in understanding the technology could greatly improve the performance of calorimetry in future HEP experiments. Table 14 maps these PRDs to the Technical Requirements defined in Sections 3.1 and 3.5.

Priority Research Direction (PRD)	Technical Requirement (TR)
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	TR 1.3, TR 1.4, TR 5.5, TR 5.10, TR 5.12, TR 5.15
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	TR 1.4, TR 5.1, TR 5.10
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification	TR 1.3, TR 1.4, TR 5.7

Table 14: Summary of calorimetry Priority Research Directions to corresponding Technical Requirements.

4.1.2 PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements

Thrust 1: Improve jet energy resolution using spectral separation of scintillation and Cherenkov signals and timing, and provide fine segmentation to match with incident tracks

The information that is available from modern calorimeters, such as lateral and depth segmentation (imaging) combined with tracking information (particle flow), has led to calorimeters that have been shown in simulations to give jet energy resolutions of 3-4% for 100 GeV jets, which would meet the demanding physics requirements of future electron-positron colliders discussed in Section 3.1.4. This is also true for calorimeters that employ wavelength sensitive readout to detect both Cherenkov and scintillation light (dual-readout) in the same hadron shower. Combining these two approaches in a calorimeter with a high degree of segmentation *and* wavelength identification, will lead to calorimeters with excellent hadronic resolution for high sensitivity particle searches at colliders (TR 1.3 in Table 2). Studies have shown that timing measurements of energy deposits with a precision of less than 1 ns can also be used to distinguish the EM and hadronic component of a hadronic shower leading to an improved jet energy resolution, as with the dual readout technique.

In addition to wavelength and segmentation, precision timing information can add a further dimension to the information available from a calorimeter. Simulations and test-beam measurements have shown that the timing resolution of electromagnetic calorimeters can be approximately 30 ps for EM showers above 10 GeV, and approximately 1 ns for jets in the same energy range.

Thrust 2: Improve EM energy resolution using noble liquids or crystals

Achieving both excellent jet and EM resolutions with the same calorimeter, as in TR 1.3, is a very difficult problem. As discussed in Section 3.5.2, good EM resolution is necessary for the b-quark physics programs at electron-positron colliders, and as discussed in Section 3.5.3 for searches for charged lepton flavor violation, and as as discussed in Section 3.1.2, for searches at hadron colliders for new resonances that decay to photons or electrons, and for measurements of the Higgs self-coupling in the $\gamma\gamma$ channel. As the sensitivity of these searches scales directly with the EM resolution, improving the EM resolution to $10\%/\sqrt{E}$ or better, while still meeting the jet energy requirements, would be transformational.

There are several possible implementations of high-resolution, highly segmented sampling calorimeter with precise timing. For example, an EM calorimeter could be built with multiple-anode liquid noble elements (Ar, Kr, or Xe) technology measuring ionization and equipped with UV sensitive photodetectors to measure scintillation light at shower maximum for precision timing. The ATLAS liquid argon calorimeters has a stochastic resolution of $10\%/\sqrt{E}$ and $6\%/\sqrt{E}$ has been demonstrated with a sampling liquid krypton calorimeter.

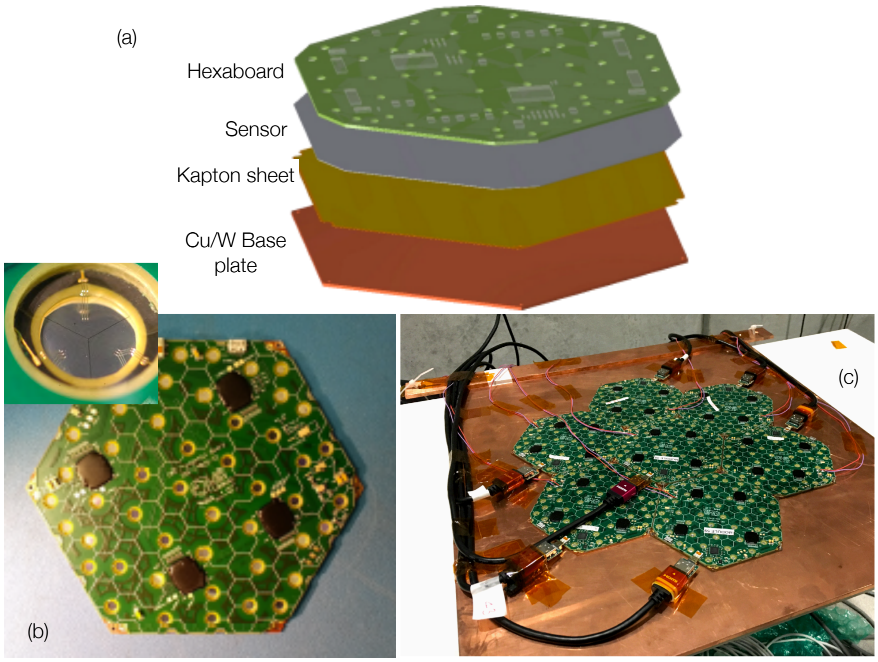


Figure 20: The CMS HGCAL calorimeter [173] is made of approximately 27,000 silicon detector modules. (a) The stack of components forming a module. (b) Photograph of a 6" module on the carrier plate. Four SKIROC2-CMS front-end readout ASICs are mounted on the hexaboard PCB. The detail of the wirebonds for three sensor pads is shown on the top left corner of the photograph. (c) Seven 6" silicon sensor modules are mounted on the copper support and used in the 2017 beam-test campaign.

Thrust 3: Simple, cost-effective, highly integrated detector design

The experience of building the existing calorimeters for the LHC and progress in many related technologies, like connectors, data links, and high-voltage silicon have introduced many new and exciting possibilities to improve by simplifying the design and construction of calorimeters. These new techniques need to be developed and qualified with extensive testing before they can be considered for installation in a next-generation collider experiment, where repairing a detector component is very costly in time and money, if not impossible. As an example of this, the silicon sampling calorimeter currently under construction for CMS has, by necessity, a highly complex electronic structure: the electronic readout board that carries the readout ASICs, the intelligent data managers, and the optical communication components is glued to the silicon sensor, and the electrical connection is made using wire bonds (see Figure 20).

For the next generation of imaging calorimeters, there would be considerable simplification and performance gain if it were possible to incorporate the electronic readout directly onto the sensor wafer. This would be an ideal application of the monolithic active pixel sensor (MAPS) technology, discussed in Section 4.6, as it would simplify the construction and make the calorimeter more compact – an advantage as this limits the degree of lateral spreading of the shower, enabling better shower separation.

Implementing particle flow algorithms in noble liquid calorimeters is another example where highly integrated solutions need to be developed: the ATLAS EM calorimeters are segmented in narrow strips in the front layer to provide excellent pointing resolution, but have rather limited longitudinal segmentation (3 layers only). The design of multi-layer electrodes with high transverse and longitudinal segmentation, of low-power cryogenic ASICs implementing signal conditioning and high-multiplicity aggregation, and of high channel density vacuum feedthroughs becomes essential when the readout scales-up from the $1 - 2 \times 10^5$ channels of the ATLAS EM calorimeters to approximately 1×10^6 at FCC-hh so as to limit the number of penetrations through the cryostat walls, a potential limiting factor for this detector technology.

Research Plans

The three Thrust areas suggest a common strategy for future R&D directions: for any detector technology, the performance of a calorimeter can be improved by increasing the segmentation, by improving the precision of the energy and time measurements, and by integrating different types of information in a single detector system.

A possible "maximal information" calorimeter could be one that is divided into small detection volumes (voxels) that measure ionization, time, and Cherenkov and scintillation light simultaneously, either in the same or in separate voxels. Such a calorimeter, without a boundary between electromagnetic and hadronic sections, would gather all the available information and would provide the best possible measurement of electrons, photons and jets. There are many ways this could be implemented: one possibility could be to use a high-performance noble liquid sampling, or a crystal total-absorption EM calorimeter, with a sampling hadronic calorimeter with voxels that measure the scintillation and Cherenkov light. It may even be possible to extend this technology to a homogeneous hadron calorimeter, if the voxels are made with a dense enough material. Independent of the implementation, the development of a cost-effective high-density inorganic crystal, or ceramic or scintillating glass with neutron sensitivity would be a significant benefit to the high energy physics community and could have cross-over applications in nuclear physics and in homeland security.

4.1.3 PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments

FCC-hh experiments set the most demanding requirements on radiation hardness of future detector technologies: the expected total ionizing dose and the 1-MeV equivalent neutron fluence in the forward calorimeters rise to the extreme values of 5000 MGy and 5×10^{18} n/cm^2 respectively (see Table 2 in Section 3.1 and TR1.4). These values exceed, by more than an order of magnitude, the dose levels and fluences expected in the innermost tracker layer, as well as the levels expected for the upgrades of ATLAS and CMS at the end of HL-LHC running.

In the barrel and end-cap calorimeters, covering pseudo-rapidities up to $|\eta| \leq 2.5$, the radiation requirements are less severe, 4 MGy and 3×10^{16} n/cm^2 respectively for total ionizing dose and neutron fluence, still significantly higher than what has been developed so far for the HL-LHC.

In the current FCC-hh detector concept there is a liquid argon calorimeter for all the EM sections and for both the endcap and the forward hadron sections where extreme radiation robustness is required. Fine transverse and longitudinal granularity is achieved using a geometry with absorber plates and multi-layer printed circuit boards that are straight and inclined with respect to the shower development, as shown in Figure 21. An alternative for the EM section uses silicon as active material (and W or Pb as an absorber), achieving a much finer granularity but a reduced EM energy resolution.

Research Plans

All the technology candidates for calorimetry at FCC-hh require a robust R&D program to qualify materials at the doses and hadron fluences expected. Areas where R&D is required to meet the requirements of TR1.4 in Table 2 are:

- **Noble liquids:** Calorimeters with liquid argon or other noble liquids as active media are intrinsically radiation resistant as demonstrated by the R&D programs that preceded the construction of the ATLAS calorimeters and by the studies made at the time of the GEM proposal at the SSC. However, the severity of the radiation environment, in particular for the forward calorimeters, will require a major R&D program to qualify, under radiation, all the structural materials.
- **Silicon:** The CMS collaboration has chosen p-type silicon as the active material for its highly granular endcap calorimeter at the HL-LHC [174, 175]. The silicon sensors need to operate at fluences of up to $10^{14}\,\mathrm{n_{eq}/cm^2}$ at the outer and to $10^{16}\,\mathrm{n_{eq}/cm^2}$ at the inner radius, and in order to reduce the shot noise from radiation induced leakage current to a level of MIP detection, the calorimeter needs to be

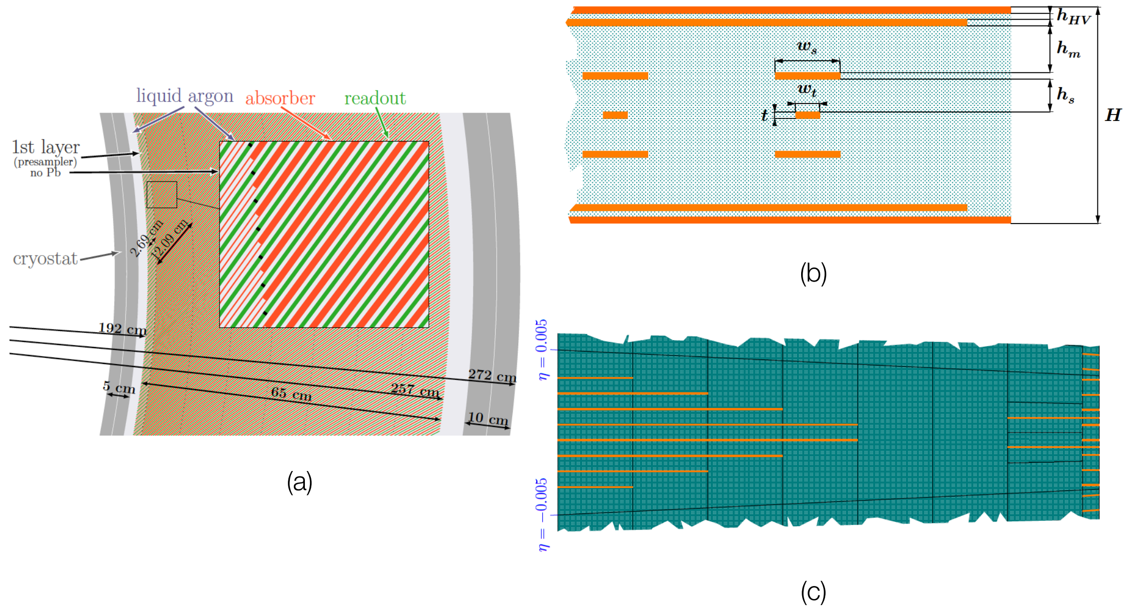


Figure 21: (a) Cross-section of the electromagnetic barrel calorimeter of the FCC-hh reference detector [170]. Straight Lead/steel absorbers are interleaved with LAr gaps (1.2 mm) and electrodes. The structure is arranged with an azimuthal inclination of 50 degrees with respect to the radial direction. (b),(c) Multi-layer printed circuit boards allow the detector to have 8 longitudinal segmentations.

cooled to -30° C or lower. For applications at FCC-hh, R&D on silicon sensors is needed to increase radiation tolerance to hadron displacement damage by a factor 3-5.

- **Inorganic scintillators:** Recent R&D on bright and fast crystals has identified promising candidate materials, like Cerium doped LYSO crystals, for which the radiation tolerance has been demonstrated to levels up to $10^{16}\,\mathrm{n_{eq}/cm^2}$. However, a further two orders of magnitude would be required before these crystals can be considered for the FCC-hh forward calorimeter. Besides LYSO crystals, cerium or praseodymium doped garnet and perovskites ceramics are possible low-cost candidates that may meet the radiation requirements. For these materials to be considered for the EM calorimeters in detectors at the FCC-hh much more R&D will be required.

- **Organic scintillators:** Organic scintillators are another potential candidate technology for the barrel hadronic calorimeters, where the expected doses and neutron fluence are lower and limited to 10 kGy and $3\times 10^{14}\,\mathrm{n_{eq}cm^2}$. Current technologies have radiation tolerances of a few kGy, therefore R&D needs to be pursued to improve their radiation tolerance, especially at low dose rates (0.01 to 10 Gy/hr), where the effects of radiation per unit dose are more severe.

- **Cherenkov radiators:** Synthetic fused-silica is one of the more radiation-hard Cherenkov radiators that is employed in the form of fibers in the CMS forward calorimeter [176]. The maximum expected dose is about a 10 MGy at $\eta \approx 5$ in a decade of LHC operation. As the radiation levels increase by factors of ten or hundred at future hadron colliders, continued search for clear and high refractive-index radiation-hard Cherenkov radiators will be needed to support advances in calorimetry.

- **Construction material:** As with the construction of tracking detectors in high radiation environments, all the materials that will be used in calorimeters at the FCC-hh will need to be tested and qualified for tolerance to very high levels of radiation. This includes, among many others, electrode structures and epoxies in Noble liquid calorimeters, printed circuit boards, where changes in the dielectric could significantly degrade the detector performance, cables, connectors and both optical transmitters and receivers that will be used to extract the calorimeter signals.

4.1.4 PRD 3: Develop ultrafast detector media to improve background rejection in calorimeters and improve particle identification

Precision timing has been a tool in high energy physics experiments that has been used in multiple applications: it is used to identify particles by measuring their velocity by their flight time inside the detector; it is used to separate individual events from nearly simultaneous events, and it is used to distinguish interesting physics events in the presence of massive backgrounds in the search for extremely rare processes. New technologies to improve and extend the precision measurement of the time of arrival of an incident particle will be needed in future experiments.

Their application could be in heavy flavor physics described in Section 3.5.2 and the search for lepton flavor-violating processes described in Section 3.5.3 with specifications given in Table 10 and Table 11, respectively. In these areas of physics separation of charged kaons from pions and other particles is essential. They can be used to disentangle complex events in high rate experiments as described in Section 3.1.2, where pileup of multiple events is a severe problem. Novel fast scintillators could also be used in highly-granular calorimeters with high-precision timing capabilities described in Section 3.1.2.

Research Plans

There are several research directions that could lead to novel precision timing detector technologies. For example, new ultra-fast inorganic scintillators, like BaF_2, could have a performance better than the current detectors, or new ultra-fast scintillators with wide band-gap semiconductor-based inorganic scintillators embedded with nano-crystals, which have recently shown promising results. The development of technologies to precisely measure the time of arrival of incident particles with a precision of ≈ 1 ps could lead to significant improvements over the LGAD or LYSO crystal detectors that are currently planned for installation at the HL-LHC.

4.1.5 Connections Outside HEP

The detection of photons, electrons, and hadrons is foundational to science as a whole, and therefore the advancements enabled by the above PRDs would immediately find application outside of HEP. One of beneficiaries would be nuclear physics (e.g., experiments at the Electron-Ion Collider and parity experiments). Medicine and national security would benefit from the improvement of organic scintillators, which could also be used in commercial nuclear fuel cycle monitoring by measuring fresh versus spent nuclear fuel.

4.1.6 Facilities and Capabilities

There are a number of existing facilities and capabilities necessary to conduct R&D into new calorimeter technologies outlined in PRDs 1, 2 and 3. We enumerate these here.

1. Detailed and reliable simulation studies will be needed to predict the performance of any new calorimeter that is proposed for future colliders. This will reduce the detector development costs and the need for expensive test beam campaigns. There is limited high quality data available with detailed timing and dual readout information for hadronic shower tuning. Recent measurements in test beams have shown that GEANT4 is not yet reliable for these studies [177]. In addition, since these calorimeters are always used in conjunction with particle flow, and the resolutions depend on the upstream material as well, support for integrated simulations in a full detector setting is needed to predict the ultimate performance. It is therefore important that the U.S. HEP community continue to develop the GEANT4 framework in support of the exploration of novel ideas in instrumentation.

2. Irradiation facilities to qualify materials for the detectors before construction. For materials to be used in the FCC-hh these will need irradiation facilities able to supply radiation at levels of $\mathbf{10^{18}}\,\mathrm{n/cm^2}$ and 10 GigaGy. Additionally, for the qualification of organic scintillators, low-rate irradiation facilities are needed.

3. Capability to characterize precision timing systems. Any system that relies on precisely measuring the time interval between signals from different detector channels requires a high quality, low-jitter and low-wander clock distribution system. To reach the 1 ṗs measurement level, the clock distribution system will need to be stable at the sub-picosecond level. An installation with user access and with the equipment and engineering resources needed to develop and demonstrate the required signal quality will be necessary.

4. Access to precision test beams. Low-dispersion electron beams for accurate characterization of calorimeter technology are needed. With the increased energies of future colliders, high-energy (100 GeV), high-rate (1 MHz) beams will be essential. While the infrastructure improvements required to provide these in the U.S. will be very costly, a compromise could be for the U.S. to establish a high-rate, low-energy beams ($\leq$ **30** GeV) with a dispersion of better than 0.5% and with efficient particle identification. This would complement the higher-energy beams available at CERN and in other facilities. Possible sites could be JLAB, SLAC or a significantly improved test beam facility at Fermilab.

5. As discussed in Section 4.7, the data rate in the next-generation calorimeters will far exceed the capabilities of current radiation-tolerant technology. This can be addressed on-detector with radiation-tolerant data processing and data links with $\geq$ 100 Gbs data rates, and off-detector with real-time event processing using advanced hardware (GPUs, FPGAs) and software (image processing and deep learning). An installation with user access and with the equipment and engineering resources needed to develop and demonstrate these capabilities will be necessary.

6. Improved, or alternate power delivery systems. As smaller feature sizes are used in ASIC technology the operating voltage decreases. This poses significant problems for delivery of the high level of low-voltage power that will be required for the readout electronics.

7. Research scientists based at universities to develop the technologies described in this section. Experienced scientists with expertise in detector technologies will allow university groups to benefit from the mechanical, electrical and computer science engineering expertise available at many U.S. universities. They will also enable university groups to make more effective use of the user facilities that are available at the national laboratories.

4.1.7 Calorimetry and the Grand Challenges

As has been discussed in this section, calorimeters are a key element of almost all HEP experiments, and advances in calorimetry will be needed for future detectors at existing or planned machines. To meet the grand challenges listed in Section 2.1 advances in the materials used in their construction and in their exploitation will be essential. Specifically all three of the Priority Research Directions for calorimetry (PRD 1, PRD 2 and PRD 3) will be needed to meet Grand Challenge 1 and Grand Challenge 3, which are to advance HEP detectors to new regimes of sensitivity, and to build next-generation detectors with novel materials and advanced techniques, respectively. For detectors that will be constructed to operate in extreme environments – Grand Challenge 4 – developments that will result from research under PRD 2 will be essential.

4.2 Noble Elements

4.2.1 Introduction

Detectors using noble elements as the detection medium, such as liquid and gaseous argon and xenon, have risen to become a prime technology for the following Science Drivers:

- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Explore the unknown: new particles, interactions and physical principles

Many of these experimental programs are pushing towards very large detectors, up to the many kiloton-scale, and plan to run for an extended time (a decade or more). The Priority Research Directions identified here aim to enhance the physics reach of these instruments, and underpin the development of new detection strategies to expand the physics sensitivity of noble element detectors to unexplored regions of parameter space.

Operating Principle: Particles interacting in noble element detectors deposit energy into three main channels: heat, ionization, and scintillation light. The partitioning into each channel is a function of the particle type and its energy, an example of which is shown in Figure 22. Depending on the physics of interest, noble element detectors exploit one or more of these signal components. In time projection chambers (TPCs), used widely in both dark matter and neutrino research (see Figure 23), charge is drifted by an electric field from a local interaction point to detection planes, which can measure the charge directly or amplify the charge into a secondary pulse of scintillation light. Direct scintillation from the primary interaction is also often detected by photosensors. Liquid argon scintillates in the vacuum ultra-violet (VUV) wavelength range, centered around 128 nm, with lighter noble elements scintillating at even shorter wavelengths. Detecting this signal is traditionally done using wavelength shifters, such as tetra-phenyl butadiene (TPB), to shift the light to >400 nm wavelength for detection by light detectors like PMTs or SiPMs. Liquid xenon (LXe) scintillation light centers around a wavelength of 178 nm, which can be observed directly by PMTs or SiPMs. Being relatively easy to purify signal trapping impurities, noble element detectors can also be scaled to large sizes. Ultimately, this combination of scalability and large signal yield, providing charge- and light-based calorimeters with excellent tracking and time resolution properties, is what makes noble element detectors such a strong technology for this type of research.

Historical Context: For neutrino research focused on oscillation and astrophysics, noble element detectors employing liquid argon targets in time projection chamber detectors have been under development since the 1970s [178, 179]. Following a suite of prototype detectors (ICARUS [180], ArgoNeuT [181], LArIAT [182], MicroBooNE [183], protoDUNE [184]), including some still under construction (SBN program [185]), the DUNE collaboration is designing a 40 kiloton fiducial mass liquid argon detector, made of four 10-kt modules [186]. The sequential construction of the four DUNE modules is planned from 2021 to 2030 (see "Neutrino Timeline," Section 3.2). In particular, the fourth module (construction currently expected in 2030) has been identified by the collaboration as the *module of opportunity*, encouraging new technologies that enhance or expand the DUNE physics program on this timescale. Near detectors are employed in oscillation searches to constrain systematic uncertainties on the neutrino interaction cross sections and neutrino flux. In current experiments, atmospheric pressure argon gas TPCs are employed [187], and in future experiments, both high pressure argon gas and liquid-based pixelated TPCs are under development.

A key open question in neutrino physics is whether neutrinos are Dirac or Majorana particles; neutrinoless double beta decay (NLDBD) searches address this question. Xenon-136 is one of the most promising isotopes in the search for NLDBD, with enriched xenon deployed in gas TPCs (Gotthard [188]), liquid TPCs (EXO-200 [189]), and dissolved in liquid scintillator (KamLAND-Zen 400/800 [190]). For the future, these technologies are pushing towards the 'ton-scale' using both liquid (nEXO [191], KamLAND2-Zen [192]) and gas targets (NEXT-100/ton [193]). Ideas for using large amounts of (natural) xenon are being considered, with NLDBD as a parasitic science goal for programs pursuing neutrino oscillation physics (organic scintillators [194], water-based scintillators [195]) and dark matter (DARWIN [196]).

Direct searches for weakly interacting massive particle (WIMP) dark matter have employed noble element targets starting circa 2000 with liquid xenon time projection chamber detectors (LXe-TPC) [197]. With its high density, self shielding, and background rejection capability, liquid xenon has proven itself to be an excellent dark matter target, gaining four orders of magnitude in sensitivity over the past decade (XENON10/100 [198, 199], LUX [200], PandaX-II [201], XENON1T [202]). LXe-TPCs currently place the most stringent limits on interactions of dark matter particles with masses above 10 GeV/c^2. The next generation of multi-ton LXe-TPCs is close to data-taking (PANDA-X4 [203], XENONnT [204], LZ [81]). The leading result in the low WIMP mass range comes from a dual-phase time projection chamber detector with a liquid argon target that has been depleted of the radioactive isotope Ar-39 (DarkSide-50 [205, 206]). Electron versus nuclear recoil discrimination at the part-per-billion level, as well as background-free operation, has been demonstrated at the 3-ton scale in single-phase liquid argon (DEAP-3600 [207]). The DarkSide-20k dual-phase TPC argon detector with a 50-ton low-^{39}Ar argon target is on the near horizon [208]. For the longer-term future on a 10-year horizon, 50-100 ton Xe TPCs are envisioned (DARWIN [196], G3-Xe), as well as 0.5-1 kiloton Ar detectors (Argo [20]), see "Dark Matter Timeline, in Section 3.3, as part of a potential suite of G3 experiments. Dedicated searches for interactions of sub-GeV mass dark matter are using, or exploring, gaseous H_2, He, and Ne targets [209, 210], as well as liquid He at the 1 kg scale [211].

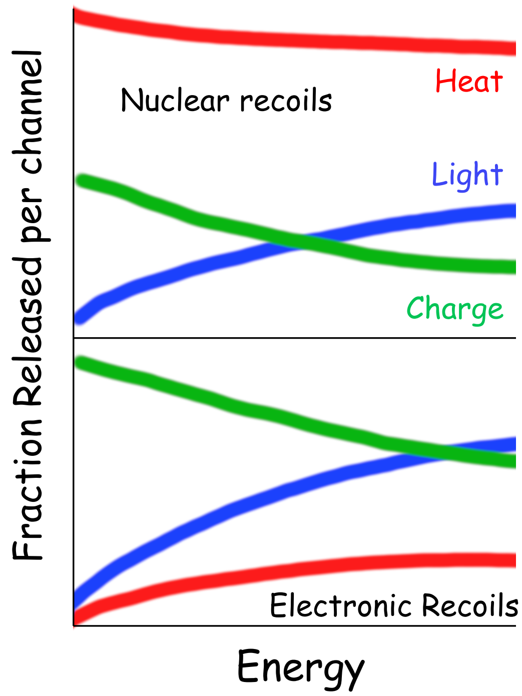


Figure 22: Energy partition of energy deposition in liquid helium for nuclear recoils (top) and electronic recoils (bottom). The three contributions sum to unity.

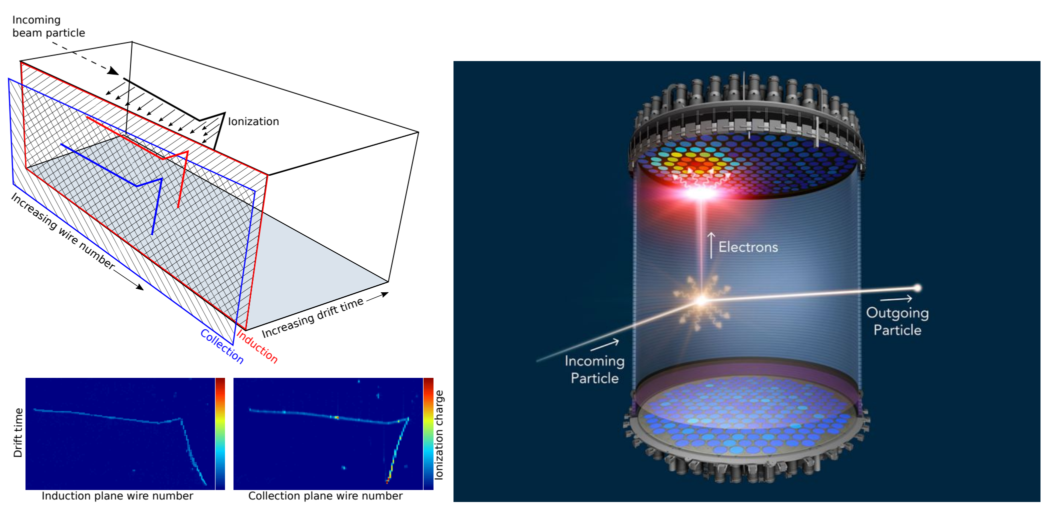


Figure 23: Left: schematic of the operation of a single-phase liquid argon time projection chamber with two projective views of the event. Figure from [182]. Right: Depiction of the operation of a dual-phase liquid xenon time projection chamber for dark matter searches. Figure from SLAC National Accelerator Laboratory.

Priority Research Direction (PRD)	Technical Requirement (TR)
PRD 4: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity PRD 5: Develop new modalities for signal detection	TR 1.3.3, 2.1, 2.4, 2.5, 2.7, 2.9, 3.3, 3.6, 3.9, 3.12, 3.13, 3.15, 3.17, 3.19
PRD 6: Improve the understanding of detector microphysics and characterization to increase signal-to-noise and reconstruction fidelity	TR 2.8, 2.9, 3.3, 3.6, 3.9, 3.12, 3.13, 3.15, 3.17, 3.19
PRD 25: Advance material purification and assay methods to increase sensitivity	TR 2.3, 3.1, 3.4, 3.7, 3.10
PRD 26: Addressing challenges in scaling technologies	TR 2.1, 2.3, 2.4, 2.7, 2.9, 3.2, 3.5, 3.8, 3.11 , 3.14, 3.16, 3.18, 3.20

Table 15: Table mapping Priority Research Directions to Technical Requirements.

Connection to physics requirements for the future: Noble element detectors operate over a wide range of energy scales, observing tracks of MeV to GeV scales for neutrino experiments like DUNE, and down to the keV nuclear recoils that would be induced by dark matter scattering. Pushing these detectors to lower energy thresholds while maintaining control of backgrounds is a priority for this technology, driven by requirements for new physics searches as discussed in Sections 3.2 and 3.3.

A major challenge in the detection of neutrinos in argon TPCs is to reach high signal-to-noise per readout channel in 10-kt scale detectors (see TR 2.7, TR 2.9). Achieving high spatial resolution readout (at the sub-mm scale) (see TR 2.1, 2.4) is an active area of R&D focused on improving reconstruction fidelity at lower energy thresholds, as well as reducing neutrino interaction systematic uncertainties (see TR 2.1, 2.7, 2.9).

Key issues in the detection of dark matter are to reach recoil energy thresholds at the keV-scale and below (see TR 3.3, 3.6, 3.9, 3.12, 3.13, 3.15, 3.17, 3.19), and to demonstrate particle identification for discrimination against backgrounds at these low thresholds. Given current constraints in physics parameter space, dark matter-induced signal rates are predicted to be at the level of 1 event/ton/year/keV.

Neutrinoless double beta decay searches share challenges similar to direct dark matter detection, as background suppression is also the primary challenge in this area. The planned ton-scale experiments aim for background rates at or below 1 decay/ton/year in a $\sim$10 keV region of interest around the endpoint of the two-neutrino beta decay (2.5 MeV in ^{136}Xe).

Five Priority Research Directions are identified where progress could be transformative for the performance of noble element detectors. Table 15 maps these PRDs to the technical requirements.

4.2.2 PRD 4: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity
PRD 5: Develop new modalities for signal detection

Significantly enhancing the amount of signal collected by noble element detectors, in the form of charge, light, heat, novel detection signals, and multi-modal combinations, as well as increasing the fidelity of the signals collected, would greatly enhance the capability of the noble element detector technology. Lower energy thresholds will improve the current level of performance achieved in existing experiments and allow future experiments to achieve entirely new physics reach.

Thrust 1: Improve and enhance light collection

Increasing the light collected from noble element detectors will improve both their calorimetric and topological reconstruction capabilities (see TR 2.1, TR 2.4, TR 2.5). Two clear ways to accomplish this are: by increasing the likelihood that any given photon will hit a light sensor, via large-area photocoverage or other means like wavelength-shifting, and by improving the detection efficiency of those sensors. We address the former here, the latter is included in Section 4.3.

Thrust 2: Improve and enhance charge collection

One key goal in the area of charge collection is to achieve unambiguous 3D charge imaging. Projective 2D readout, as shown in Figure 24, can lead to ambiguities in event reconstruction, especially for complex event topologies, and for events where the particle trajectory is parallel or perpendicular to readout channels. These ambiguities lower event reconstruction efficiencies and increase background contamination, two effects that negatively impact the physics reach of these detectors. The goal is to reach a detector readout granularity that can achieve a per-channel signal-to-noise ratio better than 10 for energies above 100 keV in kton-scale detectors.

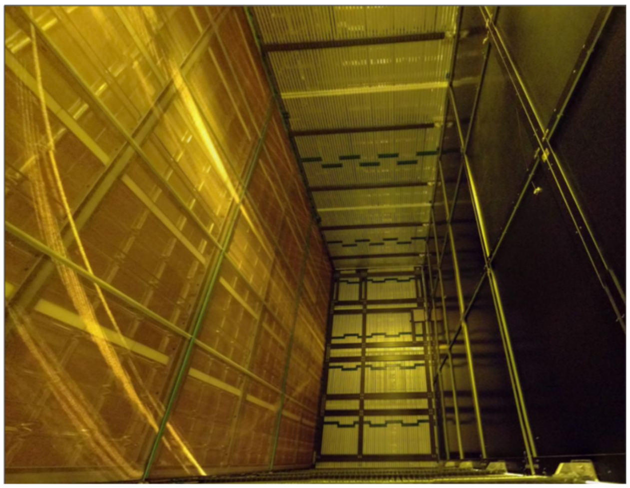


Figure 24: Inside of the protoDUNE TPC. The wire planes, offering a projective readout, can be seen on the left of the TPC [212].

A science-objective-driven priority for noble element detectors is to lower the event energy threshold (see TR 2.7, 2.9, 3.3, 3.6, 3.9, 3.12, 3.13, 3.15, 3.17, 3.19) and thus extend the physics reach of these detectors. For neutrino experiments, the goal is to achieve $\leq$10 MeV deposited energy threshold with microphysics-limited resolution. Neutrinoless double beta decay and dark matter experiments have a goal of single electron thresholds ($\sim$10 eV) with internal backgrounds subdominant to the coherent neutrino-nucleus scattering floor [213]. Lowering thresholds in liquid argon TPCs to the keV scale may require direct amplification of the signals produced by drifting electrons, similar to the gain achieved in gaseous detectors. Alternatively, the exploration of ultra-low noise charge collection devices that do not require carrier amplification should also be aggressively pursued. Another interesting research avenue is the investigation of the energy resolution enhancement of future large LAr calorimeters at colliders that could be achievable by exploiting the combined readout of the anti-correlated charge and light signals (see TR 1.3.3).

Thrust 3: Improve and enhance integration of charge and light collection

Traditionally, the detector elements used for charge detection and light detection are separate technologies in neutrino oscillation experiments using noble elements. Integration of charge and light detection modes into a single integrated detector element is an aspiration that would simplify large detectors, and enhance light collection by increasing the percent-level light sensor coverage of current systems. Moreover, if such a device could be made sensitive to the VUV scintillation directly, with reasonable quantum efficiency ($\geq \mathcal{O}(20\%)$)), detectors could exploit: (i) the collection of fine-grained information for both charge and light, opening up new possibilities to exploit previously undetectable associations from the production of the two signals; (ii) enhanced imaging capability free from the additional timing uncertainty introduced via wavelength-shifter re-emission, (iii) improved light collection via increased surface area coverage, which will improve energy resolution, and (iv) simplification of the design of larger-scale detectors.

Thrust 4: Improve and enhance heat collection

The third major mechanism for energy deposition is heat, as shown in Figure 22. This channel has been demonstrated in bubble chambers using superheated liquids, notably the PICO dark matter experiment [214], that observe heat deposition above a threshold (see Figure 25). Measurement of heat energy in addition to charge and light would allow for 100% reconstruction of the energy deposited by a particle in the target medium, and would increase background discrimination capability.

For the future, noble liquid bubble chambers hold the promise of extending the intrinsic background rejection to energy thresholds as low as a few tens of eV [215]. Achieving this threshold would open new parameter space to search for dark matter below 1 GeV/c^2 mass, and high rate detection of MeV neutrinos at reactors or other facilities via coherent interactions. Bubble chambers are discussed in PRD 24 for their broad applicability both in science goal and in medium/material. Combining quantum photodetectors with noble element technologies, superfluid helium detectors can provide sensitivity to meV-scale excitations for dark matter or other searches.

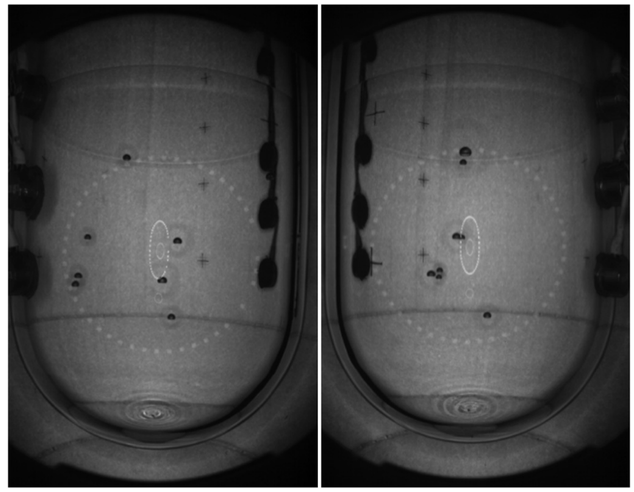


Figure 25: Two views of an example multiple bubble event in the PICO-60 bubble chamber detector, caused by a neutron interacting in the liquid [214].

Thrust 5: Enhance and develop doping and ion collection

Another promising direction for noble element detectors is target mixtures or doping with other elements. Such mixtures can improve sensitivity by changing the characteristics of the detector response in a beneficial way, *e.g.*, wavelength-shifting and time-profile compression. In gaseous detectors, some quenching of the light production is necessary for stable detector operation, and investigation of novel gas mixtures may provide an avenue for improved signal collection along with stable operations. For liquid detectors, on the other hand, mixtures can be exploited to extend the physics reach of the experiments by, *e.g.*, adding new nuclei that provide dark matter sensitivity down to lower masses. Again, the cross-cutting nature of this area of work motivates its discussion in PRD 24.

A complimentary signal channel for noble element detectors is detecting ions, as opposed to electrons, created by ionization energy deposition. Ions drift to the collection plane with diffusion lower than electrons by the mass ratio, thus signals from ions can offer more precise spatial imaging, down to the ion diffusion limit. Ions can potentially have much longer effective lifetime during the drift because attachment cross sections are less than those of electrons for a range of drift fields. For NLDBD, the detection of daughter ions, *e.g.*, via barium tagging, carries chemical information which provides orthogonal background discrimination. Ions, which are less affected by some microphysics such as diffusion, may also carry complementary information, useful for calibration. Negative ion drift also presents advantages for gaseous detectors – discussed in PRD 24.

Research Plan

High-priority research activities for the future include the following:

1. Increasing the light collected (most of which is emitted in the VUV range) over many tens to hundreds of square meters and improving the light detection efficiency of sensors, addressed in PRD 5, are crucial. Another important area of research is to enable high-efficiency wavelength-shifting techniques via novel thin films, fluorescent and scintillating structural materials, and dissolved atoms and molecules (the latter overlapping PRD 24 to some extent). In addition, the development of highly reflective surfaces over large detector components promises to greatly improve light collection efficiency.

2. Today, laboratory bench-top demonstrators exist for some promising technologies for unambiguous 3D charge imaging. On a five-year horizon, the aspiration is to demonstrate this capability at the multi-square meter scale. This R&D entails the development of readout ASICs suitable for cryogenic environments. Electron amplification in liquid is being investigated, but it has not yet been harnessed in a stable, linear, and reproducible way. Challenges include the formation of bubbles, management of heat load, and management of the additional ions created in the avalanche.

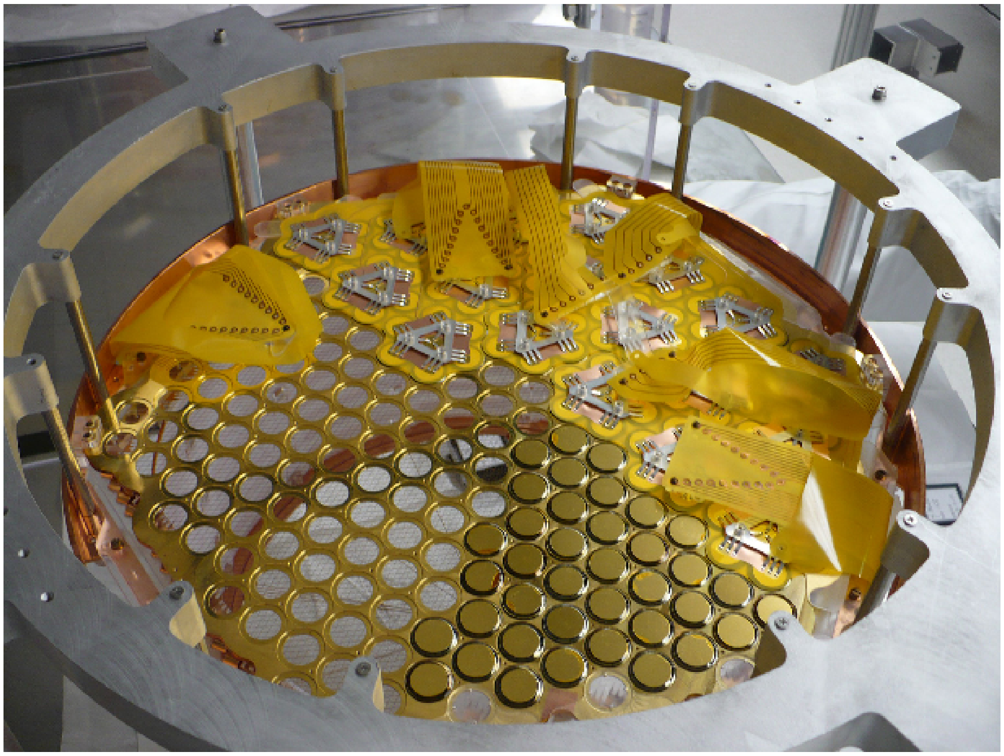


Figure 26: The silicon large-area avalanche photodiode (LAAPD)-based light collection system used by the EXO-200 experiment (during assembly of one of two planes of 250 LAAPDs) [189].

3. Realizing integration of charge and light detection modes on a single detection element will require cross-cutting collaboration with solid state, condensed matter, and material science physics to identify suitable photodetector materials. Exploration of new non-silicon based readout, novel detector structures and layouts, and realization of both small scale $\mathcal{O}(10\ cm^2)$ and large scale $\mathcal{O}(m^2)$ prototype noble element TPCs are priorities to explore this possibility.

4. To enable measurement of heat deposition, research into the relationship between material surfaces and quasiparticles is needed to develop new ways to observe either phonons or rotons directly, or via other scattering mechanisms. Similarly, the development of low radioactivity, smooth surface materials capable of sustaining a superheated noble liquid for minute time scales is important for future noble liquid bubble chamber development. Investigation of active or passive sonar techniques would improve imaging of bubbles with echolocation, ultimately eliminating the need for fused silica jars in bubble chambers, simplifying their design and scalability.

5. To take advantage of target mixtures or doping with other species, research is needed at the bench-top scale on the characterization of such mixtures. Beyond identifying the microphysics of mixtures, observing stability over time or changes in signal yield with concentration of the doped species, and how those mixtures scale, are key enabling activities. This is described in more detail in Section 4.8.2.

6. There are several applications using ion detection that are currently under investigation such as novel purity monitors for liquid argon, ν_τ detection feasibility studies, unambiguous identification of single barium ions/atoms in large xenon detectors, and, with gaseous target mixtures beyond nobles, low-diffusion ion imaging TPCs for direction-sensitive dark matter detection. Some of this work overlaps PRD 24 when it is goes beyond noble liquids.

4.2.3 PRD 6: Improve the understanding of detector microphysics and characterization

The full exploitation of the potential of noble element detectors, including efficient collection of VUV scintillation and ionization signals, requires a detailed understanding of the target microphysics at the interaction scale as well as the ability to characterize and precisely calibrate the propagation of light and charge over very large sensitive volumes.

Dark matter and neutrinoless double beta decay experiments need an improved understanding of the energy partition to achieve low energy threshold and improve background suppression. As the science requirement is to lower the energy threshold down to the single charge or light quantum, it is a high priority to characterize sub-keV recoils and the associated quenching effects for both nuclear and electronic recoils in argon, xenon, and doped mixtures as well as other potential noble targets like helium. Equally important is to reach the energy resolution limited by the microphysics. Improved model-driven reconstruction techniques will lead to a better measurements of the event topology to identify vertices and tracks. The microphysics of dimer formation and decay underpins particle identification based on the light pulse shape vs. time, and could enable the development of novel particle ID techniques to suppress backgrounds.

At the 10 m scale, noble element detectors for neutrino physics and rare event searches reach dimensions where photons and charge propagating from the interaction point to the detection plane have significant probability of interaction enroute. R&D is needed to provide key input to detailed modeling of the detector response, requiring improved calibration of the propagation of light and charge over distances up to 10 m. Large-scale detectors require new calibration techniques to map out the detector response over the entire volume and achieve uniform response, as well as time stability required for each application (energy and position resolution, light collection, etc). An important aspect of detector response that requires advances is to improve the calibration of electric field non-uniformity in large TPCs.

Research Plan

High-priority research activities for the future include the following:

1. At the interaction scale, improved understanding of the energy partition requires ex-situ characterization of noble targets at the lowest recoil energies with mono-energetic sub-MeV neutron beams or sources incident on dedicated detectors, operated at a range of electric fields. The goal of such measurements is to map light, charge, and heat response versus field strength, recoil direction relative to the drift field, and sensitivity to pressure and temperature variation. The availability of such characterization beams and facilities is an identified need which is critical for the field to make progress on the most ambitious goals.

2. The key objective of achieving uniform response via calibration across detector volumes is a high-priority problem to solve. In-situ calibration of multi-ton-scale detectors for dark matter and NLDBD requires a suite of approaches because these detectors very efficiently self-shield external radiation. Radioactive injectables (^{83m}Kr, ^{220,222}Rn, tritiated methane) have been used successfully in current generation experiments, and their deployability at larger scales needs to be demonstrated. Both types of rare event detectors and large LArTPCs are pursuing calibration methods using penetrating neutron sources.

3. Detailed modeling of the detector response requires improved calibration of the propagation of light and charge over distances up to 10 m, including in the presence of impurities at the part-per million to part-per trillion level. Field-dependent recombination and extraction efficiencies and the time-dependence of these processes requires more detailed measurements to advance sensitivity to low-energy physics, relevant to tracking of sub-MeV final state particles in neutrino experiments and to searches for low mass dark matter interactions.

Material purification and technology scalability are two additional topics of high relevance for noble element detectors. These research directions are directly addressed in PRD 25 and 26 in Section 4.8.

4.2.4 Connections Outside HEP

Noble element detectors play an important role in nuclear physics where the search for neutrinoless double beta decay is performed with liquid or gaseous xenon detectors, where the isotopically enriched xenon is simultaneously the double beta decay source and the detection medium. While most noble element detectors are built for particle physics, most of them offer significant interest to astrophysics. The detection of supernovae and solar neutrinos by large noble element detectors can shed light on several questions of that field. Finally, there is dedicated R&D on using noble element detectors, such as gaseous xenon and liquid argon detectors, for medical imaging.

Figure 27: Liquid argon inside the Liquid Argon Purity Demonstrator (LAPD). LAPD is one example of infrastructure that was used in the R&D effort to develop new purification solutions for large-scale liquid argon detectors. Picture from Fermilab.

4.2.5 Facilities and Capabilities

There are a number of existing facilities supporting R&D in noble element detectors. We enumerate these here, and highlight where future R&D needs new capabilities. A more detailed description of current and future instrumentation facilities can be found in Section 5.

1. Low-background screening capabilities are an essential capability for rare event searches. Noble element needs for these capabilities are discussed with other radiopurity screening needs as components of PRD 25 in Section 4.8.

2. Cryogenic platforms at laboratories for neutrino experiments, with capabilities in cryostat development, materials testing, optical testing, and HV testing, work well. Two such example facilities are the Cryogenic Instrumentation and Test Facility at the Proton Assembly Building (PAB) at Fermilab and the CERN Neutrino Platform. PAB has been successfully supporting research for several years, *e.g.* in early development of the Arapuca technology [216], and can be enhanced with additional support, to meet the PRD challenges identified. Impurity studies at small scales have been done effectively at universities, but translation to larger cryogenic systems at universities is a challenge. Coordination between national laboratory infrastructures is important, perhaps with new multi-laboratory modalities. Community input is essential to coordinate activities at these facilities with university R&D.

3. Test beams and sources are important to qualify the performance of novel detector readouts for both neutrino and dark matter science. Existing facilities at Fermilab and CERN are well-subscribed. University capability for neutral particle test beams and sources (*e.g.*, neutrons) for microphysics calibrations have been successfully used by the community at, *e.g.*, Notre Dame and TUNL. We identify a need for lower energy ($\sim$ keV) mono-energetic neutron sources to meet the PRD challenges. In particular, maintaining this capability for the community would benefit smaller experiments in early technology stages, *e.g.*, to explore low mass dark matter reach. Coordination of the community would be impactful here.

4. Access to expert engineering and cross-disciplinary expertise is important for many of the challenges of scaling up (PRD 25 and PRD 26; Section 4.8), and could help the community advance the R&D challenges identified in noble element detectors.

4.2.6 Noble Liquids and the Grand Challenges

The PRDs and research plans described in this section seek to develop noble liquid detectors with high resolution readout for improved particle identification and interaction classification, to measure increasingly rare phenomena at the low-background frontier. The PRDs aim to advance noble liquid detectors to new regimes of sensitivity, corresponding to Grand Challenge 1, exploit integration to enable scalability of detectors and readout systems, corresponding to Grand Challenge 2, and build next-generation HEP detectors with novel materials and advanced techniques, corresponding to Grand Challenge 3. The PRDs and research plans achieve this by advancing our understanding of noble liquid response, opening up the path to higher resolution readout and particle identification at lower energy thresholds, and by developing new readout strategies at new detector scales.

4.3 Photodetectors

4.3.1 Introduction

Photodetectors are a foundational technology. We measure photons from the edges of the known Universe and from the interaction of particles from the highest energy collisions. They are used across high energy physics and beyond, finding application in scientific fields as distant as chemistry and biology and are ubiquitous in society in general. For most of the last century, photomultiplier tubes (PMTs) have been the workhorse of high energy physics due to their excellent noise characteristics and scalability. However, as we push the bounds of which photons we want to measure, and the environments that we need to collect them in, we require both advances in existing technology and transformative, novel ideas to meet the demanding requirements of future high energy physics experiments. Advances in photodetector technology are a must to address all of the grand challenges.

The main metrics for photodetector performance are single photon detection efficiency, noise rate, and timing performance. Different technologies have different strengths and weaknesses, which depend critically on the operating environment and the design of a particular device. Photodetector technology falls into roughly four categories: PMTs, microchannel plates (MCPs), solid state devices, and superconducting devices. Representative multi-channel devices are shown in Figure 28. Solid state devices include a wide variety of technologies, from SiPMs to CCDs. Superconducting devices are the newest technology, pushing the bounds of what it means to detect a photon (see also Section 4.4 Quantum Sensors).

PMTs use a photocathode deposited on one side of a vacuum tube to convert a photon to an electron

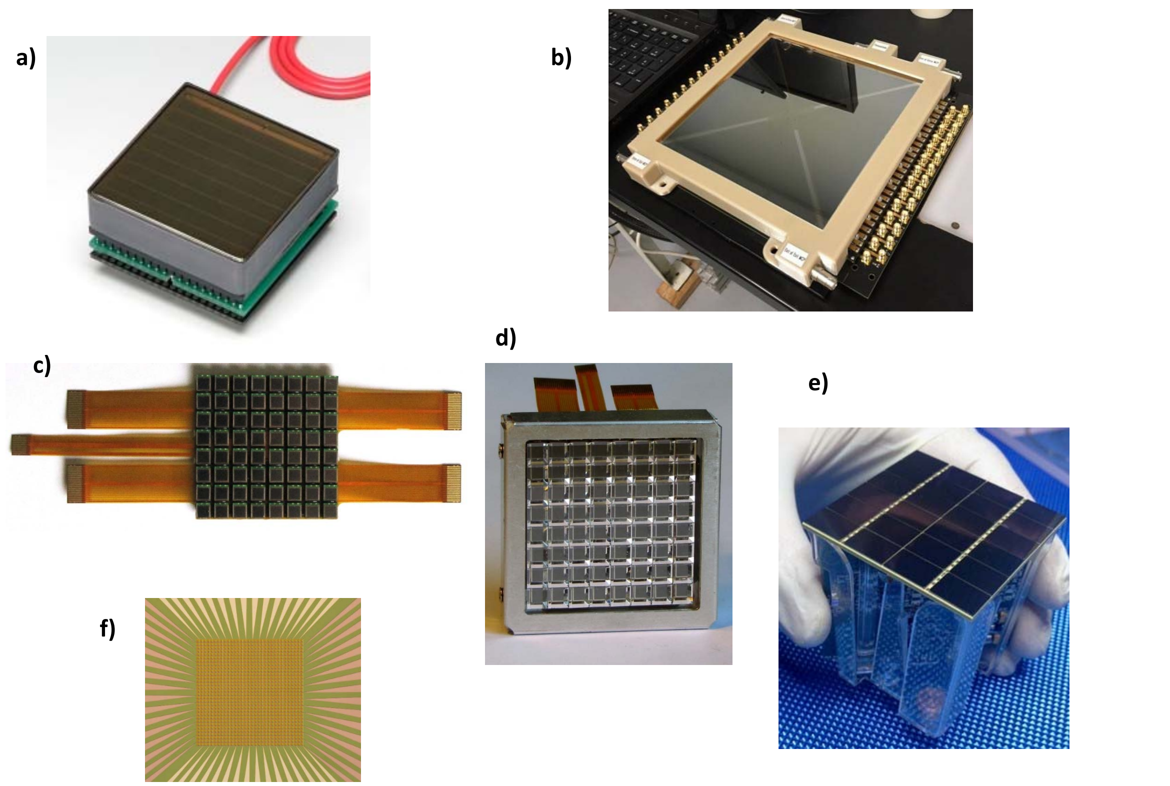


Figure 28: Photodetector Arrays: a) a modern multi-anode photomultiplier tube, b) microchannel plate PMT, c) a bare array of 64 silicon photomultiplier (SiPM) sensors, d) the array combined with quartz light collectors, e) array of SiPMs for the DarkSide experiment, f) a kilopixel array of superconducting nanowire single-photon detectors.

via the photoelectric effect. This electron is then accelerated through a series of dynodes, where the single electron is converted to multiple electrons, amplifying the signal so that it can be collected at the anode and then digitized. The quantum efficiency as a function of wavelength is determined by the properties of the photocathode, typically 20-40% in the optical range. The timing uncertainty is determined by the dynode chain and is typically >100 ps. Figure 29 (a) illustrates the operation of a PMT. They have been used in cryogenic and low background environments, but there have been performance issues and we may be hitting fundamental limits of the technology. Furthermore, the acceleration by high voltage through the dynode structure prevents PMTs from operating in high magnetic fields.

MCPs work similarly to PMTs. The amplification of a primary photo-electron occurs in many small micro-channels distributed over a plate, see Figure 29 (b). Like a PMT, the MCP is also a vacuum device, therefore the quantum efficiency is determined by the photocathode performance. The advantage of MCPs comes from the thin profile and channel structure, which results in a timing resolution much better than 100 ps and the ability to operate in high magnetic fields.

Solid state devices use biased semiconductors to convert photons to electric charge. This category encompasses a wide array of devices, from CCD and CMOS imaging detectors to direct PMT replacements, such as Silicon photomultipliers (SiPMs). The wavelength sensitivity of a solid state device is determined by the bandgap of the material and the timing characteristics are determined by the details of the device architecture. The development of these devices has many synergies with the work of PRDs 18, 19, and 20.

SiPMs are seeing wide adoption due to their excellent performance, including higher photon detection efficiency, lower levels of intrinsic radioactivity, and improved single photon resolution. In many cases there are also cost advantages over traditional PMTs. However, the small size and large capacitance of individual SiPMs introduces challenges when attempting to cover large detector surfaces, necessitating trade-

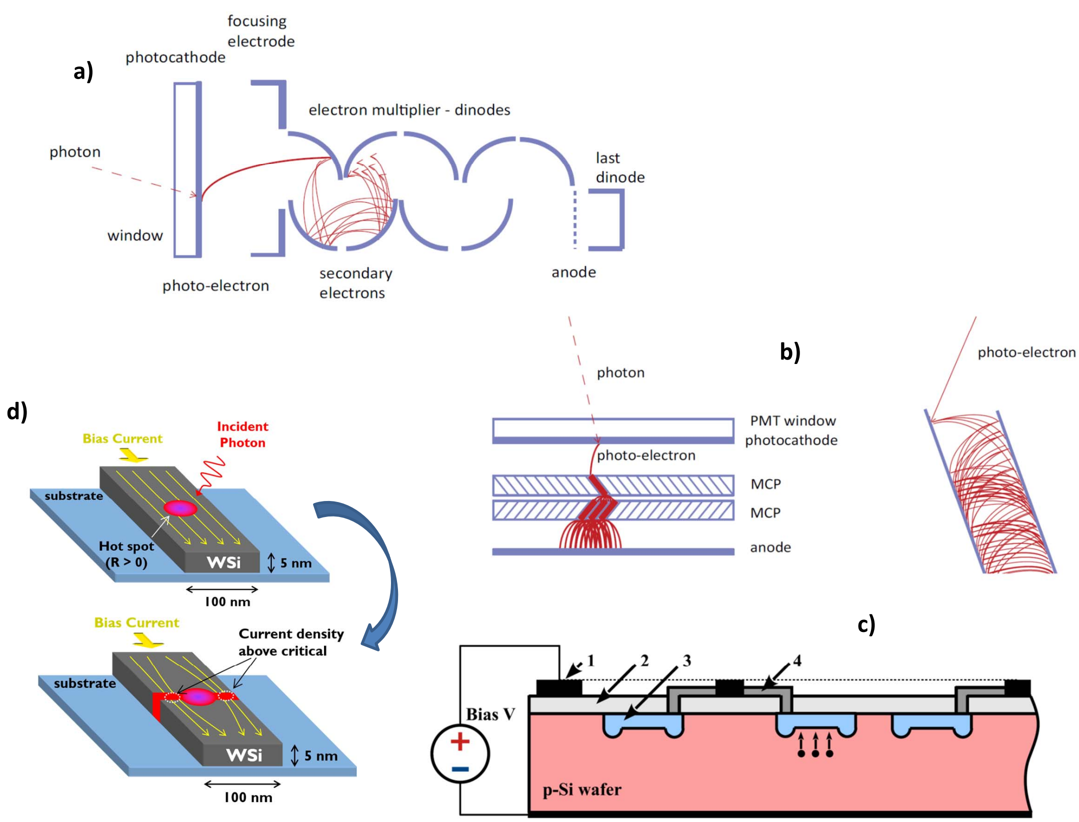


Figure 29: Principle of operation of photosensors: a) a standard single anode photomultiplier tube, b) microchannel plate PMT, c) silicon photomultiplier, d) superconducting nanowire single photon detectors.

offs between complexity, channel-count, and photo-detection performance. The operation of a SiPM is illustrated in Figure 29 (c).

The last category of photodetectors are superconducting devices. To date, they have only been deployed for astrophysics studies. This, however, is a rapidly developing technology field. The three most established technologies are the superconducting nanowire single photon detector (SNSPD), the transition edge sensor (TES), and the microwave kinetic inductance detector (MKIDs). The integration of these cryogenic sensors into accelerator-based experiments would be challenging, but the performance of these sensors is impressive.

Figure 29 (d) shows the operation of an SNSPD. It consists of a thin (4 nm) and narrow (100-250 nm) superconducting nanostrip that is current-biased just below its critical current. Absorption of a photon generates a resistive domain across the superconducting nanostrip, which leads to a transient voltage signal that can be detected. SNSPDs offer a unique combination of speed, both in terms of count rate (∼GHz) and low timing jitter (<3 ps), large range of wavelength sensitivity from VUV (120 nm) to mid-IR (10 μm), high detection efficiencies (approaching 100% for UV to near-IR), and low dark count rates (∼5-10 Hz), making them appealing for a wide variety of demanding applications. These devices have been an enabling technology for quantum information science (QIS) applications, including quantum cryptography, quantum communication, optical quantum computing, and fundamental tests of quantum mechanics. Outside of QIS, SNSPDs have been used for time-correlated single-photon counting (TCSPC), characterization of single-photon emitters, molecular spectroscopy, space-to-ground communications, integrated circuit testing, fiber temperature sensing, and light detection and ranging (LIDAR) systems.

A transition edge sensor (TES) is a calorimeter that utilizes the rapid superconducting to normal conducting transition of a superconducting film close to the critical temperature (T_C) to measure the energy of incident particles or radiation with high resolution. Depending on its design, a TES can be used to efficiently detect gamma rays, X-rays, THz waves, and cosmic microwave background or single photons from the UV to near-IR wavelengths.

The kinetic inductance detector (KID) is based on measuring the change in kinetic inductance caused by the absorption of photons in a thin strip of superconducting material. The change in inductance is typically measured as the change in the resonant frequency of a microwave resonator, and hence these detectors are also known as MKIDs. This resonator-based readout is useful for developing large-format detector arrays, as each MKID can be addressed by a single microwave tone and many detectors can be measured using a single broadband microwave channel, a technique known as frequency-division multiplexing. They are being developed for high-sensitivity astronomical detection for frequencies ranging from the far-infrared to X-rays.

The optical photon-number resolving TES, is known for its close to unity detection efficiency and has enabled novel measurements in quantum information and photonic quantum systems and has been integrated in photonic platforms. Also, because they are energy resolving, TESs, as well as MKIDs, offer the desirable prospect of non-dispersive imaging spectroscopy. A limitation of TES and MKID detectors is that they are slower (∼MHz) compared to other detector technologies.

There are five PRDs for photodetector development, listed in Table 16. The first, PRD 7, improves the sensors themselves for higher photon counting and broader wavelength sensitivity. PRD 8 integrates the sensors for spectroscopy and polarimetry applications. PRD 9 allows the sensors to operate in extreme environments, from high radiation to ultra-low background and cryogenic environments. PRD 10 focuses specifically on the developments needed for photodetectors to reach picosecond timing. Finally, any sensor, regardless of technology, will have to be coupled to a larger detector system. The efficiency of this coupling is critical for maintaining the performance of the detector. PRD 11 focuses on static and dynamic means of coupling sensors and detectors. The following sections provide more details on each of these PRDs.

4.3.2 PRD 7 - Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity

Current technology is optimized for the detection of photons in the optical wavelengths. Extending the sensitivity of photodetectors to single photons and increasing their detection efficiency at all wavelengths will directly increase the sensitivity of the detector systems they are integrated into.

Priority Research Direction (PRD)	Technical Requirements (TR)
PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity	TR 1.3, TR 1.4, TR 2.3, TR 2.4, TR 2.5, TR 2.6, TR 2.7, TR 2.8, TR 2.9, TR 2.10, TR 2.11, TR 3.3, TR 3.4, TR 3.5, TR 3.6, TR 3.48, TR 3.49, TR 3.50, TR 3.51, TR 4.1, TR 4.2, TR 4.5, TR 4.6, TR 5.10, TR 5.19
PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties	TR 4.1, TR 4.2
PRD 9: Adapt photodetectors for extreme environments	TR 1.4, TR 2.3, TR 2.4, TR 2.5, TR 2.6, TR 2.7, TR 2.8, TR 2.9, TR 2.10, TR 2.11, TR 3.1, TR 3.4, TR 5.2, TR 5.10, TR 5.15
PRD 10: Design new devices and architectures to enable picosecond timing and event separation	TR 1.3, TR 1.4, TR 2.1, TR 2.3, TR 2.4, TR 2.5, TR 2.6, TR 2.7, TR 4.3, TR 4.4, TR 5.1, TR 5.2, TR 5.7, TR 5.10
PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection	TR 1.3, TR 1.4, TR 2.1, TR 2.3, TR 2.4, TR 2.5, TR 2.6, TR 2.7, TR 2.8, TR 2.9, TR 2.10, TR 2.11, TR 3.3, TR 3.4, TR 3.5, TR 3.6, TR 3.47, TR 3.52, TR 5.2, TR 5.15

Table 16: The mapping of photodetector PRDs to physics TRs. Photodetectors are critical to advances across high energy physics and beyond.

Thrust 1: Increased IR sensitivity

The sensitivity of current photodetectors with a reasonable active area drops precipitously in the IR. There are many applications for detectors with increased IR sensitivity, from recovering light from aging scintillators to separating Cherenkov and scintillation light in scintillator detectors (see TR 4.1, TR 4.2, TR 4.5 and TR 4.6). However, the most significant and urgent need comes from cosmological measurements with galaxy surveys.

The effective band-gap of 1.1 eV limits silicon CCDs to galaxy redshifts of $z < 1.6$. At higher redshifts, singly-ionized oxygen ([OII]), the primary spectroscopic feature used to determine redshift, is moved out of the bandpass accessible by silicon and into the IR. Detectors with sensitivity at wavelengths longer than 1 μm will allow us to extend galaxy surveys to higher redshifts where enormous, relatively unexplored volumes of space remain.

While infrared InGaAs and HgCdTe CMOS detectors have been used in ground- and space-based observatories, these detectors are expensive, require substantial cooling, and suffer from low yield in the fabrication process. Calibration of the pixelated amplifiers is a considerable challenge and an impediment to data quality for long-term surveys. Germanium (bandgap 0.7 eV) CCDs offer a potentially attractive alternative to access longer wavelengths. Germanium CCDs, processed with the same tools used to build silicon imaging devices, show promise for read noise and sensitivity comparable to that of silicon detectors and offer a high quantum efficiency to wavelengths as high as 1.4 μm when cooled to 77 K. This increase in wavelength coverage will allow a spectroscopic identification of [OII] emission lines to $z = 2.6$, a factor of two increase in the observable volume of the Universe over what is accessible in the DESI galaxy set obtained with silicon CCDs. The development of germanium CCDs overlaps with the work of PRDs 18, 19, and 20.

A more general program of R&D into other infrared technologies, including the study of new materials with larger bandgaps, addressed below in Thrust 4, could also allow for extended surveys. Superconducting devices, such as TESs, MKIDs, and SNSPDs, have demonstrated high-sensitivity detection, spanning X-ray to infrared wavelength range. Both TESs and MKIDs have already been used in space-based and ground- and atmosphere-based instruments, respectively [217].

Thrust 2: UV and VUV scintillation and Cherenkov photon detection

The detection of UV and VUV photons is critical for a number of applications within high energy physics. Liquid noble elements, which will be used in future short- and long-baseline neutrino oscillation detectors, dark matter experiments, calorimeters, and in searches for neutrinoless double-beta decay, scintillate in the VUV, at the edge of current photosensor capabilities. Current-generation experiments rely on chemical wavelength-shifters to increase their photon detection efficiency, which are difficult to apply and have questionable long-term stability. Photodetectors directly sensitive to VUV light with quantum efficiencies comparable to those achieved for optical photons would see wide-spread adoption in noble liquid detectors (see TR 4.1). UV-sensitive, solar blind photodetectors also have applications in experiments detecting Cherenkov light, including future gamma ray telescopes (see TR 3.48) and neutrino detectors, and crystal calorimeters for high-rate experiments at the Intensity Frontier, where detection of the prompt-UV emission would allow for fast timing and particle identification.

Thrust 3: Single photon detection

The efficient detection of single photons is the basic feature from which all photodetector advancements proceed. Recent advances in PMTs are mainly related to photocathodes for cryogenic operation, materials selection for low background experiments, and hybrid devices that combine PMTs with solid state devices. The most widely adopted alternative to PMTs is the SiPM therefore the reduction of its dark rate, increased dynamic range and advances in timing would be interesting in themselves in addition to the goals listed in other PRDs (see example application in TR 3.48, TR 3.49, TR 3.50, TR 3.51).

Like PMTs, MCPs are room temperature devices. The Large-Area Picosecond Photodetector (LAPPD) is a promising MCP-based photodetector capable of achieving timing resolution on the order of ten picoseconds, while covering large areas, 8 inch by 8 inch tiles, with sub-millimeter spatial resolution (see TR 2.1, TR 2.4, TR 2.6, TR 2.7, TR 4.1, TR 4.3, TR 4.4, TR 5.1, TR 5.6, TR 5.7 and TR 5.11). The technology is particularly interesting for neutrino detectors based on liquid scintillators or water, but could also be deployed in ring imaging Cherenkov (RICH) detectors for studies of flavour physics, where large areas and operation in magnetic fields are required. This technology is being commercialized by industry.

The ability to count single photons offers the ultimate sensitivity for imaging and spectroscopic astronomical instruments. This is required to achieve astronomical background limited sensitivity, including in the sub-millimeter far-infrared wavelength range and at ultraviolet wavelengths. Skipper CCDs are Si-based charge coupled devices with low readout noise and a stable linear gain that allows simultaneous charge measurement at the single electron level in pixels with occupancy ranging from a single electron to thousands of electrons[218]. Skipper CCDs can also achieve high quantum efficiency between 0.87 and 1 μm, allowing them to measure fainter galaxies at the same redshifts as current surveys. Advances in Skipper CCD development offer synergies with dark matter searches, such as the SENSEI experiment[219, 220], and other similar searches. Potential partnerships with NASA are also possible because low-noise, optical photo-detectors can satisfy the need for faint exoplanet characterization with a space-based instrument.

Superconducting detectors are a relatively new technology that in specialized deployments can outperform other photon-counting technologies in a variety of performance metrics, such as detection efficiency, dark count rate, timing jitter, recovery time, and energy resolution. Semiconductor-based detectors are fundamentally limited by the band gap of the semiconductor (1.1 eV for silicon) and thermal noise sources from their relatively high ($\approx$ 100 K) operating temperatures. Superconducting detectors allow the use of superconductors with gap parameters roughly 10,000 times lower than semiconductors. This difference allows a leap in broadband response capabilities. If the cryogenic requirements of superconducting detectors could be relaxed, or if these requirements could be accommodated within a detector design, the resulting device could be transformative (see TR 2.5, TR 2.7, TR 2.8, TR 2.10, TR 2.11, TR 3.3, TR 3.6, TR 4.1, TR 4.2, TR 4.5 and TR 4.6).

Superconducting detectors include TESs [221], MKIDs [222], and SNSPDs [223]. Over the last decade, both TES and MKID arrays have been developed for high-sensitivity detection of frequencies ranging from the far-infrared to X-rays for a range of astronomical applications, especially the study of the CMB. SNSPD devices have demonstrated single photon sensitivity from X-ray to mid-infrared[224]. A kilopixel array of SNSPDs has recently been demonstrated with a mm^2 active area at 1.5 μm [225] and with a clear path identified for scaling to 100 cm^2 area. By tuning the material and device parameters, the realization of the long-term goal of SNSPDs, namely sensitivity to single photons at 100 μm, can be achieved. This achievement will impact axion searches using a quantum haloscope and low-threshold direct dark matter detection experiments. In terms of quantum efficiency, both TES and SNSPD devices have demonstrated quantum efficiencies approaching 100% at 1.5 μm wavelengths with a clear path towards optimizing efficiencies from UV to mid-IR. SNSPDs also have excellent timing resolution and very low,$\sim 10^{-4}$ Hz/mm^2, dark count rates [226].

Thrust 4: Advanced materials for photodetectors

The development of new materials for photodetectors is critical for enabling advances in their performance. This work includes the development of new photocathode materials, high temperature superconductors, and large band-gap materials. The design of solid state devices that build on the success of SiPMs, but allow for increased wavelength sensitivity by utilizing new materials, is an active area of research. These materials include but are not limited to Silicon Carbide (SiC) and variations of Gallium Nitride (GaN, InGaN, and AlGaN). Such devices have lower thermally excited dark count rates and are more tolerant to radiation damage. Similar improvements in wavelength sensitivity can be achieved by pursuing novel photocathode materials such as GaAs at longer wavelengths and CsTe at shorter wavelengths.

Moving to more novel approaches, Dirac materials and nanocrystals offer a fine tuning of the bandgap that could revolutionize the design of photodetectors. Similar to CCDs, Dirac materials are also interesting to dark matter direct detection experiments[227]. For superconductiong devices, the recent discovery that bilayer graphene is a superconductor could produce new and interesting devices for the field.

Research Plan

To address Thrust 1, an investment in germanium CCDs is logical and offers synergies with Light Source Applications and NASA X-ray observatories due to the sensitivity at X-ray energies as high as 100 keV. The requirement for ultrapure germanium wafers offers a synergy with nuclear physics, where germanium is used in neutrinoless double-beta decay experiments based on scintillating bolometers as secondary light collecting bolometers[228].

Fabrication of germanium CCDs faces several challenges that need to be addressed before these devices can be integrated onto large focal planes. Several processes in doping, etching, and film deposition are similar to those in silicon CCD fabrication but need to be tested with the new vendor's capabilities. However, GeO_2 water solubility and low-temperature limitations result in the need for changes in gate insulator and electrode technologies. In addition, there is only one wafer vendor for germanium and further investigation is required to ensure that purity requirements can be met for production at scale on large wafers. Finally, germanium has higher density than silicon and requires a full assessment of handling and packaging techniques. At present there are no foundries specializing in germanium devices. Based on these challenges, a program exploring alternative technologies is warranted.

To address Thrust 2, there are a number of promising avenues to extend photosensor sensitivity to shorter wavelengths and increase their detection efficiency, including novel device architectures, sensor coatings, UV-sensitive photocathodes, such as CsI or CsTe, and doping configurations. Alternative wavelength shifting materials and methods for deploying them in large detectors should also be explored.

Superconducting devices can also be optimized to operate with high-sensitivity, fast timing and high detection efficiency at shorter wavelengths. In a recent experiment, SNSPDs have been integrated with a $^9Be^+$ ion trap demonstrating high efficiency and low background noise at 315 nm wavelength [229].

Beyond these specific goals of increased wavelength sensitivity encapsulated in Thrust 1 and 2, new technologies and new materials for existing technologies will lead to breakthroughs in the performance of photodetectors. Therefore, investment in new and possibly more speculative technologies and materials of Thrust 3 and 4 is needed for the future of high energy physics and more generally any imaging application.

4.3.3 PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties

Extracting the full information content of a measured photon requires simultaneously measuring the signal's spatial distribution, spectral distribution, and polarization. Direct illumination of large photodetector arrays provides high throughput optical imaging. However, measuring polarization and spectral information, especially with high resolution, typically requires complex fore-optics (such as dispersive optics for spectroscopy), which are not readily scaled to large throughput applications. Realizing new photodetectors across the electromagnetic spectrum that simultaneously measure both a photon's position and energy would transform optical measurements, eliminating the common trade-off between imaging and spectroscopy/polarimetry (see [230] for a review).

The two Thrusts of this PRD reflect two approaches to achieving this capability. The first approach is sensor-integrated spectroscopy and corresponds to developing compact coupling optics that can be directly integrated into individual photodetector pixels. The second approach is energy-resolving single-photon detection using detectors that measure, with high resolution, the energy of individual photons. The priority is the realization of high-density spectroscopy, but polarization may have unlocked potential in these studies.

Currently implemented technologies include superconducting photodetectors, such as TES and MKIDs, that are intrinsically energy-resolving or photon-number-resolving. More recent technologies like SNSPDs, though not currently used as energy-resolving detectors, may provide new approaches to integrated functionality. For example, multi-pixel device designs [231] and novel device architectures [232] have been explored to achieve photon number resolution, as well as spatial and temporal information of individual photons through a nanowire imager [233] and arrays of SNSPDs [225].

Thrust 1 - Sensor-integrated spectroscopy

Sensor-integrated spectroscopy aims to develop compact pixel-scale dispersive optics and integrate these structures with high-sensitivity detectors (see TR 4.1 and TR 4.5). At mm and sub-mm wavelengths, compact dispersion structures can be fabricated using superconducting transmission lines, which can then be incorporated into the design and fabrication of superconducting detectors such as MKIDs and TESs [234]. These on-chip spectrographs have been demonstrated in the lab and are being deployed in experiments [234–236]. On-chip spectroscopy at shorter wavelengths (optical/IR wavelengths) may also be possible by integrating appropriate detectors with photonic dispersion structures.

Thrust 2: Energy-resolving single-photon detection

Energy-resolving single-photon detection provides an alternative approach to the sensor-integrated dispersive approach of Thurst 1. For high energy photons (X-rays, γ rays), excellent energy resolution single-photon detection has been demonstrated using TES microcalorimeters [237]. For photons in the optical/IR, lower-resolution energy detection of single photons has been demonstrated using both TES [221, 238] and MKIDs [222]. Improving the resolving power of these devices at optical and longer wavelengths by developing new detector designs and utilizing novel materials would provide a transformative photodetector at these longer wavelengths (see TR 4.5).

Research Plan

Potential high-priority research activities to address this PRD are the continued development of fabrication techniques and designs for dispersion structures to realize on chip spectroscopy for Thrust 1. Addressing Thrust 2 requires a program to improve the single photon resolving power of devices such as TESs, MKIDs, and SNSPDs.

4.3.4 PRD 9: Adapt photosensors for extreme environments

In many applications, photosensors have to be operated in extreme conditions, including cryogenic operation at noble liquid temperatures and operation in environments with a high radiation load (as also discussed in PRD 26); in some applications they are inaccessible for a very long time or need to have low intrinsic radiological background.

Thrust 1: Cryogenic operation at noble liquid temperatures

Large noble liquid detectors planned for future neutrino and dark matter experiments will use photodetectors directly immersed in cryogenic liquids, such as xenon, argon, and neon, that must be robust to multi-year operation at cryogenic temperatures. Additionally, the large instrumented surface of these detectors and the need to detect single photons necessitates the use of co-located, low-power, cold electronics to minimize the number of cryostat penetrations and improve the signal to noise ratio of the sensors. Addressing this challenge will require the development of novel sensor materials, including low-temperature photocathodes, new sensor architectures, integrated electronics capable of cryogenic operation, and fabrication processes and detector packaging techniques robust to the mechanical stress induced when cooling to cryogenic temperatures (see TR 2.1, TR 3.1, TR 3.3, TR 3.4, TR 3.5 and TR 3.6). These innovations will require cryogenic test facilities where the long-term performance of these materials, devices and electronics can be characterized.

Thrust 2: Low-radiological-background sensors and detector packages

Photodetectors, photosensor front-end electronics, and sensor packaging are integral components of many low-background experiments for studying neutrinos and dark matter. This Thrust is highly related to PRD 25 and all advancements made in that program will help this effort (see TR 2.3).

Thrust 3: High-durability and radiation hard sensors

The application of SiPMs in harsh radiation environments is currently being pioneered by upgrades of the CMS detector for the high-luminosity phase of the LHC. Two projects, the barrel timing layer [239] based on LYSO crystals and the scintillator tile-based hadronic section of the endcap calorimeter [240], will use several hundred thousand SiPMs and expose them to neutron fluences up to 10^{14} n_{eq}/cm^2. Radiation-induced noise hampers signal discrimination and ultimately also degrades the photon detection efficiency (see TR 1.3, TR 1.4, TR 4.6, TR 5.2 and TR 5.10).

To meet the challenges of future hadron colliders, like the FCC-hh (see Section 3.1), with one to two orders of magnitude higher neutron exposure, significant advances in the radiation tolerance of SiPMs [241] are needed, a requirement that is driven exclusively by particle physics. The internal structure of the semiconductor sensor could be optimised to achieve smoothly varying electrical fields that minimize trap-assisted tunneling effects. Additional improvements could be made by developing low-power devices (low bias and gain), which reduces self-heating effects, with fast recovery times, which keeps the occupancy small, and are therefore more resistant to radiation damage. Advances will become possible through the ever-increasing precision in semiconductor manufacturing, but dedicated co-developments by academic and industrial partners are required, including the development of robust packaging techniques, such as radiation-hard optical coatings and efficient means of detector cooling.

Hybrid or monolithic integration of the sensor with a read-out ASIC coupled to each individual pixel opens additional capabilities. Damaged pixels with elevated dark rate can be disabled and fast transistor switches, replacing the quenching resistor, allow for active gating of the sensor with the collider time structure reducing noise pile-up.

A particularly difficult challenge is the detection of single photons with radiation damaged sensors, since the increased dark rate counts cannot be separated from single-photon signals by applying a discriminating threshold. Mitigating technologies should be explored, including on-device cooling, annealing at elevated temperatures, Si-structure optimization, and exploration of alternative materials with a higher band-gap (e.g., GaInP).

Degradation effects are also observed in MCP PMTs, including LAPPDs. Following illumination over extended periods of time, the photocathode degrades due to bombardment by ionized rest-gas ions. Coating the microchannel plates with a secondary emission material by atomic layer deposition (ALD) prolongs the lifetime of the tube, typically to about 10 C/cm^2 accumulated charge on the anode. Further research is needed to go considerably beyond this limit in high rate experiments like Mu2e and Belle II.

4.3.5 Research Plan

To address the challenges in Thrust 1 and 2, novel sensor materials with integrated electronics will be developed, capable of cryogenic operation and operation with low radiological backgrounds.

Thrust 3 will require further development of SiPMs that would be radiation-hard by optimizing their inner structure, further development of precision manufacturing, on-device cooling and annealing, as well as further development of digital SiPMs and investigation of materials with a wider band-gap. Mitigation of degradation effects in MCP PMTs requires further development of ultra-clean microchannel plate production and elimination of other sources of ions.

4.3.6 PRD 10: Design new devices and architectures to enable picosecond timing and event separation

A timing resolution from a few to tens of picoseconds in photon detection is an important requirement for future experiments. The required R&D includes optimization of the SiPM structure, large scale production of MCP-PMTs, integration of very fast read-out electronics, and larger area SNSPD detector arrays.

Thrust 1: Sensor structure optimization

Reducing the optical cross talk in SiPMs would remove one of the main obstacles in the use of SiPMs for picosecond timing of single photons. While considerable progress has been made, further sensor structure optimization is essential to accomplish this goal (see TR 2.4, TR 2.6, TR 2.7, TR 2.9, TR 4.5 and TR 5.10).

MCP PMTs have excellent timing resolution for single photons. The main obstacle for using them to cover large surfaces is their cost. Further research on LAPPDs, a potentially considerably less expensive version of MCP PMTs, could open a up a host of new applications. For these large-area devices, R&D should be pursued towards improvements in timing resolution, magnetic field tolerance, and UV light detection, as well as in new production methods (like 3D printing of capillary arrays and new approaches to produce photocathodes), which have the potential to reduce the cost of the LAPPD by an order of magnitude.

SNSPD devices have excellent timing resolution and can in principle outperform any other free-running single-photon detection technology. Recently, SNSPDs have demonstrated timing jitter down to 2.6 ps in the optical and 4.3 ps in the near-infrared [242]. A kilopixel array with GHz counting rates has recently been fabricated [225], demonstrating the potential to get to larger area detector arrays that can eventually achieve 100 GHz rates with optimized sensor and readout design.

Thrust 2: Sensor and electronics integration

For a further breakthrough in sensor timing, optimized read-out electronics and signal routing will be needed. To reach the ultimate resolution possible, it is of great advantage if both the sensor and the readout electronics are on the same substrate. This will be highly correlated with work to design the readout including custom ASICs, as described in PRDs 16 and 17 (see TR 4.2, TR 4.3, TR 4.4, TR 4.5, TR 4.6, TR 5.1, TR 5.6, TR 5.7 and TR 5.11).

Research Plan

A further optimisation of both the internal structure of SiPMs (to reduce the optical cross-talk) and of the signal routing which address the challenges in Thrusts 1 and 2 is needed. To address the reduction of the production cost of MCP PMTs, a further development of production methods of LAPPDs is needed in a collaboration of academia with industry. To pave the way towards a wider use of the SNSPD devices, development of sensors with a large active area fraction is needed. Another challenge to be addressed is the integration of the cooling of these superconducting sensors in large detector systems.

4.3.7 PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection

Enhanced and dynamic light collection of multi-channel devices is essential for an improved signal-to-noise operation in low-light-level detection with SiPMs and for a fast reconfiguration in the telescope focal plane. For the High-Luminosity LHC, R&D of optical fibers for scintillation-fibre based tracking systems is needed to achieve a higher light yield.

Thrust 1: Novel light propagation and collection systems

Often a photodetector must be coupled to the detecting medium. Light guides and optical fibers are mature technologies, however there is the possibility to make interesting new systems by making use of anti-reflective films or moving from non-imaging to imaging collection schemes. For instance, SiPMs are an attractive choice for RICH detectors with one exception, dark counts (see TR 5.2). With a dark count rate of a few 100 kHz/mm^2, spurious signals cannot be distinguished from single photon pulses. One way to improve the signal-to-noise ratio is to develop dedicated light collectors, either as quartz Winston cone like arrays [243, 244], or by developing suitably designed meta-materials [245]. In this way, photons would propagate from a larger entry window to a considerably smaller sensor, resulting in an improved signal photon to dark count ratio. Another interesting idea uses light concentrators constructed from di-chroic reflectors to sort photons by wavelength to aid Cherenkov-scintillation separation and ultimately direction reconstruction in kiloton-scale neutrino detectors [246]. Increasing the scale of the system substantially, ground based searches for dark matter annihilation, require large fields of view with high light collection efficiency (see TR 3.47 and TR 3.52), which could lead to novel systems of light collection.

Thrust 2: Dynamic physical reconfiguration of multi-channel devices

Novel collection systems may not be stationary. In order to achieve multiplexing factors of 20,000 to 50,000 in future galaxy surveys for dark energy studies, new technologies are required to reconfigure the telescope focal plane in real time to collect spectra from targeted galaxies at a very high density. Positioners at a pitch (packing) of 5-6 mm provide the observational path to probe the high-redshift volumes for Dark Energy and Inflation (see TR 4.1, TR 4.2, TR 4.5 and TR 4.6).

The fiber positioners for the Stage-IV DESI galaxy survey consist of 5000 individual robots supported by a 812 mm diameter aspheric focal plane at a 10.4 mm pitch between neighboring units. Assembly of these fiber positioners was complicated by the tight spacing between positioners, need for manually applied glue joints, splicing of fibers, and large numbers of individual parts (675,194 in total). It may be possible to improve the two-axis DESI positioners by using smaller motors, press-fit instead of glue joints, alternatives to splicing, and new approaches to handling a one-ton focal plane assembly.

The current state-of-the art fiber positioner designs also include the "Cobra" Twirling Post design being constructed for the Prime Focus Spectrograph (PFS) and the "Tilting Spine" developed by the Australian Astronomical Observatory (AAO) for 4MOST and the proposed Mauna Kea Spectroscopic Explorer. The Tilting Spines position the end of the fiber by tilting about a long axis rather than positioning in a plane about a central coordinate. This technique allows for more close packing capability, but because the end of the fiber moves on an arc, excessively large tilt angles can lead to light loss and PSF calibration errors. The 4MOST instrument will have 2436 such fiber positioners with a 9.5 mm pitch.

Piezoelectric designs offer the potential for smaller, simpler positioners, but no significant study has yet been carried out. In addition, there is potential for micro-shutters or micro-mirrors to redirect the light in real time for single object spectroscopy. Given the lack of large moving parts, it may be possible to obtain even larger multiplexing power with advanced microelectronics.

Thrust 3: Tracking systems with optical readout

Scintillating fibres offer a cost-effective way of instrumenting large areas for charged particle tracking at relatively low material budget. With the availability of small-pitch SiPM arrays, high resolutions are possible, as shown with the LHCb SciFi tracker upgrade [247] just being completed. To further advance the technology, e.g. for a second upgrade of the tracker envisaged for the High-Luminosity LHC (see section 3.1), not only the photo-sensor but also the optical fibers need to be optimised to obtain higher light yield, allowing for smaller diameters and thus higher precision and improved radiation tolerance. Innovative materials [248], such as Nanostructured-Organo-silicon-Luminophores (NOL) scintillators, exhibit stronger and faster light output than presently achieved. Here the energy transfer from the primary excitation to the wavelength shifter is enhanced by silicon links with respect to the radiative processes in standard materials (see TR 1.4, TR 2.3, TR 2.4, TR 4.4, TR 5.1, TR 5.2, TR 5.6, TR 5.7, TR 5.10 and TR 5.11).

Research Plan

High-priority research activities to address this PRD include, for Thrust 1, further development of light collection schemes, preferably integrated with sensor arrays, as well as a development of meta-materials and di-chroic reflectors. Thrust 2 requires development of promising piezo-electric fiber positioners. To address research needed in Thrust 3, development of innovative scintillating fiber materials with higher light yield and improved radiation tolerance such as NOL scintillators, should be pursued.

4.3.8 Connections Outside HEP

The detection of photons is foundational to science as a whole and therefore the advancements enabled by the above PRDs would immediately find application outside of HEP. Obvious beneficiaries would be nuclear physics experiments and detectors at the light sources. Astronomy would also benefit from, for instance, the increased IR wavelength response, which would allow infrared astronomy to study fainter objects.

Fast and compact photosensors would pave the way towards the ultimate goal, 10 ps time resolution in Time-Of-Flight (TOF) PET medical imaging, opening new treatment opportunities in the context of personalized (precision) medicine, detection of smaller size tumors, development of full-body scanners and reduction of the radioactive doses injected into the patients without compromising the image quality.

Fast light sensors will also find use in a wide variety of fields, from biology to LIDAR-based 3D environment perception systems. Very fast light sensors will also be an essential component of photon based quantum computers.

Finally, the improvement in particle detection enabled by the above PRDs would directly impact particle detection for national security applications whether it is studies in high radiation environments, like those found in high energy density experiments, or to improving the resolution of scanners for radioactive materials.

4.3.9 Facilities, partnerships, and resources

The development of new photodetector technology requires close connections to industry both for the fabrication of devices and the procurement of materials. The above PRDs will require new infrastructure that would necessitate upgrades at existing DOE facilities or partnerships with other federal facilities and industry. This infrastructure ranges from new equipment for GE CCD R&D to the infrastructure needed for the development of readout and ASICs (see also Section 4.5). An overview of the required facilities is given in Section 5.2.

4.3.10 Photodetectors and the Grand Challenges

As has been described in this section, photodetectors are a key element of almost all HEP experiments and advancements in photodetectors are needed to address all four Grand Challenges. PRD 9, the adaptation of photodetectors for extreme environments directly addresses the mastering of extreme environments in Grand Challenge 4. Photodetectors made of or coupled to novel materials are needed to address PRD 7-11 and are specifically highlighted in PRD 7 Thrust 4 and therefore directly achieve the goals of Grand Challenge 3 to build detectors with novel materials. Grand Challenge 2 has the goal of integrating readout and sensor to enable scalability and this is also the goal of PRD 8, to enable high density spectroscopy, although this integration would also enable improved performance such as the picosecond timing highlighted in PRD 10. Finally, PRD 7-11 are all directly needed to push HEP detectors into new regimes of sensitivity as outlined in Grand Challenge 1.

4.4 Quantum Sensors

4.4.1 Introduction

A revolution in the tools and techniques making use of quantum mechanics has produced new sensitive measurement techniques that can help the High-Energy Physics (HEP) community to achieve its science objectives. New quantum sensors, for the first time, allow measurements to be made near the intrinsic noise limits imposed by the Heisenberg uncertainty principle, as well as enabling enhancements in sensitivity, resolution, and robustness, thereby accelerating searches for new physics. The connections to the P5 Science Drivers include dark matter and dark sectors, inflation, and exploring the unknown. Related fields that will also be impacted are gravitational wave cosmology, astrophysics, and fundamental tests of quantum mechanics. This leverage works in the other direction also: bringing the unique resources and expertise of the HEP community to bear on the development of quantum sensors will lead to rapid technology advances that will benefit the quantum information science community as well as other research programs within the DOE Office of Science.

Of great relevance to all measurements using Quantum Sensors is the Standard Quantum Limit (SQL). Heisenberg's uncertainty principle tells us that when both the phase and amplitude of an electromagnetic signal are measured, the precision of the measurement can be no better than the SQL, equivalent to one photon of noise per second per unit of bandwidth. Similar limits apply to other quanta measured with quantum sensors, such as spin. As noted above, Quantum Sensors provide gains in sensitivity by approaching and in some cases evading the SQL.

Here we present a natural organization of quantum-sensor technologies for HEP quantum sensor research into four approximate quantum sensor energy ranges (Figure 30). These four energy ranges represent either the quantum energy associated with the target signal frequency, or is typical for the absorbed or transferred energy. These four energy ranges form natural breakpoints in HEP science, quantum sensor technology, and useful quantum protocols. More specifics of each energy range, including HEP science and sensor technology, are shown in Table 17.

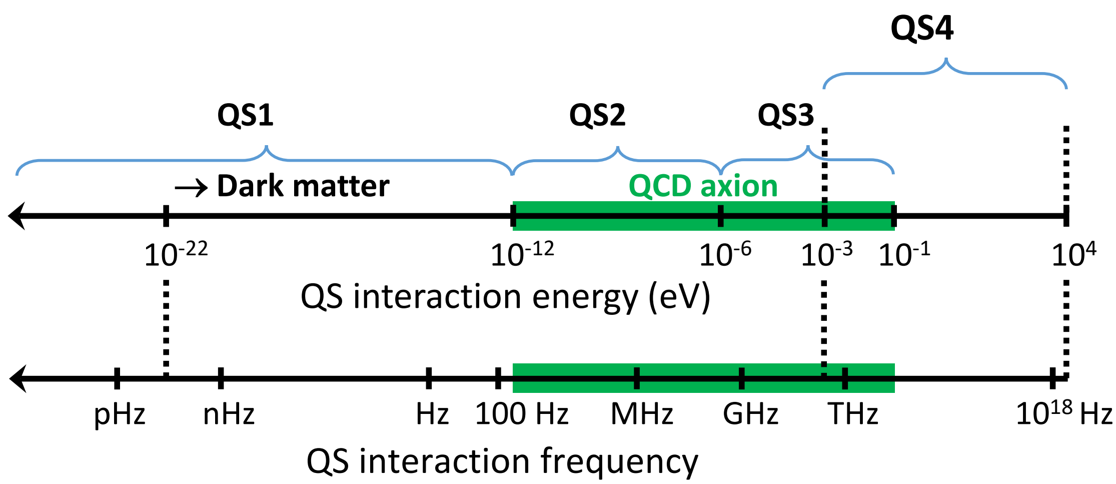


Figure 30: Organization of quantum-sensor research for HEP into four approximate quantum-sensor energy ranges (QS1–4). Energies E (units of electron volt) are shown on the top axis, while associated frequencies $f = E/h$, where h is Planck's constant, are shown on the bottom axis. The energies are either the quantum energy associated with a frequency, or typical absorbed or scattered energy. QS3 and QS4 use different techniques, but partially overlap in energy coverage.

Some of the distinction in quantum sensor energy ranges are determined by scale: for instance, in QS2, the wavelength of photons is larger than the typical experimental apparatus (larger than $\sim$ 1m), whereas in QS3, the wavelength of photons is smaller than $\sim$ 1m. The wavelength of the signal relative to the experiment has a significant impact on the measurement techniques used. Some of the distinctions in quantum sensor energy ranges are determined by how important thermal fluctuations are. For instance, in QS2, the typical energy of a thermal fluctuation ($\sim k_B T$) at the 10 mK temperature of a commercially available dilution refrigerator is greater than the energy of the relevant photon (hf), so the experiment is considered to be in a "thermal state." However, in QS3, this ordering is reversed, so the experiment is sometimes considered to be in a "ground state," characterized by relatively few thermal fluctuations. The goal is always to improve HEP experiments by the use of quantum sensors. When an experiment can be made more sensitive through the use of quantum techniques, it can often be conducted more quickly than can be done with classical techniques, in which case "quantum acceleration" has been achieved.

We present a careful planning effort to address the full scope of research needed to achieve the HEP science objectives in terms of PRDs and Thrusts. A summary of the PRDs and their mapping to the Technical Requirements set out in the physics sections of this report are in Table 18.

4.4.2 PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit

Quantum devices are needed to measure electromagnetic signals for HEP science objectives across a broad frequency range (∼240 Hz (1 peV) – 24 THz (100 meV), corresponding to QS2 and QS3 in Figure 30 and Table 17). New techniques for the control and manipulation of coherent quantum states enable measurement of signals at the SQL, and operation below the SQL is possible through techniques including backaction evasion, squeezing, and photon counting. Such techniques will be required to accomplish all of the science objectives of the High Energy Physics community, with different frequency ranges requiring different SQL-evading techniques. At frequencies below 240 MHz (QS2), when experiments are cooled with commercially available dilution refrigerators to ∼10 mK, systems are in a thermal state ($k_\mathrm{B}T > hf$), containing a fluctuating population of thermally excited quanta. In this frequency range, quantum upconversion techniques incorporating backaction evasion are needed to improve integrated sensitivity to beyond the SQL (Thrust 1). Above 240 MHz (QS3), $k_\mathrm{B}T < hf$, so systems cooled in dilution refrigerators are in the ground state and vacuum squeezing can be used. At frequencies 5–30 GHz, qubit-based photon counters that use Quantum Non-Demolition (QND) techniques are needed (Thrust 2). Finally, at higher photon energy (frequency $\gtrsim$ 30 GHz), qubit-based single photon counters can be developed that absorb photons by breaking Cooper pairs (Thrust 3). Quantum devices incorporating opto-mechanical systems are also useful over a broad range of frequencies (Thrust 4).

Thrust 1: Develop backaction-evading quantum upconverters operating below the Standard Quantum Limit (SQL) from 1 peV to 1 μeV (QS2)

Superconducting devices that operate at better than the Standard Quantum Limit can increase experimental science reach, even when resonators are in the thermal state ($k_\mathrm{B}T > hf$). In this frequency range (QS2 in Figure 30 and Table 17), photon counting is not useful, since the number of photons in the resonator fluctuates in accordance with classical thermodynamics.

However, coherent measurements that measure signal phase information can provide dramatic quantum acceleration in HEP experiments. In resonator-based experiments, the noise associated with these thermal photons is suppressed at frequencies detuned from the resonance. When significantly detuned from the resonance, the added imprecision sensor noise (which is approximately flat in frequency), rather than the thermal noise, sets the ultimate sensitivity bandwidth over which useful signal-to-noise ratio is achieved. This sensitivity bandwidth can be many times larger than the resonator linewidth.

Reducing amplifier noise to the Standard Quantum Limit and below increases the useful sensitivity bandwidth even if the added sensor noise is already well below the thermal noise. Measurements better than the SQL can be made if some information about the signal—such as its amplitude or phase—is not measured. One reason that the SQL applies is that the very act of measuring a signal fundamentally perturbs it—by introducing a backaction force on the measured signal. One way to measure some aspects of a signal (such as its amplitude or phase, but not both) better than the SQL is by using techniques to design a circuit so that the backaction only affects some aspects of the signal, and then measuring other aspects. These "backaction evasion" techniques [249] can greatly improve the sensitivity of measurements of electromagnetic signals. Below 240 MHz, Josephson devices exist that upconvert (or transduce) lower-frequency RF photons to

	Quantum Sensor Energy Range	**HEP Science**	**Quantum Sensor Technology**	**Quantum Protocols**
QS1	$< 10^{-12}$ eV ($<$ 240 Hz)	Ultralight dark matter (generalized axions, hidden photons, scalars), Electric dipole moment (electron, nuclear, neutron), Gravitational waves, Dark energy, Violation of fundamental symmetries	Atomic and molecular spectroscopy, atom interferometers and mechanical sensors, clocks, atomic magnetometers, nuclear, electronic, and other spins, quantum defects in solids	Superposition, entanglement, squeezing, coherence
QS2	10^{-12} –10^{-6} eV (240 Hz – 240 MHz)	QCD axion, Ultralight dark matter (generalized axions, hidden photons) New forces & particles, Violation of fundamental symmetries	Nuclear, electronic, and other spins, electromagnetic quantum sensors, optical cavities, quantum defects in solids	Superposition, entanglement, backaction evasion, squeezing, coherence
QS3	10^{-6} –10^{-1} eV (240 MHz – 24 THz)	QCD axion, Ultralight dark matter (generalized axions, hidden photons) New forces & particles, Violation of fundamental symmetries	Superconducting and other qubits, Nuclear, electronic, and other spins, Rydberg atoms, quantum defects in solids	Parametric amplifiers, superposition, entanglement, squeezing, coherence, Quantum Non-Demolition photon counting
QS4	10^{-3} –10^{4} eV	Scattering / absorption of dark matter, New forces & particles, Violation of fundamental symmetries	Single-photon counters (superconducting, avalanche photodiode (APD)), Low-threshold phonon and charge detectors, quantum defects in solids	Non-QND photon counting, high spatial resolution measurements of particle tracks

Table 17: Quantum-sensors organized by interaction energy range and HEP science. HEP-relevant sensors naturally organize into four approximate quantum sensor energy ranges (either the energy of an absorbed quantum, or typical scattering energy). The HEP science is described for each research priority. Each energy range has its own characteristic quantum sensor technologies and quantum protocols. The listed examples of HEP science, quantum sensor technologies, and quantum protocols are meant to be illustrative and not exhaustive.

microwave frequencies above 5 GHz. These “quantum upconverters” can implement backaction evasion, accelerating HEP science experiments (See Figure 31(d)).

Priority Research Direction (PRD)	Technical Requirement (TR)
PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit	TR 3.25, TR 3.26, TR 3.27, TR 3.28, TR 3.29, TR 3.30, TR 3.31, TR 3.32, TR 3.33, TR 3.34, TR 3.35, TR 3.36, TR 3.43, TR 3.44, TR 5.20, TR 5.21
PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics	TR 3.21, TR 3.22, TR 3.23, TR 3.24, TR 3.37, TR 3.38, TR 3.39, TR 3.40, TR 3.41, TR 3.42, TR 5.16, TR 5.18, TR 5.20, TR 5.21, TR 5.22
PRD 14: Advance the state of the art in low-threshold quantum calorimeters	TR 3.13, TR 3.14, TR 3.15, TR 3.16, TR 3.17, TR 3.18, TR 3.19, TR 3.20
PRD 15: Advance enabling technologies for quantum sensing	TR 3.21, TR 3.22, TR 3.23, TR 3.24, TR 3.25, TR 3.26, TR 3.27, TR 3.28, TR 3.29, TR 3.30, TR 3.31, TR 3.32, TR 3.33, TR 3.34, TR 3.35, TR 3.36, TR 3.37, TR 3.38, TR 3.39, TR 3.40, TR 3.41, TR 3.42, TR 5.17, TR 5.18, TR 5.20, TR 5.21, TR 5.22

Table 18: The mapping of quantum sensors PRDs to physics TRs. Quantum sensors are critical to address needs across a wide range of high energy physics topic areas and beyond.

Thrust 2: Develop qubit-based quantum non-demolition (QND) photon counters from 5 to 30 GHz (20μeV to 120μeV) (QS3)

When systems are cooled to where the energy of a typical thermal fluctuation is much less than the energy of a photon of the frequency of interest ($k_B T < hf$), squeezing is already used. For example, the HAYSTAC experiment uses Josephson Parametric Amplifiers to obtain sensitivity below the Standard Quantum Limit (Figure 31(a,b)). More dramatic accelerations beyond the Standard Quantum Limit can in principle be achieved with background-free photon counting. Whereas operation at the SQL introduces one photon of noise per resonator coherence time, background-free photon counters can set a limit of one noise photon over the full integration time (which can be many coherence times), as long as there are no dark counts from thermal fluctuations or other sources. The ratio of the dark-count-free integration time to the resonator coherence time is thus a measure of how far the performance can be below the SQL using a photon counter. In this regime, photon counters thus increase the sensitivity within a given bandwidth rather than increasing the sensitivity bandwidth as was discussed in Thrust 1.

Completely background-free operation (with no dark counts) is a challenging goal in the 5-30 GHz range. The higher the frequency of an electromagnetic signal, the higher the energy $E = hf$ of its quanta, the photon. When a photon has very low energy it is very difficult to detect, and it may need to be measured many times to acquire sufficient sensitivity. Quantum Non-Demolition (QND) techniques make it possible to measure a photon without perturbing it, so that it can be measured multiple times. Repeated non-demolition measurements of the signal photon can in principle improve the measurement fidelity to the point where the dark count rate vanishes. Such systems have been demonstrated in laboratory settings, and work is ongoing to implement them in physics experiments.

A difficult challenge in implementing background-free photon counting in an HEP context is to efficiently couple the signal to the photon counter. Efficient coupling is more straightforward to accomplish if the photon counter is coupled directly to the resonator mode. Photon counters strongly coupled to the resonator mode are a near-term target. However, some larger scale sensor implementations will need to count itinerant photons that have been transmitted out of the resonator into a transmission line. There is thus a longer term need to develop efficient photon counters for such architectures.

Thrust 3: Develop qubit-based pair-breaking photon counters above 30 GHz (120μeV) (QS3)

Above 30 GHz, it becomes more straightforward to achieve completely background-free operation (with no dark counts) using photon-counting techniques involving Josephson circuits (similar to qubits) that measure pair-breaking and quasiparticle generation. Such measurements absorb the energy of the photon, and thus can be done only once.

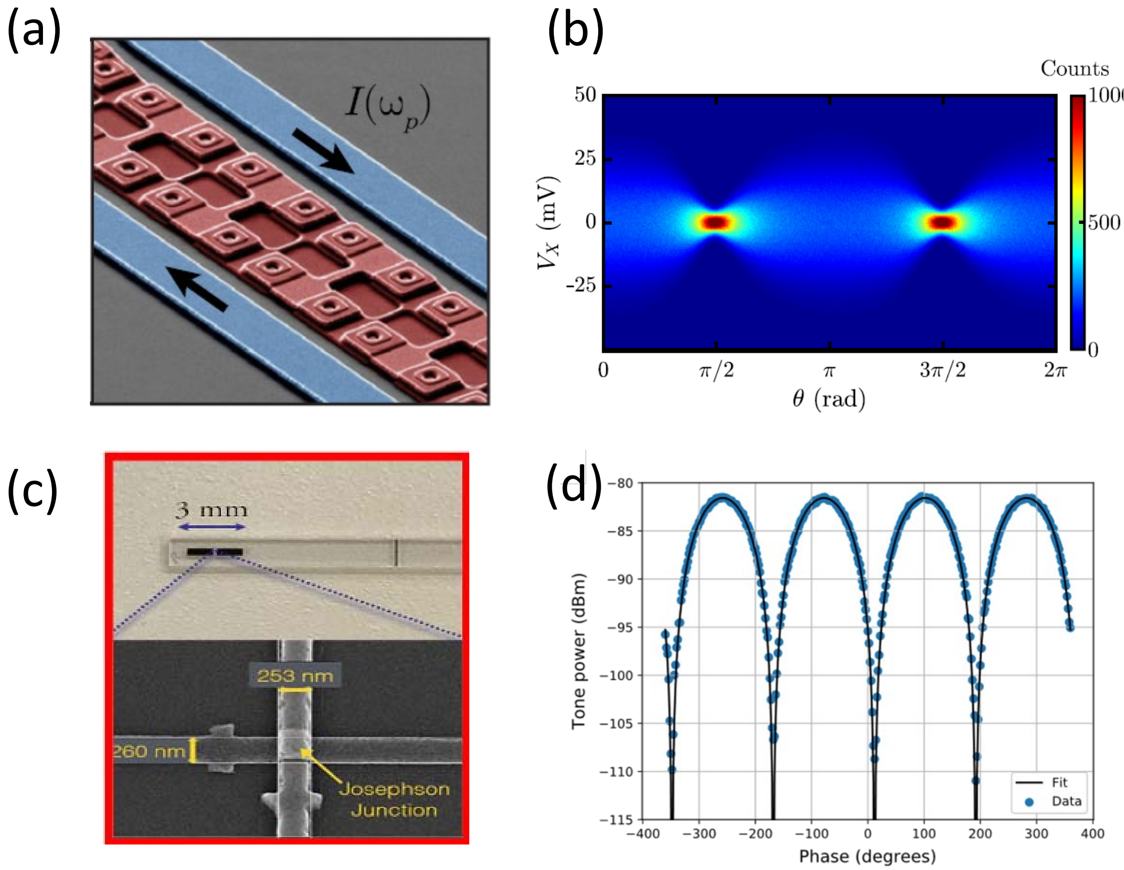


Figure 31: (a) A flux-pumped Josephson Parametric Amplifier for the HAYSTAC axion search. A scanning electron microscope image shows, in false color, a few of the Josephson loops and a flux-pumping line (adapted from [94]). (b) Squeezing achieved in the HAYSTAC experiment: histogram of voltage fluctuations V_X showing vacuum squeezing as a function of the relative phase Θ (Adapted from [94]). (c) Photograph of a superconducting qubit used as a single microwave photon detector for dark matter searches. Inset shows an electron microscope image of the Josephson junction, the active non-linear element that makes detection possible (Figure credit: D.I. Schuster, University of Chicago). (d) 30 dB of phase-sensitive gain demonstrated at 50 kHz with coherent quantum upconversion to 5.5 GHz – a step towards a full backaction evasion protocol. (Figure credit: S.E. Kuenstner, Stanford University).

Thrust 4: Develop opto-mechanical quantum sensors for DM experiments (QS1-2)

Opto-mechanical sensors have attained remarkable sensitivity, allowing the detection of gravitational waves from distant astrophysical objects. For example the space-time strain from inspiraling black hole mergers has been detected on the Earth at the level of one part in a billion-trillion [250]. Quantum-based squeezing techniques have the potential to further enhance the sensitivity of opto-mechanical systems by an order of magnitude or more. Opto-mechanical systems are also detectors which can be used to search for wave-like dark matter, as many models predict a strain-like behavior in objects as a result of the oscillating background dark matter bosonic wave. For example, optical cavities can be used to search for dilatonic dark matter in the audio band. Other opto-mechanical systems have been proposed to search for wave-like DM over a range of masses [251, 252], and such systems can also be used for mechanical impulse sensing [253]. In those regions of DM parameter space without strong observational and/or theoretical guidance, a figure-of-merit for such techniques is the number of square decades of unexcluded mass-coupling strength parameter space that can be probed.

Research Plan

A number of common technologies are needed in the four Thrusts in PRD 12. These include superconducting coherent quantum circuits incorporating active elements including Josephson junctions, tunnel junctions, nonlinear kinetic inductances, and Cooper-pair boxes. In all cases, it is relevant to know the ratio $\eta = P_{noise}/P_{SQL}$, first introduced in Section 3.3.4, which quantifies how large the measurement noise is relative to the Standard Quantum Limit.

Thrust 1 focuses on the development of backaction-evading quantum upconverters. The near-term performance target flowing down from Section 3.3 (Dark Matter) for the noise of these quantum upconverters is $\eta < 20$, at which point they outperform available DC SQUIDs in this frequency range (see Table 6 TR 3.27). While initial work would focus on this goal, implementation of backaction evasion in the longer term will enable $\eta < 0.1$, significantly increasing the mass range over which QCD axions can be probed (see Table 6 TR 3.28). Thrust 2 describes efforts to develop QND photon counters, with a near-term target flowing down from Section 3.3 of $\eta < 1$ (see Table 6 TR 3.33). Longer term, the target is for background-free photon counting with $\eta < 10^{-6}$, significantly increasing the mass range over which QCD axions can be probed (see Table 6 TR 3.34). Thrust 3 describes the development of pair-breaking photon counters above 30 GHz, also relevant to TR 3.34. Two promising technologies to achieve these measurements are the quantum capacitance detector and single photon counters based on superconductor-insulator-superconductor (SIS) tunnel junctions. Finally, in Thrust 4, a program for research and development of opto-mechanical sensors would be valuable, focused on maximizing the number of square-decades of mass-coupling parameter space.

4.4.3 PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics

Ensembles of quantum systems can enable fundamental experiments with broad science reach. Such experiments can be schematically described as transducers sensitive to fundamental science effects, resulting in quantum system evolution. Some examples are shown in Figure 32. The fundamental quantum limit on sensitivity of such transducers is quantum projection noise. When measuring an ensemble of uncorrelated spins for example, this projection noise or "shot noise" that occurs when projecting the quantum superposition state of each individual particle into its ground or excited state scales as the square-root of the number of particles contributing to the measurement [254] (see Figure 33). Taking quantum projection noise into consideration results in a figure-of-merit $\xi = xpN^{1/2}\tau^{\alpha}$, where x is the factor that quantifies the sensitivity of the system to the specific fundamental science effect (proportional, for example, to effective electric field for EDM experiments and some spin-based dark matter searches), p is the purity of the ensemble quantum state (for example, spin polarization), N is the number of individual quantum systems in the ensemble (spins, atoms, molecules, etc.), and τ is the relevant coherent evolution time for the ensemble. For example, for magnetometry experiments, $\alpha = 1/2$. The figure-of-merit scales differently if the experiment is limited by the sensor that detects the ensemble evolution. In some cases to optimize progress on broad science goals, such as sensitivity to the QCD axion and EDM searches, ongoing research and development is needed toward realizing sensor readout technology that enables ensemble measurements to be limited by quantum projection noise. We identify four particular Thrusts where ensemble-based quantum sensors are ripe for development in order to impact HEP, including nuclear-spin-based sensors and atomic/molecular-based sensors.

Thrust 1: Develop spin-based sensors for the QCD axion, axion-like particles, and wave-like dark matter (QS1-3)

Spin-based sensors operating on the principles of NMR are a promising avenue for searching for QCD axion dark matter in the mass range 1 peV – 10 neV (QS2) with haloscopes [256] and and for the QCD axion and axion-like particles in the mass range 10 μeV – 10 meV (QS3) with fifth-force searches [257]. The minimum energy of the interaction which can be measured in a bandwidth b is $\Delta E = \frac{\hbar}{p}\sqrt{\frac{b}{N\tau}}$, with $\Delta E = d \cdot E_{\rm eff}$ or $\Delta E = \mu \cdot B_{\rm eff}$ depending on the coupling of the axion field to the sensor nuclei. For example, the corresponding figure-of-merit in the case of magnetic coupling would be $\xi = xpN^{1/2}\tau^{\alpha}$ with $x = \mu$ and $\alpha = \frac{1}{2}$. This figure-of-merit $\xi = xp\sqrt{N\tau}$ motivates efforts to increase the relevant spin coherence time τ,

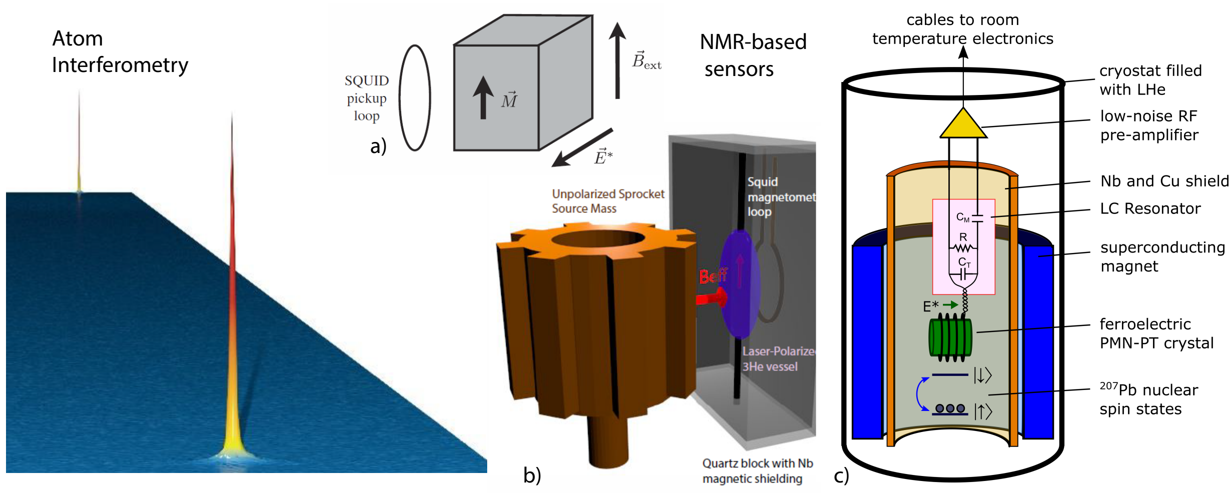


Figure 32: Examples of quantum ensembles and sensor networks relevant for fundamental physics. (Left) Atom-Interferometer sensors. Large wave-packet separations consisting of half-meter-scale coherent quantum superpositions have been achieved, leading to unprecedented sensitivity in atom interferometers [255] (Figure credit: T. Kovachy, Northwestern University). (Right) Examples of NMR-based quantum spin sensors: (a) Schematic of NMR-based sensor for cosmic axion searches (adapted from [256]). The axion-gluon coupling induces a time-varying electric dipole moment M parallel to the nuclear spin. The interaction of M with an effective external electric field, E^* causes a torque on the nuclear spin. When the axion Compton frequency matches the nuclear Larmor frequency, the nuclear spin precesses around B_{ext} and is measurable with a SQUID magnetometer. (b) Schematic of an NMR-based "fifth-force" axion search (ARIADNE [105, 257]). The unpolarized mass produces an effective magnetic field via the axion potential, with a range set by the Compton wavelength of the axion. The rotating sprocket-shaped source mass modulates this field at the ^{3}He nuclear Larmor frequency, driving ^{3}He spin precession that can be measured with a SQUID magnetometer. (c) Schematic of a magnetic resonance-based experiment (CASPER [256]) searching for axion-like dark matter using the principle described in (a). The magnetic field created by a superconducting magnet splits the ^{207}Pb nuclear spin states. The coupling of an axion-like dark matter field to nuclear spin is proportional to the effective electric field E^*in a polarized ferroelectric (Figure credit: A. Sushkov, Boston University).

the number of interacting spins N, and the polarization fraction p in these approaches. Considering the interaction energy and the corresponding figure-of-merit for a given experimental platform, we can define a requirement on the product $\sqrt{N\tau}$ for known experimental techniques for searches for the QCD axion and for axion-like particles/fifth forces based on the necessary sensitivities discussed in Section 3.3.4.

Thrust 2: Develop atomic clocks and interferometers to search for gravitational waves, wave-like DM, and other new physics (QS1)

Atomic clocks and interferometers are established tools for searches for new physics and tests of fundamental symmetries [258, 259], and are also promising techniques to search for gravitational waves, wave-like dark matter, and other new physics due to weakly-coupled dark sectors [260, 261]. Configurations of atomic clocks and interferometers have been developed for detecting space-time strains due to gravitational waves for frequencies below those studied at Advanced LIGO and extending above those predicted to be readily accessible in future spaced-based interferometers such as LISA (see TR 5.22 in Table 13). As noted earlier in Section 3.5.5, such gravitational waves themselves can be messengers of heavy or dark sector physics from the primordial Universe. Furthermore, as noted in Section 3.3.4, a somewhat analogous strain results from oscillating wave-like dark matter, rendering atomic clocks and interferometers ideal tools for searching for such effects. Wave-like DM (Section 3.3.4) and other weakly coupled dark sectors (Section 3.5.5) can also produce variations in fundamental constants, which cause time-varying and material-composition-dependent accelerations, strains, or atomic energy-level shifts that can be detected by precision atomic clocks and interferometry [251, 260, 261]. These techniques enable, in particular, searches for for wave-like dark matter with masses below 1 peV down to fuzzy DM in the sub-zeV mass range corresponding to the size of dwarf galaxies. Since such sensors probe, like opto-mechanical sensors, regions of dark matter/dark sector parameter space without strong observational and/or theoretical guidance, a figure-of-merit for such techniques is the number of square decades of unexcluded mass-coupling strength parameter space that can be probed.

Thrust 3: Develop technology for EDM searches (QS1)

Sources of time-reversal (T) symmetry beyond those in the Standard Model are required to generate the observed cosmological matter-antimatter asymmetry (assuming CPT symmetry holds as is generally expected). Precision measurements with quantum sensors are at the forefront of searches for violation of T-violation, which generically manifests itself as the existence of a permanent electric dipole moment (EDM) along the spin of fundamental and composite particles. Standard Model extensions, such as supersymmetry, typically predict EDMs near the limits set by current experiments. In fact, state-of-the-art EDM experiments probe new physics at higher energy scales than those accessible with the LHC. New quantum sensor technology enabling more precise measurements of both nuclear- and electron-spin-dependent interactions can extend the reach of EDM searches to even higher energy scales. One example of a highly promising technology for electron EDM searches has been beams of cold polar molecules or trapped molecular ions, with excellent quantum control over the molecular states. Cold polar molecules also can have pairs of states with "built-in" field reversals which are useful for rejection of systematic errors.

Thrust 4: Develop entanglement as a resource for quantum sensors such as clocks and magnetometers (QS1-3)

Entanglement is a key technique available for improving the sensitivity of quantum sensors. Entanglement-induced correlations in the states of quantum ensembles, squeezed light, and squeezed spin states (see Figure 33) have been critical tools for demonstrating proof-of-principle improvements in noise floors and sensitivities of detectors. Entanglement between electronic and nuclear spins in quantum diamond sensors have improved real-world applications like single-protein NMR. Beyond squeezing and laboratory scale non-classical states, large-scale entangled sensor networks, where entanglement over long distances is harnessed for dramatic improvements in sensitivity, may lead to profound improvements in astronomical interferometers and other sensors. The application of entanglement to global networks of clocks and magnetometers could also enhance the sensitivity of searches for transient signatures of beyond Standard Model physics connected to dark matter and dark energy. Arrays of quantum sensors will also be a resource for background rejection and even track-like signals in certain scenarios. With such techniques, a number of square decades of unexcluded mass-coupling strength parameter space can be probed.

Research Plan

Thrust 1 requires efforts to increase the relevant spin coherence time τ, the number of interacting spins N, and the polarization fraction p in spin-based NMR platforms, with Technical Requirements as indicated for QCD axion dark matter in Table 6 TR 3.21-3.24 and for the QCD axion and axion-like particles in Table 7 TR 3.37-3.42 of Section 3.3.4. Additional research should be undertaken regarding choice of material for the NMR medium to seek enhancements in the factor x in the figure-of-merit. In addition, new quantum protocols should be investigated that can enable experiments to beat quantum projection noise with spin squeezing in NMR-based detectors for the QCD axion strong force coupling below $\sim$1 μeV and for the detection of short-range spin-dependent interactions from $\sim$1 μeV to 10 meV. Thrust 2 requires development of long-baseline approaches for comparing measurements between atomic clocks and interferometers, including techniques sensitive to oscillating strains due to gravitational waves and/or wave-like DM (see Table 13 TR 5.22) and/or time-varying and composition-dependent forces and accelerations resulting from variations of fundamental constants induced by wave-like DM or other dark sectors (see Table 13 TR 5.21). Thrust 3 requires research into spectroscopy of cold molecules with improved sensitivity and development of techniques for cooling and trapping of the molecules, with Technical Requirements TR 5.16-5.18 (Table 12 in Section 3.5.4). Thrust 4 requires basic research into the generation and utilization of such entanglement-based resources. Accelerated

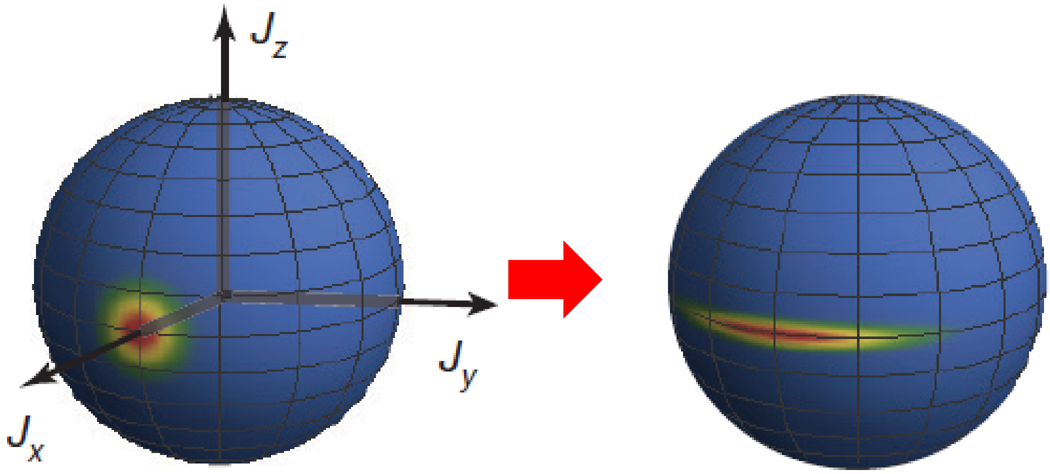


Figure 33: Quantum projection noise limits the phase resolution of a standard measurement to $1\sqrt{N}$. Spin-squeezing techniques can improve the resolution ultimately by an additional factor of $\sqrt{N}$ in one quadrature at the expense of additional noise in an orthogonal measurement quadrature. Adapted from [262].

research and development into techniques for upconversion and transduction will be critical in realizing such distributed, entangled sensors. Work is needed to enable atomic clocks, magnetometers, or interferometers to be operated with entangled states that can achieve sensing at the Heisenberg limit, improving upon the standard quantum projection noise in uncorrelated systems by a factor of $\sqrt{N}$ for an ensemble of N particles.

4.4.4 PRD 14: Advance the state of the art in low-threshold quantum calorimeters (QS4)

Searches for dark matter candidates with mass less than 1 MeV can also benefit from advances in quantum sensor technology searching for individual scattering events. As is discussed extensively in Section 3.3.3, there is a need for detectors with energy thresholds below the eV scale to detect these low-mass dark matter particles. New quantum sensors have the potential to extend searches for individual events to much lower masses.

Such detectors might be sensitive to interactions with electrons or nuclei in materials below the threshold for ionization and scintillation in existing detectors. These include ultrasensitive alternatives to existing bolometers and superconducting detectors for the detection of athermal phonons produced by a particle interaction within a gram-to-kilogram scale mass detector or the detection of the production of phonons or rotons in superfluid helium. New quantum sensor modalities have the potential to enable optical readout to detect single ∼GHz scale (∼μeV) phonons provided energy from a particle interaction can be coupled into the modes of interest.

Electron (E) or nucleon (N) recoils (R) can be used to search for low mass dark matter (DM) particles (abbreviated "ERDM" and "NRDM"). For recoil energy below the ionization energy of the material (or promotion of one charge carrier across a band gap), all the recoil energy appears initially as athermal phonons (or also rotons in superfluid He). While they will eventually down-convert to thermal phonons, the time constant for this can be significant depending on material and surfaces. Bolometric sensors (for example, based on transition-edge sensor (TES) or kinetic inducance detector (KID) devices) can be used to measure such athermal excitations before they thermalize. Fig. 34(a) illustrates an example detector using TESs.

There are other theorized DM interactions besides scattering that can excite athermal phonon modes, such as dark photon absorption, which favors polar materials (e.g., GaAs, sapphire). Superfluid He is a unique target in that it offers a signal collection mechanism with noiseless gain in the form of quantum evaporation. Phonons evaporate He atoms from the surface into the vacuum above, and these atoms can then

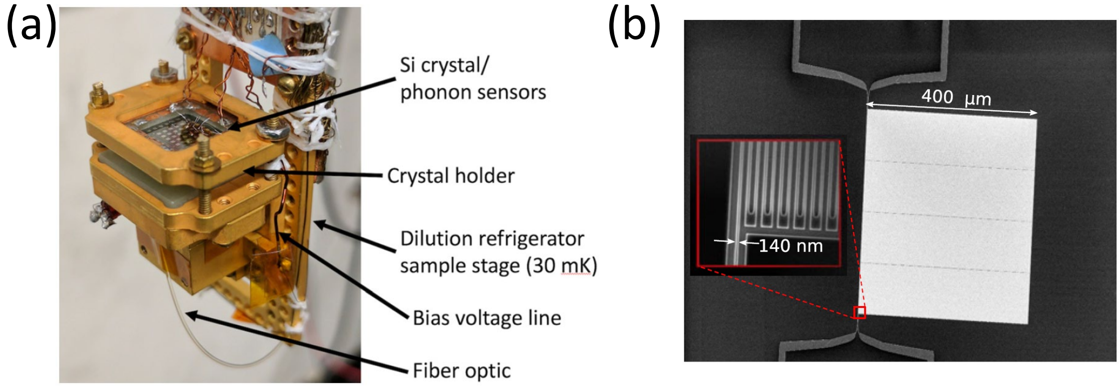


Figure 34: (a) Photograph of a detector using TESs on Si substrate to detect phonons from electron-hole pair drift in an applied field. The substrate is a 1 cm^2 in area, 0.4 cm thick, and has mass 0.93 g. This device was used to demonstrate the detection of single electron-hole pairs. (Adapted from [226]). (b) SEM image of a prototype WSi SNSPD device for sub-GeV dark-matter detection. The 7-nm thick film has an area of 400×400 μm^2 and a mass 4.3 ng. (Adapted from [226]).

be detected when they are adsorbed onto the surface of a bolometric sensor. Improved pixellated arrays of bolometric sensors are needed for superfluid helium detectors, including sensors developed for photons, such as superconducting nanowire single-photon detectors (SNSPDs). In all cases, the low-threshold detection must be accomplished with extremely low dark counts so that the experiment is limited by the radioactive background of the detectors and the environment rather than by false triggers. Fig. 34(b) illustrates a WSi SNSPD device.

Research Plan

Research is needed for athermal and low-threshold sensors for multiple candidate targets in order to address PRD 14. Athermal phonon sensor optimization depends on phonon transport in and collection from a given target material, not on the primary ERDM or NRDM interaction (NRDM prefers some targets while ERDM others, absorption others, and coupling to magnon modes still others). Research is needed on ultrasensitive sensors of phonons in solid-state targets and phonons and rotons in superfluid helium. As described in Table 5, near-term goals for both nuclear and electron recoil threshholds are < 1 eV, and longer term goals are < 1 meV (TR 3.13-3.20).

4.4.5 PRD 15: Advance enabling technologies for quantum sensing

Realizing the potential of quantum sensors for HEP applications requires the advancement of key enabling technologies.

Thrust 1: High-Q electromagnetic resonators and supporting technologies (QS2-3)

Many searches for dark sector bosons (Section 3.5.5) and for wave-like dark matter (Section 3.3.4), including those for axions and axion-like particles as well as for dark photons, use electromagnetic resonators (RF cavities or lumped-element circuits) to enhance the potential dark boson/photon conversion rate. Hence, increased resonator quality factor is generically useful. Additionally, high-Q RF/microwave cavities provide a high-coherence environment for qubits used as detectors, isolating them from a noisy environment. Fig. 35 shows recent examples of state-of-the-art electromagnetic resonators used in dark matter experiments.

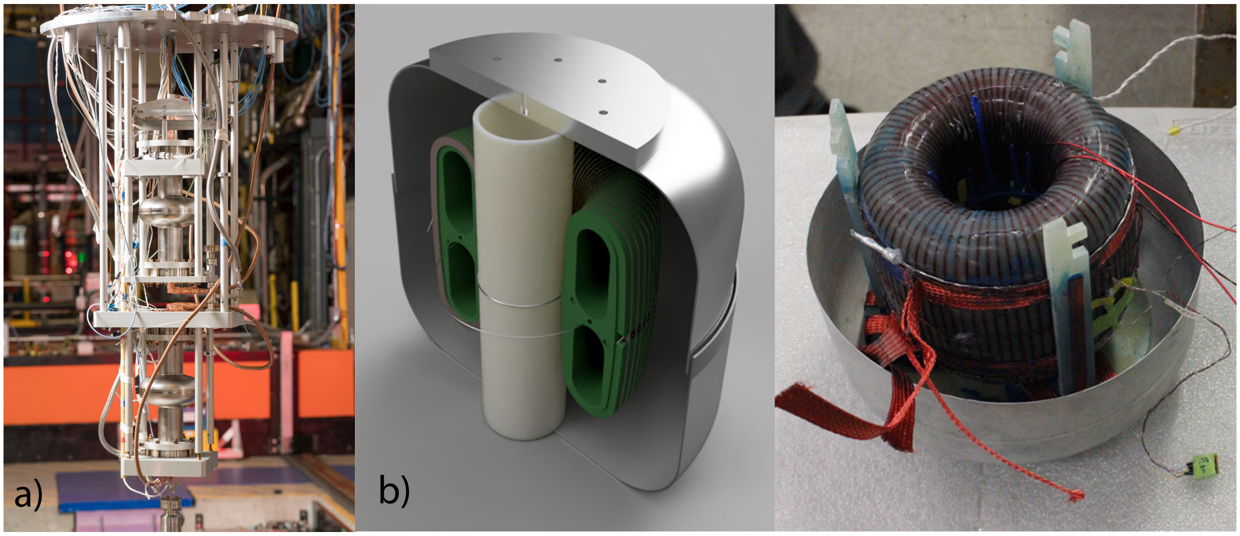


Figure 35: (a) Nb cavities used in the Dark SRF experiment at Fermilab (Image credit: A. Grasselino, Fermilab) (b) Left: Rendering of the ABRACADABRA-10 cm setup. The primary magnetic field is driven by 1280 superconducting windings around a POM support frame (green). The axion-induced field is measured by a superconducting pickup loop mounted on a PTFE support (white). A second superconducting loop runs through the volume of the magnet to produce a calibration signal. All of this is mounted inside a superconducting shield. Right: Picture of the exposed toroid during assembly. Adapted from [263].

Thrust 2: Optimized materials for quantum sensing (QS1-4)

Advancing the performance of quantum sensors requires a continued focus on improving the materials that instantiate and/or support these sensors, as well as developing new types of quantum sensors through materials research and development. Here, some illustrative examples of such quantum sensor materials research are given.

- In nuclear spin-based searches for ultralight dark matter that probe spin ensembles in non-centrosymmetric materials, such as ferroelectrics, sensitivity is linked to the polarization (or crystalline asymmetry) of a material that hosts an element with nuclear spin and large atomic number. Developing the techniques for growing large single crystals of such materials is a necessary requirement for extending the sensitivity reach down to the QCD axion level.

- Atomic-scale quantum defects in diamond — such as Nitrogen Vacancy (NV) color centers — have long-lived electronic spins that can be prepared and read-out optically under ambient conditions, allowing precision sensing of electromagnetic fields, temperature, forces, and crystal stress/strain. Quantum diamond sensors have become a leading modality for precision measurements with high spatial resolution (nanometer to millimeter), with wide-ranging applications, including for HEP, such as directional-detection of WIMP dark matter, as well as for other areas of interest to the DOE. Despite this success, the performance of current, state-of-the-art quantum diamond sensors is many orders of magnitude from fundamental limits set, e.g., by spin-projection noise. Much of the current limitation comes from issues with the diamond material itself.

- Two-level system losses. One of the main problems limiting quantum devices' coherence and therefore ultimately performance are loss to so-called two-level systems (TLS). They are often localized in surface oxides or at interfaces between oxides and the materials employed for the quantum device.

- Superconducting magnetic shielding for axion and ALP experiments. Many axion and ALP search experiments, particular those relying on spin-based sensors, require exquisite magnetic field sensitivity and thus require excellent shielding of background magnetic noise. Materials with low penetration depth and minimal trapped flux noise are needed for the most sensitive experiments.

Thrust 3: Atomic/Molecular/Optical and Nuclear-Spin based methods and enabling technologies (QS1-3)

Sensors based on atomic-molecular-optical systems and nuclear spins are ripe for development that can lead to profound improvements in quantum sensing for HEP applications. Some illustrative examples are:

- Lasers for probing molecular transitions in EDM experiments

  Probing molecular transition for EDM experiments requires tuneable, stable lasers with narrow linewidths, across a broad range of wavelengths. While tunable sources exist in the infrared, for next generation EDM experiments high-power, tunable lasers in the ultraviolet and visible regime are needed.

- Adaptation of nuclear magnetic resonance tools to HEP spin-based experiments

  Spin-based experiments exploring HEP science necessarily use nuclear magnetic resonance techniques. NMR is a mature field with an extensive list of applications, but Technical Requirements for experiments probing HEP science are different. Nuclear magnetic resonance applications are usually spectroscopic, whereas fundamental discovery experiments typically search for small spin torques, requiring large (order liters) ensemble sizes and sensitivity approaching spin projection noise. Adapting NMR techniques to such large sample sizes and ultra-low noise environments will extend the science reach of spin-based fundamental discovery experiments.

- Optimized production of high phase-space-density samples of cold atoms and molecules

  A broad range of quantum sensing experiments depend on the production and application of cold and ultra-cold atomic and molecular gases, including atom interferometry, atomic clocks, and EDM searches. Next generation quantum sensors will rely on the quantum coherence and control present in these systems, including interferometers and networks of entangled clocks and sensors. Current sensors are often limited by the production time for creating high-space-density samples of cold atoms and molecules.

- Optimized laser and optical cavities for optical clocks relevant to gravitational wave detection and searches for new forces and particles

  Lasers locked to ultra-stable optical cavities provide extremely narrow line-width optical fields that serve as the local oscillator for optical atomic clocks. The fundamental noise that limits the stability of optical cavities is thermal noise present in the spacer, mirror substrate, and high-reflectivity mirror coatings. Silicon has been identified and implemented as a promising material for next-generation ultra-stable optical cavities. Recent results show that crystalline silicon optical cavities can provide < 10 mHz linewidth stability at averaging times from one to a few thousand seconds. This laser system has allowed two JILA Sr clocks to demonstrate world-record stability, and also allowed for the first time an all-optical time scale.

Thrust 4: Optimized quantum sensing algorithms (QS1-4)

Quantum sensors have the potential to significantly outperform classical techniques at a wide variety of tasks relevant to HEP science, as outlined above. However, the diversity of quantum sensing modalities and applications–from few-qubit defects in solids to large entangled networks of sensors–require development of tailored quantum algorithms optimized for each sensor application. For example, quantum algorithms need to be developed to address major shortcomings of near-term quantum sensors, such as the different types and effects of noise as well as heterogeneity between qubits and/or their couplings within a sensor network. Fruitfully executing quantum algorithms in practice will also require developing optimized software toolchains for efficiently translating algorithms from an abstract specification to a concrete implementation.

Research Plan

To develop the supporting technology needed for HEP applications in quantum sensing, the following work should be undertaken:

Thrust 1: Searches for dark photons are now being developed using very high-Q cavities without a magnetic field. Some search schemes are based on coupled, very high-Q cavities — for example with the

DarkSRF experiment at Fermilab, a light-shining-through-walls search for dark photons. A near-term target flowing down from Section 3.3.4 for Q of coupled cavity resonator experiments is $Q \geq 10^{11}$ (see Table 7 TR 3.43). The long-term research goal is to raise the quality factor of these resonators two more orders of magnitude to $Q > 10^{13}$ (see Table 7 TR 3.44). This ambitious goal would need to be accompanied by R&D in frequency control of these resonators with sub-mHz precision. This could also enable their use for gravitational wave detection. Axion dark-matter searches require the development of microwave cavities that provide high Q in large magnetic fields. The near-term target from Section 3.3.4 is to achieve $Q \geq 10^5$ (see Table 6 TR 3.31), and the long-term goal is $Q \geq 10^6$ (see Table 6 TR 3.32). High Q in large magnetic fields can be achieved by the use of superconducting materials like Nb_3Sn that have high (several tesla) upper critical fields. This would bring substantial improvement in sensitivity for experiments like ADMX near 1 μeV mass. At lower masses, lumped-element resonators that achieve high Q in high magnetic fields are needed. This can be achieved by the use of toroidal magnets with low fringing fields, which isolate the magnetic field from the resonator materials, or by the use of high-critical-field materials in different geometries. The near-term target from Section 3.3.4 is to achieve $Q \geq 10^6$ (see Table 6 TR 3.25), and the long-term goal is $Q \geq 10^8$ (see Table 6 TR 3.26).

Thrust 2: Development of large ferro-electric crystals will require engagement of expertise in crystal growth. Advances in the use of diamond quantum defects will require systematic studies of: diamond material growth; treatment improvements; the spatial distribution of defect concentrations; defect spin and optical properties; and optical wavelength and intensity effects on charge state dynamics. Studies towards developing a better understanding of two-level system losses are necessary to improve the fabrication of devices from qubits to resonators and more. Development of low-background-flux-noise, low-penetration-depth superconducting magnetic shielding, either in bulk materials or deposited thin films, will be essential for realizing the ultimate performance of spin-based axion and axion-like-particle sensors for a range of masses, and this requirement also applies to NMR-based fifth-force searches. The diversity of applications for these improvements renders it challenging to list a specific set of quantitative Technical Requirements to be met, but, in all cases, such developments should be motivated by either such a specific requirement or by an expectation that a specific quantitative development goal will enable the coverage of appreciable (typically, decades or square decades) of unconstrained parameter space.

Thrust 3: Achieving high-power (>500 mW) lasers meeting the stability requirements for molecular spectroscopy of candidate EDM molecules (see Table 12 TR 5.17) will require either a robust and versatile frequency comb or transfer cavities with the ability to both narrow the line-width and the ability to lock lasers of many different wavelengths. For spin-based magnetic resonance experiments, the research plan will include developing new methods for applying traditional magnetic resonance techniques, such as hyperpolarization, magic-angle spinning, and dynamical decoupling, so they can be applied to large sample sizes and ultra-low noise environments to satisfy TR 3.21-3.24, TR 3.37-3.42, and TR 5.20 (Tables 6 and 7 in Section 3.3.4 and Table 13 in Section 3.5.5). Developing new techniques for cooling and trapping of molecules and for optimizing the production of ultra-cold atomic samples satisfying TR 5.16 and 5.18 (Table 12 in Section 3.5.4) would advance the sensitivity of next-generation atomic and molecular quantum sensors. Research directions to achieve optical cavities with lower thermal noise (necessary to satisfy TR 5.20-5.22, Table 13 in Section 3.5.5) and longer coherence times (a $10\times$ increase to >120 s, the coherence time offered by lattice-confined cold atoms such as Sr) may include investigations of enhanced thermal isolation, reduced thermal noise from the mirror coating (e.g., via crystalline AlGaAs), and cavity operation near a zero-crossing point of the coefficient of thermal expansion (CTE) of silicon.

Thrust 4: Large-scale engagement of the quantum algorithm community is needed to address effectively the current computational and engineering challenges and to efficiently realize applications on scalable quantum sensor hardware. Diverse problems will need to be solved, including the synthesis and control of optimal quantum sensor networks; machine-learning methods for characterizing and controlling quantum sensors that face dynamic target signals and systematic effects; novel methods for simulating quantum algorithms to facilitate debugging of quantum programs; and a quantum operating system to manage the functioning of realistic quantum sensors. Generically, development of such "quantum sensor software" should be targeted at ensuring quantum sensors can achieve the sensitivity limits imposed by fundamental physics.

4.4.6 Connections Outside HEP

The work discussed in the Research Plan for developing novel and improved quantum sensors for HEP has significant ties to research in quantum information science, quantum computing, materials science, and biology. Developing higher Q superconducting cavities could lead to enhancements in superconducting qubits. Quantum sensing will play a critical role in the development of coherent signal transduction of multiple qubit modalities to optical signals, which will make it possible to develop quantum networks at the inter-city scale. Developing large-volume high-field magnets could have synergy with the research aims of the National High Magnetic Field Lab. The work on ensemble-based sensors for magnetic fields is relevant for high precision magnetometry and magnetic imaging at small length scales and at lower cost. These breakthroughs will impact a variety of disciplines including materials science, biology, and biophysics. Atom-interferometry and opto-mechanics research may lead to enhancements in inertial sensing, navigation, or time-keeping applications.

4.4.7 Facilities and Capabilities

Large volume high field magnets in solenoidal and toroidal geometries. To achieve the higher magnetic fields required for axion dark-matter searches using conversion to photons, new magnet technology is needed for both solenoidal geometries (often used in microwave cavity experiments) and toroidal geometries (often used in lumped-element resonator experiments).

For microwave cavity experiments, the near-term target from the dark-matter section of this report is to achieve solenoidal magnets with $B > 4$ T with volumes of 100 L (see Table 6 TR 3.35), and the long-term goal is to achieve $B > 30$ T with volumes of 2 L (see Table 6 TR 3.36). For magnetic fields of 30 Tesla or above, one possible solution consists of nested systems using, for example, a high-temperature superconductor inside NbTi and/or Nb_3Sn. Generally, studies should be performed to identify the optimal materials and bore/magnetic field interface between nested layers. A new HEP-Fusion Energy Sciences (FES) very-high-field-magnet test facility is currently under development at Fermilab and may be explored as a potential future testbed for these types of developments.

Lumped-element experiments frequently use toroidal magnets to isolate the field from the conducting materials of the resonator. For such experiments, the near-term target from the dark-matter section of this report is to achieve toroidal magnets with $BV > 4\ \mathrm{T\,m^3}$ (see Table 6 TR 3.29), and the long-term goal is to achieve $BV > 10\ \mathrm{T\,m^3}$ (see Table 6 TR 3.30).

Faster turnaround, cheaper, larger mK dilution refrigerators. Quantum sensing technologies require operation at mK temperatures to reduce thermal noise so they can operate in the "ground state" (as defined in Section 4.4.1). The recent surge in quantum computing architectures based on superconducting devices has greatly increased the demand for dilution refrigerators. These systems currently have three main weaknesses that slow down and increase the expense of R&D: 1) long turnaround time: a large dilution fridge can require up to a week to reach few mK temperature, and several days also for warm up; 2) cost: system costs are in the range $0.5–1M; 3) size: readily available, commercial systems are less than about a meter in diameter, limiting the number of experiments that can be run in parallel or the size of individual quantum sensing architectures or networks. Therefore, the development of cost-effective and scalable mK cooling systems would improve the accessibility of these technologies for R&D and enable implementation on currently unachievable scales.

4.4.8 Quantum Sensors and the Grand Challenges

The Priority Research Directions, Thrusts, and Research Plans indicated for novel quantum sensors and networks will drive several important advances relevant for three of the Grand Challenges. These are Grand Challenge 1: Advancing HEP detectors to new regimes of sensitivity, Grand Challenge 2: Using integration to enable scalability for HEP sensors, and Grand Challenge 3: Building next-generation HEP detectors with novel materials and advanced techniques.

4.5 Readout and ASICs

4.5.1 Introduction

An Application-Specific Integrated Circuit (ASIC) is an integrated circuit explicitly designed for a specific purpose, in other words, is a chip developed for doing one thing extremely well. ASICs continue to replace discrete electronics to a point that entire systems are now integrated in a chip (system-on-chip). The shrinking of feature size (gates) with the advancement of technology (nodes) has enabled the integration of increasingly more functionalities with higher density and performance.

A majority of the R&D tasks described in this BRN report will require some form of ASIC development to support the research goals. Most will need to be compatible with an extreme environment, e.g. high radiation, cryogenic temperature, or space. Current and future custom integration allows higher density, enhanced circuit performance, lower power consumption, lower mass, much greater radiation tolerance or better performance at cryogenic temperatures than is possible with commercial ICs or discrete components. Transistors, invented in the 1940s became commercialized as discrete components in the 1950s and soon after specialized function circuits with multiple transistors on the same substrate became available. By the end of the 20th century complex Printed Circuit Boards (PCBs) with broad and sometimes programmable functionality were commonplace. Today much or all of the analog and digital functionality once relegated to a PCB can be found on a single substrate (see Figure 36).

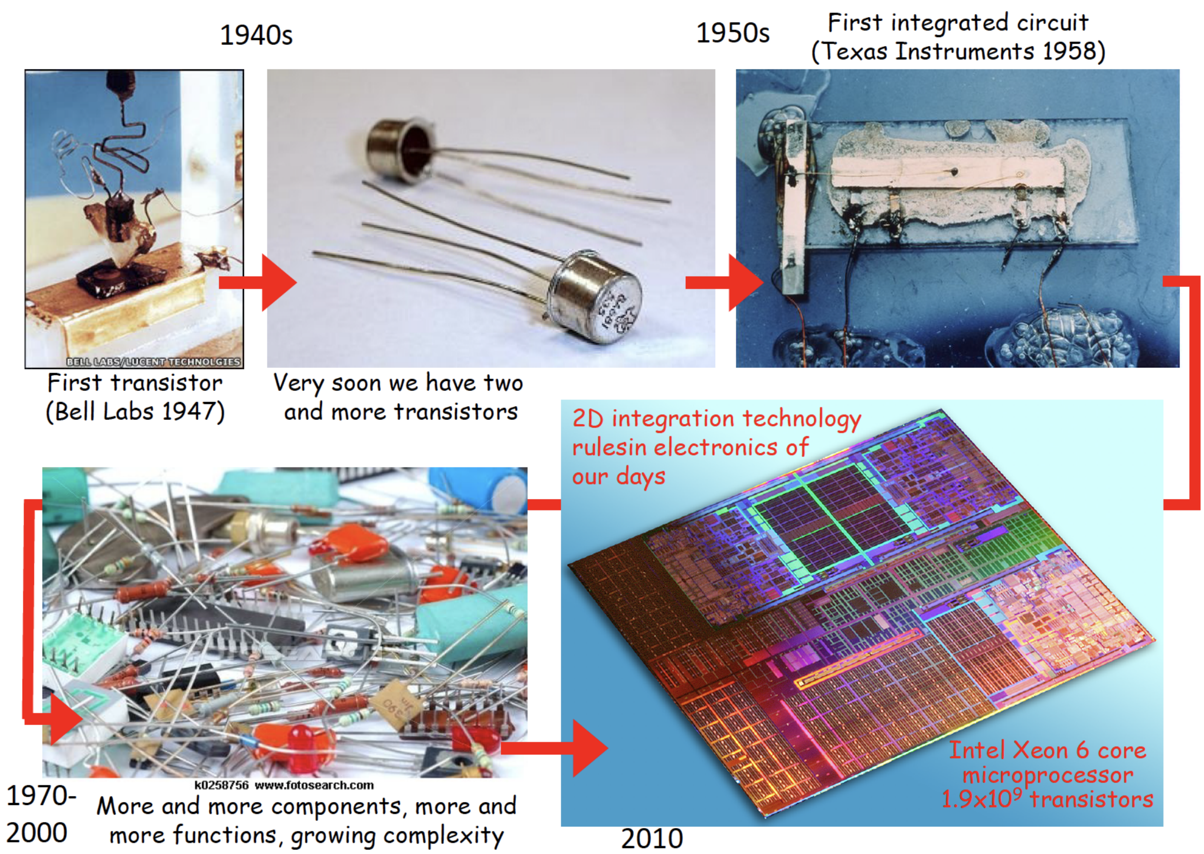


Figure 36: Highlights of the development of single transistors to Systems-on-a-Chip. The past 70 years have seen amazing developments in the performance and versatility of integrated circuits. The history above gives a sense of this progression which continues to evolve.

The Microplex chip, designed in 1984 at SLAC for the MARK II detector is perhaps the first example of how integrated circuits technology can enable breakthroughs. Four 128 channel Microplex chips placed side by side were used to read out the newly developed silicon strip sensor with 512, 25 μm pitch channels enabling a 5 μm track resolution for the 18,000 channel vertex detector (see Figure 37). Its high density analog outputs still required a significant amount of processing to be translated into usable data.

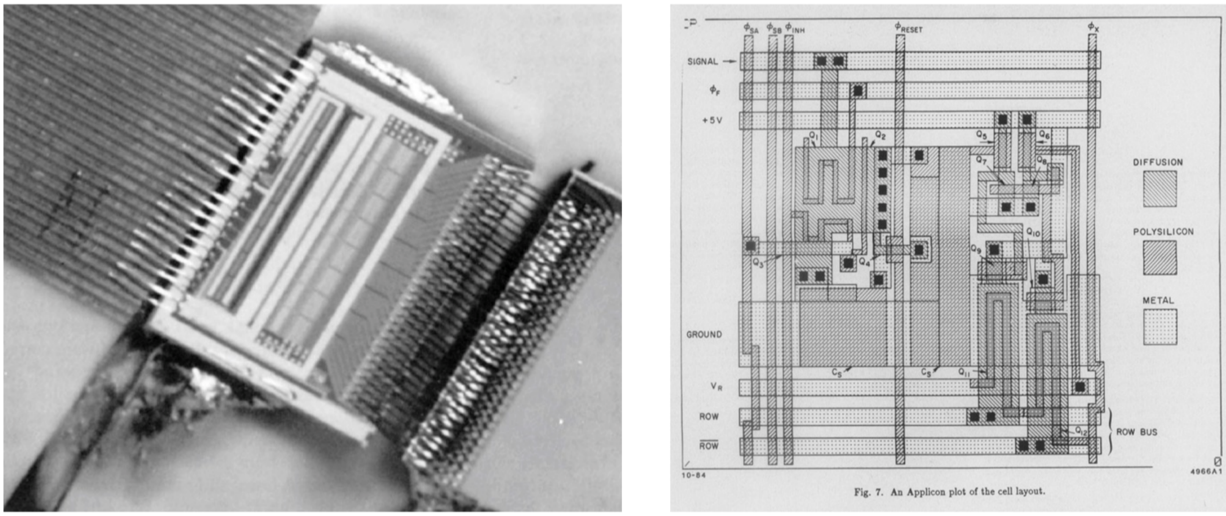


Figure 37: The 128 channel Microplex chip was designed at SLAC in 1984 in 5 μm N-type metal-oxide-semiconductor (NMOS) technology to readout early silicon strip modules. Its 14 mW per channel power dissipation was a significant gain from single channel readouts. The 500 ns rise time and 2500 e^- equivalent noise charge (ENC) was impressive for the time.

Pixel detectors under development today integrate both sensor and readout on the same ASIC, saving significantly on cost, power per channel and material burden, while improving spatial resolution and potentially replacing highly inefficient raw data transfer off detector with abstracted parameters.

These advances come at a cost, however. The time frame for development and risk associated with these highly concentrated ASIC-based system designs depend on having a multi-institutional, experienced workforce familiar with current (at the time of need), moderate scale, affordable technologies and the relevant synthesis, simulation and verification tools. New ASIC-based SoC (System on a Chip) designs will have common, but complex functional requirements (power regulation, high speed communications, data storage, internal clock multiplication etc.) that will benefit in schedule and cost from having pre-designed intellectual property (IP) blocks in the target technology or, in the case of new technologies, from the help of experienced designers to develop these blocks for the first time.

Two ASIC-related Priority Research Directions are identified here to provide the infrastructure necessary to support the breakthrough technologies identified as research needs throughout this document. This ASIC R&D is needed to maintain the relevance of U.S. High Energy Physics contributions in the international arena and encourage throughout the community the creative spirit that powered, for example upgrade designs through two generations of LHC detectors and is pushing us now to explore new approaches to the readout of multi-kiloton noble element detectors. Table 19 summarizes all Readout and ASIC PRDs and Thrusts presented in this section along with related technical requirements.

4.5.2 PRD 16: Evaluate process technology and develop models for ASICs in extreme environments

Cryogenic Temperature Environments There is a natural progression of technology following both IC industry advances and experimental needs. The cryogenic, 100 K (-173 C) and deep cryogenic $\leq$4 K (-269 C) operational requirement for the readout of neutrino and dark matter detectors are well matched to smaller feature size, commercially available CMOS nodes. The high doping concentrations introduced into these commercial CMOS processes to enhance gain and high speed performance also have eliminated the low temperature charge carrier freeze-out that previously prevented consideration of commercial CMOS for use

Priority Research Directions	Thrusts	Technical Requirements
PRD 16: Evaluate process technology and develop models for ASICs in extreme environments	Develop models, standard cell libraries, and demonstrators for extreme rate and radiation; Develop models, standard cell libraries, and demonstrators for intermediate cryogenic range: Develop models, standard cell libraries, and demonstrators for quantum sensor controls and data acquisition for deep cryogenic range; Investigate emerging design and verification methodologies; Investigate CMOS with integrated photonics nodes when commercially available; Investigate processes with Internet of Things (IoT) technology to enable self-assembly or assembly-free very large scale detectors; Adopt Artificial Intelligence (AI) and Machine Learning (ML) techniques	TR 1.1, TR 1.2, TR 3.47, TR 5.3, TR 5.6, TR 5.8, TR 5.11
PRD 17: Create building blocks for Systems-on-Chip for extreme environments	Develop advanced low power high speed I/O protocols; Develop wireless blocks beginning with control and monitoring; Develop power management blocks (DC/DC) converters, regulators, pulsed power; Circuit development for monolithic designs with sensor and readout integrated (MAPS, SPADs, SiPM); Develop Single Event Effects flows and techniques relevant for new technologies; Develop analog and multiplexing blocks for 4K environments and below; Develop fault tolerant communications for long lifetime inaccessible readout; Develop precision clock and timing circuits (PLL, DLL, Timing Discriminators, Delay Lines, Picosecond TDCs); Develop multi-channel RF digitizers	TR 1.5, TR 2.1, TR 2.3- 2.5, TR 2.6- 2.7, TR 4.3- 4.4, TR 5.3,TR 5.6, TR 5.8,TR 5.11

Table 19: Summary of Priority Research Directions, Thrusts and Technical Requirements for Readout and ASICs.

in these detectors. The LArASIC chip currently under development at Brookhaven National Laboratory, see Figure 38, for the DUNE detector will be located inside the cryogenic liquid near the readout wires. Its outputs will be digitized locally and data will be aggregated before sending out of the cold environment. This technique has multiple advantages: improved signal to noise by locating the amplifiers near the the sensor readout reduces capacitance and pickup and significantly lowers thermal noise in the amplifier operating at 77 K. A reduction in the number of cold to warm feed-throughs will reduce the interconnect and cabling cost as well as the heat load on the detector.

Some of the immediate benefits of developing dedicated readouts capable of operating at even lower temperature include replacing SQUIDs with CMOS amplifiers and reducing the number of expensive feed throughs from cold to warmer environments by concentrating information from many sensors into one feed-through port.

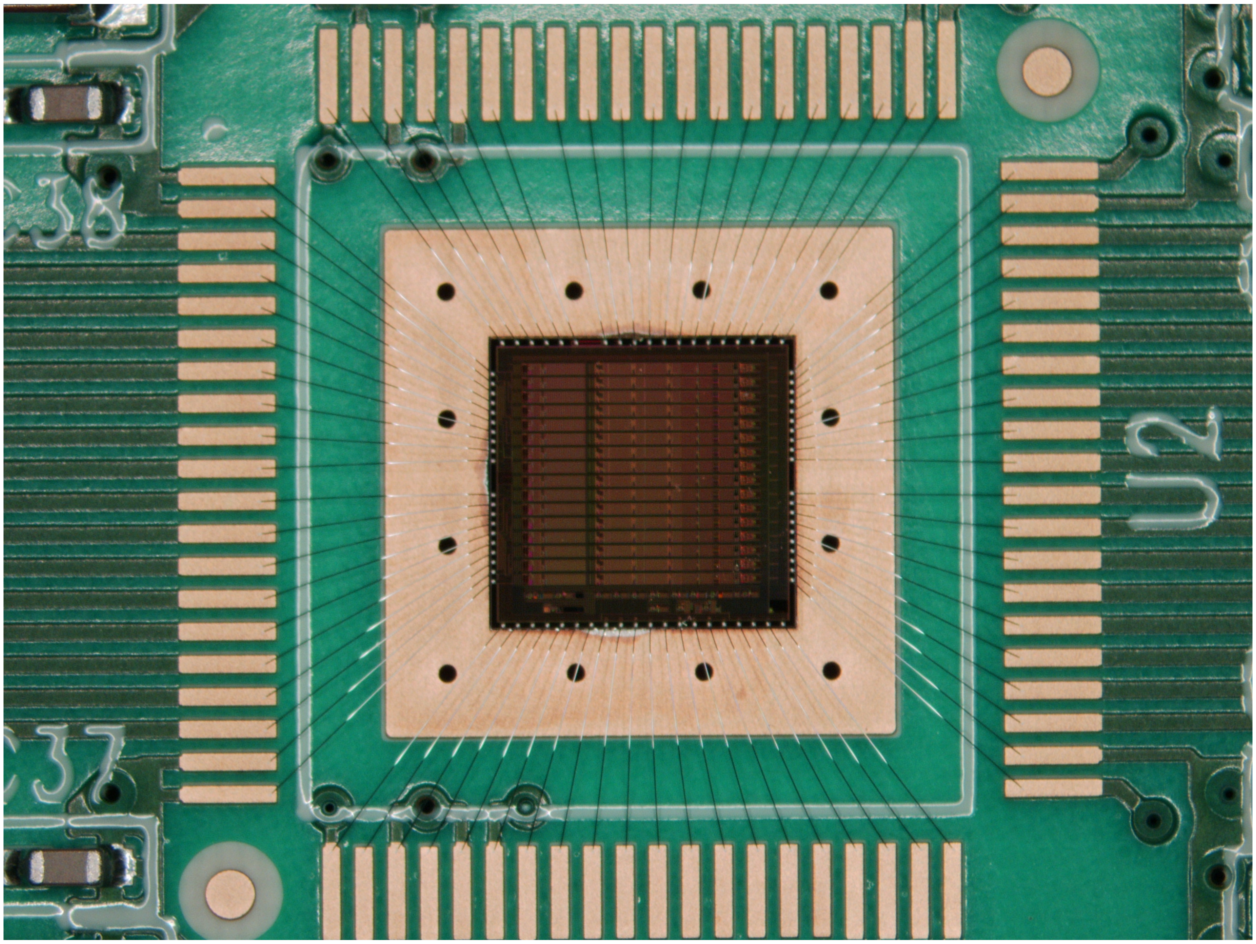


Figure 38: The 5.7×6 mm^2 LArASIC pictured above is designed for wire readout of liquid argon TPCs. It is designed for use between temperatures of 77 and 300 K and houses 16 channels of a low-noise charge amplifier, analog filter and output driver. It measures both charge and time sending its analog outputs to a custom ADC. LArASIC has been used in the 8200 channel MicroBooNE detector with excellent signal to noise and stability results, and is currently being optimized for use in the Deep Underground Neutrino Experiment (DUNE). The liquid argon 87 K (-186 C) operational temperature requirement is well below the lower limit of 233 K (-40 C) of the manufacturer provided simulation models.

Extreme Radiation Environments In order to support the next generation of hadron colliders we must have predictive models that help assess and support operation during the lifetime of an experiment where the electronics will accumulate a dose of up to 300 MGy and 10^{18} neutrons/cm^2. The growing data rate and radiation requirements of progressive upgrades to and new collider experiments (HL-LHC experiments' inner layer pixel detector replacement, LHCb phase 2 upgrade, future lepton collider and finally a future hadron collider) can be addressed by the corresponding anticipated access to smaller feature technology nodes, from 65 nm in use today to 28 nm and beyond.

Thrust 1: Develop models, standard cell libraries, and demonstrators for extreme rate and radiation (TID >10MGy)

ASIC design for particle physics will continue to apply technology well outside the commercially specified operating conditions. In fact, designs for the inner layer pixel detectors at the LHC ideally require 1 10MGy survivability but the technology with the smallest feature size currently available to the field, 65 nm, can only withstand radiation doses up to 3 MGy (see Figure 39).

The success of the FEI4 pixel readout chip depended on a collaboration primarily between ATLAS and CMS under a CERN research initiative (RD53). This kind of collaborative effort is a good model for the development of the highly complex integrated circuits that will be needed for future experiments.

Significant R&D effort is needed to explore radiation sensitivity of smaller node technologies (e.g. 28 nm) for detector applications within a time frame of 5-10 years. There is potential for collaboration with other fields that have similar challenges such as the stockpile stewardship, nuclear fuel cycle, and deep space exploration.

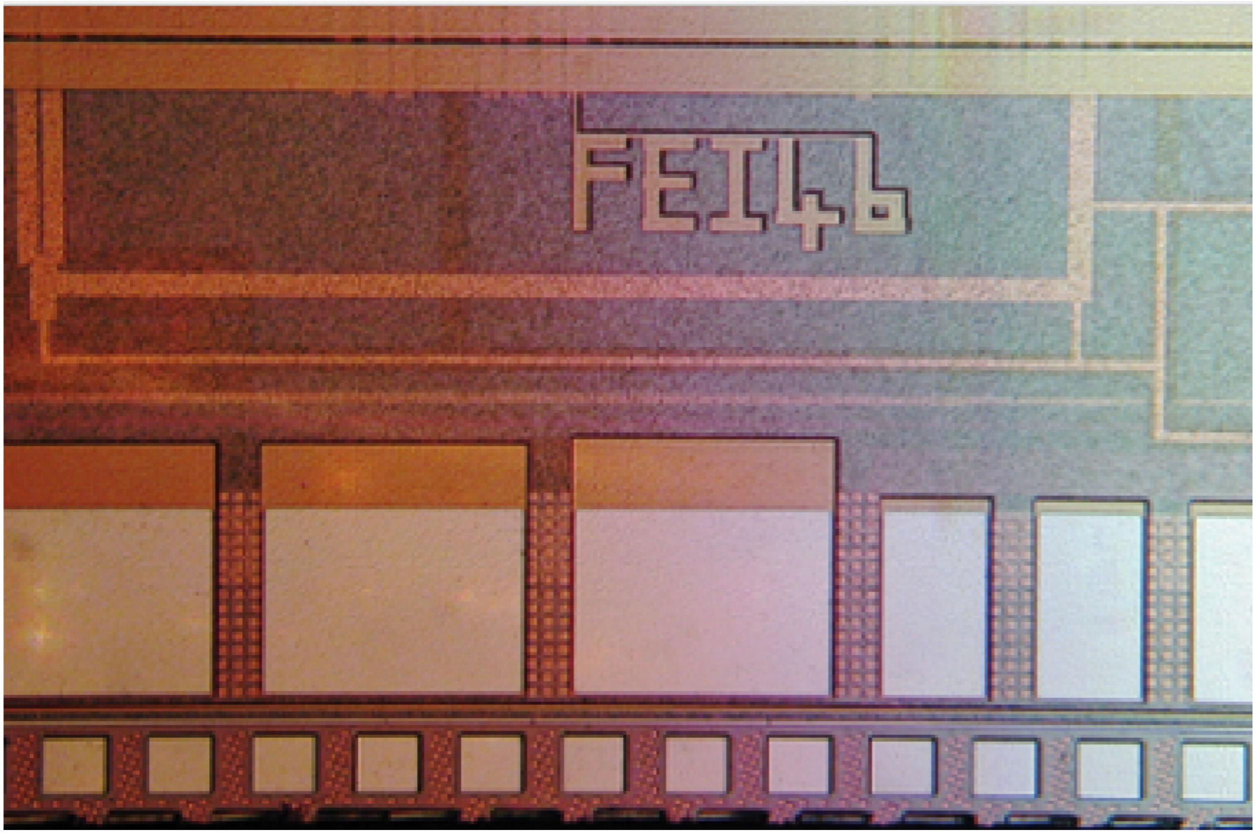


Figure 39: The FE-I4 chip designed in a 65 nm CMOS process represents a 2^{nd} generation significant advance for silicon pixel detector readout. This ASIC contains 100M transistors and requires 800 mW power to readout 26,880 pixels bump bonded to its underside. It is optimized to be directly mounted on a pixel detector with a 50×250 μm^2 pitch. The time-of-threshold crossing is accurate to 25 ns (one beam crossing) for each pixel channel and has an ENC of 400 e^-. A 4-bit charge resolution is recorded and used to correct for time walk. An important design issue has been the requirement to have as high as possible ionizing radiation tolerance. FEI4 reliably achieves 3 MGy which is about 1/3 of the expected 10 MGy exposure expected for the inner pixel layers of the two upgraded LHC detectors.

Fast timing is a rapidly developing new direction for HEP detector instrumentation that provides an independent dimension to particle tracking and calorimetry. Significant R&D is still needed to achieve the required picosecond timing resolution, while at the same time meeting size and power constraints. R&D areas of interest within this topic are:

- Low-power CMOS, bi-CMOS readout technology
- Low-power circuit techniques for timing extraction
- Novel pixel based highly segmented readout architectures for position and timing extraction

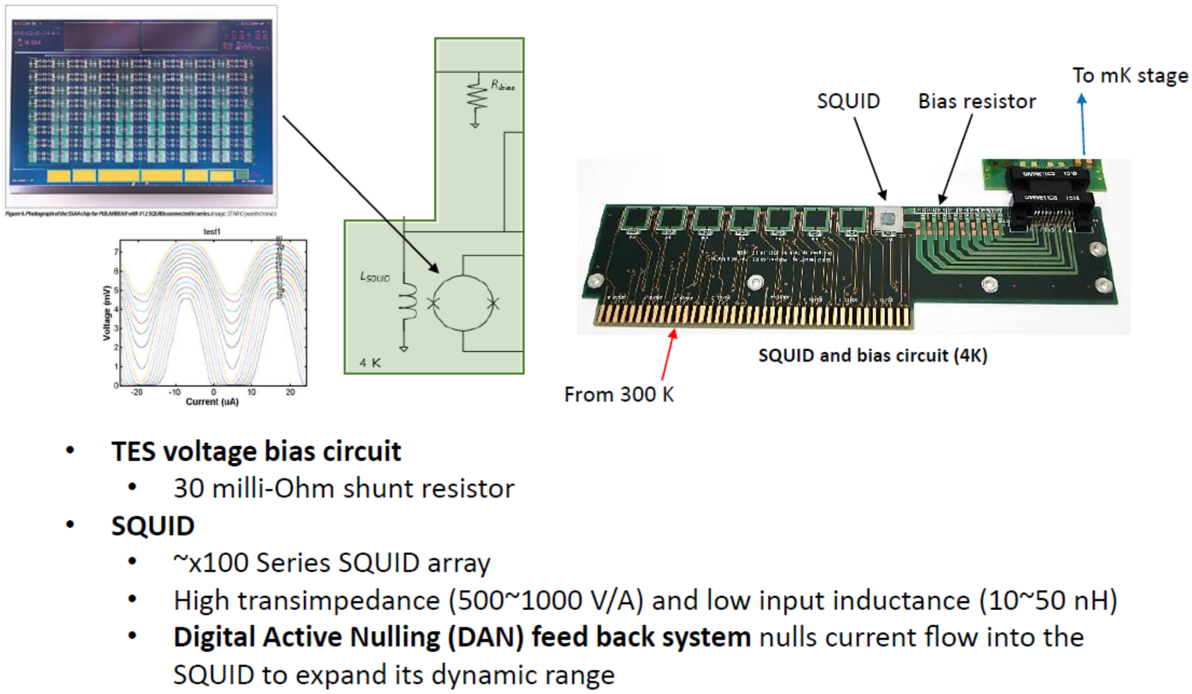


Figure 40: This figure, showing today's typical 4 K electronics for bolometer readout, is reminiscent of the electronics boards from the 1990's discussed in the introduction with many separate functions on several printed circuit boards reading out hundreds of channels. As the astrophysics community looks to gear up to instrument more than 100,000 channels in an arrayed detector it will be necessary to turn to integration of functionalities on smaller substrates to keep the power low, the channel density high and the number of I/O cables to a minimum. CMOS amplifier readouts instead of SQUIDs, and high levels of multiplexing on CMOS switches, offer promise to do this in future astronomical detector systems.

Thrust 2: Develop models, standard cell libraries, and demonstrators for intermediate cryogenic range

Important progress is being made on low-power immersed Noble Liquid cold electronics. Systems designed for these environments, 103 K (-170 C) and lower, need good transistor models that are not available from ASIC manufacturers and need quality assurance to guarantee reliable performance over the decadal lifetime of an underground experiment. Future experiments will require increased sensitivity, granularity, digitization speed and a SoC approach to minimize radioactive material background. A second significant issue is the high reliability, low-power data acquisition communications, i.e. ASIC-to-ASIC, board-to-board and sub-detector-to-warm DAQ. Support should be given to developments that result in deployment of moderate sized readouts in Noble Liquid detectors. This will develop the relevant experience necessary to mature readout designs that will need to be sustained for the lifetime of large underground experiments.

Thrust 3: Develop models, standard cell libraries, and demonstrators for quantum sensor controls and data acquisition for the deep cryogenic range

Suitable IC fabrication processes need to be investigated and identified for use at 4 K and below. For these processes, transistor models and standard cell library elements need to be evaluated at low temperature and then the extracted parameters fed back into the design tools. Strong motivation for doing this is the need to increase channel counts by several orders of magnitude for bolometer-based readout and other applications (see Figure 40).

Thrust 4: Investigate emerging design and verification methodologies

The increasing complexity of ASIC technology and the move towards SoC solutions are universal issues not limited to high energy physics. Consequently, industry, academia, and other government agencies are working on design flows with higher levels of abstraction and reduction of human effort. For example, the DARPA Intelligent Design of Electronic Assets program [264] seeks to reduce the time from schematic or hardware description code to design to just 24 hours (typical time for this step in HEP projects is presently measured in months). Another example is the Berkeley Analog Generator [265], which attempts to automate the analog schematic design and layout process. Clearly, it is critical to evaluate the suitability of such design methodologies for HEP requirements, as they become available.

1. Investigate CMOS with integrated photonics nodes when commercially available

   The presently used data link architecture in which front-end ASICs communicate electrically to optical converters does not scale to data rates needed in the future. For the HL-LHC this architecture will handle 1 Gbps/cm^2 of front-end output, while 10 Gbps/cm^2 is projected by future hadron collider requirements. Projected improvements in both channel bandwidth and on-chip data compression will fall short by a factor of two, even before considering the need to reduce mass. New architectures will need to be explored to solve this problem. In terms of ASIC technology, industry predicts that photonics will be integrated with CMOS processes within 5 to 10 years. We expect to explore this technology for radiation hard ASIC design applications in a 10-15 year time frame.

2. Investigate processes with Internet of Things (IoT) technology to enable self-assembly or assembly-free very large-scale detectors

   Assembly and integration costs limit the scale of high granularity neutrino experiments. Emerging technologies such as smart dust, power scavenging, distributed networks, positioning, etc. could enable much lower cost per unit volume for high granularity detectors. Commercial ASIC technology underlying such potential developments may become available on a 10 year timescale and should be investigated for compatibility with precision measurements and cryogenic operation, for example.

3. Adopt Artificial Intelligence (AI) and Machine Learning (ML) techniques

   AI and ML systems are already changing the way large data sets are interpreted, increasing the potential for discovery of current experiments. Currently, sequential processors (requiring multi-GHz clocks) and general purpose new generation FPGAs are the main vehicles for implementing such type of systems with some inherent limitations. We can expect ML and AI to have a more powerful impact when these systems will operate *in-situ* or on-hardware units optimally designed to implement neural networks, neuromorphic processing and asynchronous techniques. Two directions are distinguishable. First, the study and development of ML programmable ASICs (FPGA-like) with architectures optimized for solving high energy physics-related problems such as in-hardware implemented teaching methodologies, weights calculation and back propagation, and algorithm implementation. Second, on-detector electronics capable of extracting high level abstract information from the received signals. This can be achieved through the interplay of in-hardware simultaneous multi-channel processing, resulting in a transformation of data into physics information.

Research Plan

It is necessary for the HEP community to invest in evaluating commercial ASIC processes to understand how to exploit these technologies in HEP-relevant applications and environments. To ensure reliable, long-term operation for electronics immersed in noble liquid detectors (100 K), we need to develop temperature specific models and specialized standard cell libraries for digital electronics that eliminate lifetime-limiting damage arising from cold temperature induced electron impact ionization. These temperatures are far from the manufacturer's lowest guaranteed operating range of $\sim$230 K that serves their commercial base. Similarly, in the deep cryogenic region at 4 K and below where TES, MKID, KID and Nanowire detectors operate, quantum effects need to be characterized if CMOS processes are to be exploited. Deep cryogenic CMOS development is highly synergistic with Quantum Information Science R&D seeking to control large numbers of qubits with manageable connections to warm electronics. Significant R&D is needed before new nodes, 28 nm and beyond, are understood in enough detail to design the higher performance radiation-hard or cryogenic ASICs high energy physics will need to develop over the next decade and beyond.

4.5.3 PRD 17: Create building blocks for Systems-on-Chip for extreme environments

The development of Systems-on-Chip is essential to cope with the increasing complexity and the ability to add new required functionalities. A series of critical blocks and techniques for HEP-specific needs are identified and need to be developed to constitute a good platform for the design of complex sensing and readout electronics.

Thrust 1: Develop advanced low power high speed I/O protocols

- High speed data transmission interfaces copper links and encoding. Within a few years of the start of the HL-LHC running, the inner layers of the CMS and ATLAS pixel trackers will need replacement due to the extreme radiation environment they will operate in. This will offer a near-term opportunity to implement data transmission technologies to significantly improve the bandwidth of communication links of these layers presently limited to about 0.5Gbps. Bandwidth improvements in cables and potential radiation tolerant ASIC technology (such as PAM4) make it possible to consider 5X improvement in data transmission over copper links to areas of the detector where radiation levels are low enough to allow a switch to sufficiently radiation tolerant 10 Gbps optical links presently under development to carry the data to the readout areas.
- Silicon Photonics - Optical transmission standards in industry are very advanced, now getting to 400 Gbps links. There is a large "impedance mismatch" between industry and high energy physics needs. In addition to radiation tolerance and low mass, HEP data sources in a detector are not concentrated at one point, as suitable for very high speed links, but distributed over cubic meters of volume. Adaptation of silicon photonics technology, such as wavelength division multiplexing, is needed to meet HEP needs. Such out of the mainstream use cases could in turn meet niche commercial application needs.

Thrust 2: Develop wireless blocks beginning with control and monitoring

Wireless communication is a mature technology that is not yet exploited in HEP detectors but would be transformative. Bluetooth, as an example, is already ubiquitous in the Internet of Things. Instrumentation and technology currently exists in IC form using chip antennas. A simplified adaptation for slow control and monitoring applications in HEP would serve to un-clutter high speed physics data communications and could be a stepping stone to next uses where trigger or other event related data could be transmitted independent of a wired control path.

Thrust 3: Develop power management blocks (DC/DC converters, regulators, pulsed power)

As ASIC technologies have moved towards smaller feature sizes the channel count has increased and both analog signal and digital processing have become increasingly complex. An important side effect of this decrease in feature size is that supply voltages have been getting lower and current requirements have been significantly increasing while the power density remains nearly the same. In order to also minimize the material budget (higher current requires more copper to route voltages to the ASICs), experiments have turned increasingly to DC/DC conversion, often locating DC/DC converters on the same board as the front-end electronics. This allows designers to provide input power with 10X the voltage that ASICs on the front-end boards require reducing the cross section of copper supply lines by the same fraction - a huge win in material reduction. While there have been a few attempts to put DC/DC conversion on the front-end

ASIC, so far none has been successfully implemented in an experiment. Meanwhile the microelectronics community has published successful on-chip DC/DC conversion techniques since the turn of the century.
Power reduction can also be accomplished by topological partitioning of logic functions on SoC designs leading to the ability to maintain blocks that are not in use at safe dormant power levels by gating the clock and potentially lowering the supply voltage until those functions are required. Since many SoC functions will be generic, parametrically described blocks could be defined in advance to drive silicon compilers to create these custom regional blocks for new designs.
For experiments with low repetition rates, such as electron colliders, power could be maintained at reduced levels between beam spills allowing much higher current to be utilized during data taking without requiring the accompanying massive cable plant and related material burden for cooling that 100% duty cycle machines require for similar operating conditions.

Thrust 4: Circuit development for monolithic designs with integrated sensor and readout (MAPS, SPADs, SiPM)

- Standalone and 3D-integrated MAPS: Monolithic Active Pixel Sensor (MAPS) technology is an enabling technology for tracking systems at future colliders. For electron colliders, stringent material requirements and segmentation lend themselves to a monolithic solution for the sensing element and readout ASIC. For future hadron colliders, the size of the planned trackers (500 m^2) and tracking calorimeters (5000 m^2), the desired resolutions and material thickness makes MAPS an economically and technically viable choice. MAPS in high resistivity with drift-assisted charge collection, for example, could also provide picosecond timing capability.
- Standalone and 3D-integration of Single Photon Avalanche Diodes (SPADs) and Silicon PhotoMultipliers (SiPMs): Future photodetector applications will require higher segmentation and improved timing resolution. Integration of the sensor and readout in monolithic or hybrid form will be required to meet these goals. As we look to extract improved physics measurements in noble liquid detectors, optimized performance of cryogenic silicon photodetectors and readouts, operated in conjunction with ionization signal readouts, will offer important triggering and data filtering advantages. Consortia interested pursuing these opportunities should be encouraged with calls for the development of these multi-dimensional inputs.

Thrust 5: Develop Single Event Effect flows and techniques relevant for new technologies

Single Event Effects (SEE) include:

- Single Event Upset (SEU): The unintended change of state of a register or latch or mode of operation due to the collection of ionization causing a bit flip or logic transition.
- Single Event Transient (SET): The hard, unintended change of state of a transient nature, often classified as a glitch, on a system clock line or lines, causing a progression of a sequential circuit or its part through its functional steps, leading to corruption of state machines, executing unintended operational sequences and corrupting data flows.
- Single Event Latch up (SEL): The hard, potentially destructive error usually requiring a power cycle or major reset to clear.
- Single Event Burnout (SEB): The circuit failure caused by a destructive latch-up or similar effect that causes a permanent circuit failure.

SEUs may be mitigated in a variety of ways, the most common being triplication of the circuit (usually latch or register) with each part placed a safe distance from the other and the addition of a voting circuit requiring a majority (2 of 3) to change the logic state. This is most conveniently handled by special routines that control the synthesis and layout of digital circuitry, the synthesis flow. In all cases, the required mitigation technique needs to be validated by exposing fabricated circuits to the appropriate levels and types of radiation and measuring their response. A radiation-optimized coherent design flow applicable to the targeted technologies for future experiments is required and needs to be validated via experimental tests.

Both SEL and SEB can be mitigated with automated tools by adding rules and using the manufacturer's Design Rule Checking (DRC) software. SETs are caused by generation of charge due to impacting charged particles on the nodes of clock buffers, reset lines, etc. These effects are least studied and do not have efficient prevention methods. Techniques like clock triplication are used in some ASICs developed in the community, but structural methodologies implemented in CAD/EDA tools are not mature. Triplication of clocks requires new methodologies for distribution of clock trees and clock domain management. As we engage these new ideas it will need to be understood that techniques like clock triplication are resource hungry in both silicon area and power. Along with implementation techniques, guidelines should be developed to prioritize their application.

Thrust 6: Develop analog and multiplexing blocks for 4 K environments and below

A wide range of QIS systems and high sensitivity detectors operate at cryogenic temperatures, ranging from a few milli-Kelvin to LHe (4 K) temperatures. Some of the components of these systems need to be superconducting, but others can be resistive. In most existing systems, the resistive component control is often performed by warm electronics through interconnect cables. In many cases a large number of interconnect cables are required, increasing heat loss and adding complexity and cost. Developing semiconductor devices capable of operating at these temperatures would allow a large reduction in system cabling and heat leaks. Useful device types include analog switches, digital logic, and amplifiers from low frequency to RF up-converters.

Thrust 7: Develop fault-tolerant communications for long-lifetime inaccessible readout systems

In many applications, ASICs and associated boards become inaccessible after installation. The downloading of control registers and readout of status often require dedicated communication pathways. Communication paths to these ASICs must employ fault-tolerant techniques such as multi-path repairable connections that can omit specific ASICs or ASIC paths that fail. Common protocols for single or multi-drop communications would simplify system design.

Thrust 8: Develop precision clock and timing circuits (PLL, DLL, Timing Discriminators, Delay Lines, Picosecond TDCs)

Timing information is an essential tool in background reduction techniques in HEP experiments. Future experiments will require 4D or 5D detectors capable of time resolution in the picosecond range. Circuit blocks for precision timing generation such as Phase-Locked Loops (PLL), Delay-Locked Loops (DLL), Timing Discriminators and Time to Digital Converters (TDCs) that operate with low power in extreme environments need to be developed in suitable technologies. To synchronize operation precision clock distribution strategies need to be investigated and optimized for precision timing SoCs.

Thrust 9: Develop multi-channel RF digitizers

Future large-scale neutrino experiments will require ASICs to operate in extreme conditions. In ultra-high energy neutrino studies fast digitization in extreme conditions at low power will be required. Analog-to-digital converters (ADCs) are one of the foundational building blocks for these systems. As experiments move to higher granularity and higher sampling frequencies, the power consumption of ADCs can become a limiting factor. Multi-channel ADCs with at least ten times better power efficiency than the current state of the art commercial off-the-shelf components (<1 W) at RF sampling rates (>3 GHz) will need to be developed.

Research Plan

In order to streamline the design of future extreme-environment ASICs, it will be necessary to develop a set of functional building blocks, possibly accessible to research groups, that can address common design areas such as I/O, high speed data transmission, and core analog and digital functions. Generally required blocks include but are not limited to: power management (pulsed-power regulators, DC/DC converters and intelligent clock gating techniques), advanced high-bandwidth I/O protocols, wireless blocks for control and monitoring, fault-tolerant communication blocks, precision clock and timing circuits (PLL, DLL, Timing Discriminators, delay lines, and TDC's). Future designs will likely also require correlator blocks that combine information from multiple detector elements to send out abstracted track and other information. The Silicon Strip ASIC (SSA) for the CMS experiment (see Figure 41) is an early example. It combines a 120 channel silicon strip readout with a correlator block. This block utilises cluster information from the silicon strips it is connected to and correlates it with data from a silicon pixel layer located on the same module to report out abstracted track segment information rather than simply cluster data. This significantly reduces the I/O bandwidth off-detector and the computing required downstream providing for a much lower latency. These correlation functions are likely to be similar for future detectors and may easily lend themselves to parametrically driven code designed for use with silicon compilers that will greatly reduce the design and prototyping effort required to add functions to an ASIC with access to multiple tracking layers.

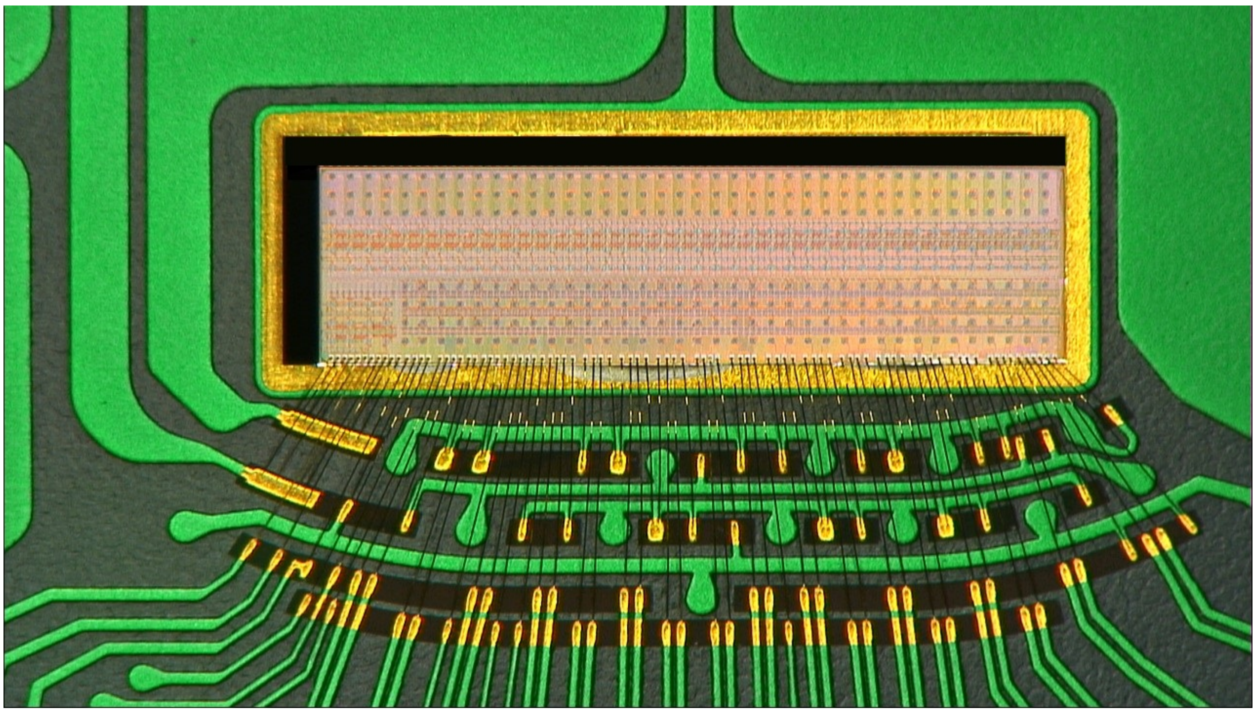


Figure 41: A photograph of the Silicon Strip ASIC (SSA), which provides signal processing for 120 silicon strips and combines its hit cluster information with the Macro Pixel ASIC to generate hit cluster coordinates for a combined pixel-strip module readout of the CMS outer tracker in real time. It has a maximum trigger rate of 1 MHz and readout latency of 12.8 μs. The SSA is fabricated in 65 nm CMOS and has a radiation tolerance of 200 MRad with a 330 e^- ENC and power requirement of 60 mW.

Providing designers with access to silicon proven versions of these critical blocks will be cost-effective, eliminating avoidable mistakes and allowing designers to focus their efforts on the unique areas of their designs while reducing the amount of funding required for new designs and speeding up the design cycle.

4.5.4 Connections outside HEP

ASICs are being used in many disciplines other than particle physics. Instrumentation for Basic Energy Sciences and NASA already uses several of the ASIC designs from HEP. There are many interfaces with other agencies that have complementary expertise. For example, the stockpile stewardship has stringent requirements on radiation hardness and share in the difficulties of foundry access and workforce development. There are very clear opportunities of these disparate communities to collaborate. Efforts to better leverage and improve the coordination between groups and collaborations would be beneficial for HEP and other scientific instrumentation communities.

4.5.5 Facilities and Workforce

Foundry access, including design tools and third party intellectual property, is essential for ASIC development but difficult to access in the U.S. There are legal hurdles to signing non-disclosure agreements for access to foundry processes, especially in a collaborative way. Lincoln Laboratories and Sandia, for example, provide in-house foundry capabilities in technologies that are suitable for many particle physics applications. Utilization of these facilities should be explored by the HEP community. Access to advanced nodes can be provided through multi-project wafer organizations such as Europractice, MOSIS and TAPO. These organizations provide access to large foundries, like TSMC and Global Foundries. Coordination for radiation-hard nodes between NNSA and HEP is highly desirable to ensure long-term access to special technologies. The intrinsic international and collaborative nature of HEP developments should be taken into account when considering technologies with limited use capability.

While there are significant challenges in maintaining high energy physics expertise long-term within a workforce that is only partly supported by HEP, and within HEP has only project-based support, there are also opportunities. Collaborative efforts with other sponsors would alleviate some of these issues and be mutually beneficial. This would also address the challenge in developing and maintaining IC literacy within the next generations of researchers, as IC designs become more complex. We must draw on a diverse group in developing this pool of researchers to deepen the expertise and talent in the workforce. It is essential to drive IC design to meet the science needs.

The above mentioned challenges could be addressed through HEP or cross-program collaborative efforts and consortia.

Within HEP, there is an exchange of information through the HEPIC activity of the Coordinating Panel for Advanced Detectors (CPAD). This kind of forum can be used for shared multi-institution IC fab technology access: a model similar to the CERN's well known and successful frame contracts with commercial IC foundries.

In order to collaborate on, develop and supply state of the art ASIC designs to the experimental HEP community it is crucial that we have shared access to ASIC processes through negotiated multi-institution NDAs. An improved relationship with CAD providers that enable U.S. collaborations to be on par with European counterparts, who have mutual access to design kits and process support through Europractice, would be most advantageous.

4.5.6 Readout and ASICs and the Grand Challenges

The PRDs and research plans described in this section seek to develop readout and ASICs concepts, design, and development models to advance detectors and more broadly instrumentation for HEP. The development of building blocks for complex integrated readouts (SoC) with particular focus on extreme environments will enable new regimes of sensitivity corresponding to Grand Challenge 1, and contribute to the management of high data rates in HEP experiments corresponding to Grand Challenge 4. New process technology will further improve the level of functionality that can be integrated in HEP sensors corresponding to Grand Challenge 2. The next generation of readout electronics will surely exploit ASIC technology to transform novel sensor signals into digital formats suitable for manipulations by new and more conventional techniques corresponding to Grand Challenge 3. To cope with issues of scale (sensor granularity, coverage and channel count) advanced techniques for electronics design and manufacturing will also likely need to be developed for next-generation HEP detectors also corresponding to Grand Challenge 3.

4.6 Solid State and Tracking

4.6.1 Introduction

Solid state tracking detectors play a key role in the future physics program for both Energy and Intensity Frontier experiments and facilities. For a hadron collider the requirements are driven by a possible future HE-LHC [266] or 100 TeV FCC-hh machine [27], and informed by the experience of the recent HL-LHC upgrades [267, 268]. For a lepton collider, the R&D for an ILC [28] or other mid-hundred GeV facility such as FCC-ee [269], CLIC [270] or CEPC [271] is the reference point. For experiments which explore the unknown the requirements are similar to those of future collider experiments. In all cases, all-solid state systems have been considered as either required (hadron collider) or a strong option (electron collider and others). There are significant commonalities which span a broad technological range. The key differences are the more stringent speed and radiation hardness required for hadron colliders, and, while both machine options require low mass, high resolution trackers, this requirement may be more stringent for electron machines.

We note that the Micro Pattern Gas Detector (MPGD) is another important tracking technology. Since its invention in 1988 an extensive and very successful R&D program has been executed. This program has been concentrated in Europe, with only a very small involvement from U.S. groups and this situation shows no signs of changing. Accordingly, since the MPGD is not a priority of the U.S. community, PRDs and research plans have not been developed for MPGDs in this report.

Operating Principles The ideal tracking detector would register the passage of an ionizing particle with sufficient signal to noise ratio and resolution, and have a negligible effect on its trajectory, to meet physics performance requirements. Gas filled detectors attempt to achieve this goal using high electric fields, avalanche multiplication, and drift. These lead to well known limitations in position resolution, and stability. For precision tracking, where occupancy requirements are greater, the solid state detector is chosen, which, through higher density, avoids the need for high gain while still achieving relatively low mass and extremely high segmentation through modern microlithography. Solid state detectors can, under appropriate conditions, act like solid ionization chambers, collecting electron-hole pairs. The primary ionization will be collected by drift or diffusion. In the case of drift, an electric field must be present in the ionized bulk. Such a field will be present within the depletion zone of a diode or within insulators, some of which also support drift.

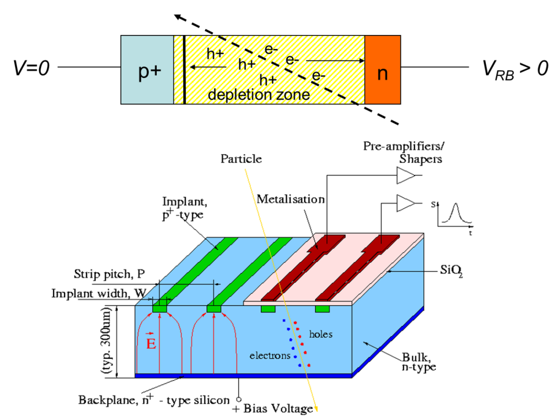


Figure 42: Top: The charge collection mechanism in a reverse-biased silicon diode: electron-hole pairs created by the energy deposited in the sensor drift in the electric field produced by the reverse bias applied across the bulk. Bottom: schematic of the operation of a silicon microstrip detector, where the diode segmentation allows to reconstruct the position of the ionizing event [272].

While there exist a large variety of solid state tracking detectors, the most basic and iconic example is the silicon microstrip. This device is based upon the properties of a reverse biased PN junction shown in Figure 42 (top). With sufficient bias voltage applied, the natural depletion zone can be extended well into the bulk, creating a region with a drift field. Electron-hole pairs, created in the process of primary ionization, will drift in the field inducing currents in nearby electrodes, which may be sensed, amplified, and read out. With sufficient segmentation, and proper low noise electronics, this simple device is generalized to a powerful position sensitive array shown in Figure 42 (bottom). Many variations on this concept have emerged utilizing specific segmentation approaches, additional biasing and signal processing structures, enhanced radiation resistance, and alternative materials. In particular, Figure 43 shows a device that allows equal spatial resolution in two dimensions, the pixel silicon sensor. Here the electronics is either bump-bonded on top of the sensor or integrated in the sensor

Figure 43: Example of a hybrid pixel detector: the silicon sensor is connected to the readout electronics fabricated on a silicon wafer via “bump-bonds” that connect the sensor electrodes to the inputs of the sensor. This structure allows for comparable resolution in two dimensions. Here the TIMEPIX3 cell is shown [273], it features a square pixel size of 55×55 μm.

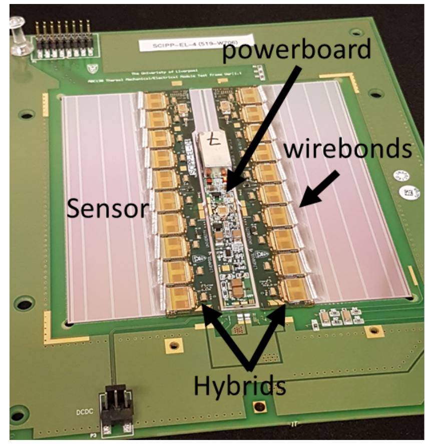


Figure 44: Example of a silicon microstrip detector module featuring $\sim$ 5000 channels. The module includes the silicon microstrip sensor, the readout front-end electronics ASIC, and support circuits providing power regulation, experiment control, and monitoring.

element itself. This type of device has become ubiquitous. And solid state sensors have been embedded in complex and highly engineered systems (an example is given in Figure 44). It is these generalizations and new approaches which form the basis of further research and development in the area of solid state tracking detectors.

Historical Context Solid state tracking technology has a history going back to the 1970s when first adapted from high resolution nuclear spectroscopy systems with just a few channels of low noise readout electronics [274]. Through the intervening decades there has been a steady increase in the scale of this technology resulting in today's systems featuring about 10^8 channels. This growth has been punctuated by both transformative and incremental developments or improvements. This history allows us to place future directions in an informed context. To be specific, a transformative development is one which enables a scientific application which would otherwise be impossible. Alternatively, an incremental one clearly builds, and improves upon, an existing capability. When viewed with this lens we can already identify some key elements:

- Both the silicon microstrip detector, introduced in the 1970s, and the use of application specific integrated circuits (ASICs), beginning in the 1980s, were transformative [275]. They opened the possibility of precision tracking with solid state detector systems. This led to the direct observation of heavy quark decays in fixed target experiments, and later to numerous applications in lepton and hadron colliders. Both the discovery of the top quark, and a diverse program of precision b-physics were the direct consequence of these developments.
- The radiation hard hybrid pixel detector [276], demonstrated in the 1990s was transformative. It enabled silicon to be placed close to the beam line at the Large Hadron Collider and led to the discovery of the Higgs particle.
- The application of carbon composite materials [277] and the development of CO_2 evaporative cooling [278] was transformative. It enabled large precision systems to be built with relatively low mass at colliders.

Taking the basic constraints and characteristics of the aforementioned future facilities, and the detector performance requirements articulated by the future Energy and Intensity program physics studies, the following challenges are being confronted:

PRD	Thrust	TR
PRD 18: Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments	Thrust 1: Lepton colliders, requiring timing on the order of 10 ps; pixel pitch on the order of 10 microns Thrust 2: Hadron colliders, requiring timing resolution down to 1 ps to achieve HL-LHC-like pileup, in a high radiation environment (up to fluences in the order of $10^{18} n_{eq}/cm^2$)	TR 1.1, TR 1.2, TR 5.1, TR 5.4, TR 5.9
PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	Thrust 1: Adapting non-silicon and novel-configuration sensors (diamond, large-bandgap semiconductors, thin film materials, nanotechnology, 3D sensors, new emerging materials) with new industrial partnerships Thrust 2: Development of readout electronics matched to new sensor characteristics, including new processing such as 3D-integration	TR 1.1, TR 1.2, TR 5.9, TR 5.13, TR 5.14
PRD 20: Realize scalable, irreducible-mass trackers	Thrust 1: Highly integrated monolithic, active sensors Thrust 2: Scaling of low-mass detector system Thrust 3: Systems for special applications: space-based tracking detectors, and dedicated searches for rare processes and dark matter	TR 1.1, TR 1.2, TR 3.46, TR 5.4, TR 5.9, TR 5.14

Table 20: Summary of solid state tracking Priority Research Directions (PRDs) and Thrusts and corresponding Technical Requirements (TRs).

- How can we achieve the granularity, speed, and pileup rejection needed to function in a collider with the luminosity required in future applications (up to $\mathcal{L} = 3 \times 10^{35}\text{cm}^2 s^{-1}$)?
- What new materials could exhibit the necessary radiation resistance (fluence of $10^{18} n_{eq}/cm^2$)? (The damage effect caused by a fluence of particles of a given species and given energy spectrum may be expressed in terms of n_{eq}, the damage caused by a 1 MeV equivalent neutron fluence.)
- How can we achieve high resolution, low mass, reliability, and cost effectiveness in large systems requiring increasingly greater precision and stability?
- How can we maintain the perspective of a full system and remain cognizant that it is the integrated performance, and the optimization of many technical aspects, which results in a successful tracker, rather than a bench-top demonstration of component performance?

These challenges, and the perspective of past developments, lead to the transformative PRDs for solid state tracking. Table 20 gives a brief summary of the proposed PRDs, the main Thrusts, and the Technical Requirements driven by specific physics goals described in Section 3.1.

4.6.2 PRD 18: Develop high spatial resolution pixel detectors with high per-pixel time resolution to resolve individual interactions in high-collision-density environments

The Energy and Intensity Frontier physics studies identified small-pitch pixels, each with fast time resolution as a performance target. There are two Thrusts, both requiring specific sensor and electronics developments:

Thrust 1: Lepton colliders, requiring timing on the order of 10 ps; pixel pitch on the order of 10 microns

Thrust 2: Hadron colliders, requiring timing resolution down to 1 ps to mitigate HL-LHC-like pileup, in a high radiation environment (up to fluences of $10^{18} n_{eq}/cm^2$)

In the present decade a technological innovation occurred with the introduction of high granularity ($\sim$1mm^2), low gain, avalanche based, solid state timing detectors (LGADs) [279] and 3D silicon sensors [280], which achieve timing resolution of some 10's of picoseconds LGADs, are already being applied to LHC detector upgrades to suppress pileup at high luminosity [281, 282]. The present generation of LGADs are limited to relatively large cell size, due to inefficient charge collection around pad edges, and existing readout electronics. Furthermore, large systems of either technology are yet to be designed or demonstrated. A transformative development, aimed at future colliders, would be to achieve both high spatial and timing resolution, in a fine-pitch pixel geometry. Furthermore, these technologies must achieve the required radiation resistance at future hadron colliders and must be read out by adequate front-end electronics.

Research Plan

A major limitation of current LGAD technology for future application in hadron colliders is radiation tolerance, as performance is significantly affected at fluences beyond $2 \times 10^{15} n_{eq}/cm^2$, due to loss of gain. The 3D pixel sensor technology, that is, for example, used in the ATLAS IBL inner tracker layer, has been proven to be radiation hard up to $3{\times}10^{16} n_{eq}/cm^2$ [283]. While preliminary results indicate timing performance of 30 ps in both cases [284–286], radiation resistance remains an important challenge. Specifically for applications in very high radiation environment, fast-timing with silicon will be challenging, and the development of timing detectors to withstand fluences up to $10^{18} n_{eq}/cm^2$ will be transformative. The R&D program will need to study radiation induced degradation of the gain layer through acceptor removal as well as interactions with bulk damage effects. A combination of LGAD technology with a gain layer and the radiation-hard 3D silicon sensor technology, and new admixtures of doping elements hold promise to achieve this.

A transformative R&D program will also need to approach the study of these detectors in an integrated way as a single system, i.e. combined sensor and readout ASIC development and specialized cooling and mechanics. This R&D program should address the different challenges arising for different applications, i.e. low and high radiation environments. On the side of sensor development, AC-LGADs [286, 287] and trenches in LGADs should be pursued to remove interpad limitations and allow fine segmentation. A current example is shown in Figure 45. A major challenge for readout electronics needing systematic investigation is how to accommodate preamp, TDCs, and RAM in a small pixel pitch of the order of tens of microns, while maintaining power consumption not significantly greater than non-timing pixel ASICs (<1W/cm^2). This challenge can be tackled in several ways, for example with sub 65nm technology or novel ideas, e.g. 3D integrated ASIC architecture. The medium-to-long term exploration of a monolithic timing detector, that includes sensor and ASIC in the same silicon substrate, may lead to a game-changer. By eliminating the need for interconnections between the sensors and read-out electronics, it will not only reduce material budget, manufacturing and assembly costs, but will also improve manufacturing reliability of the assembly due to industrial scale fabrication process as well as time resolution by reducing parasitic capacitances associated with the connections of the hybrid systems.

4.6.3 PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking

As noted already, the many improvements which have occurred since the 1970s, in radiation hardened silicon sensors and readout electronics, have been significant. In some sense, however, we have survived, not by attenuating the effects of radiation, but in spite of them. We have learned to live with them at a cost. The cost has been in power, cooling, electronics, and ultimately mass and money. An example is the practice of operating silicon detectors at the relatively low temperatures required to slow, or control, the rate of radiation damage effects including leakage current and type inversion. This need has driven the

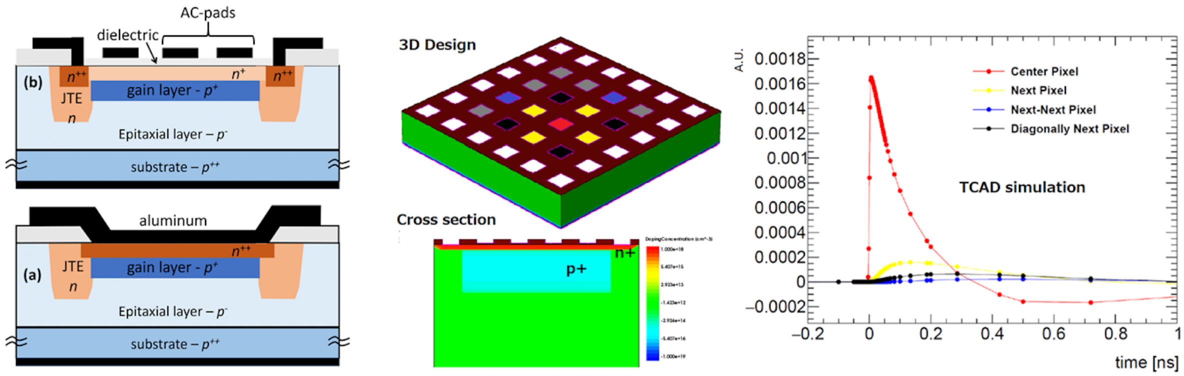


Figure 45: Low Gain Avalanche Diodes (bottom left) are the current best structure to provide both high spatial resolution and precise timing. To meet the challenges of future colliders, discussed here, increased segmentation is required and is being studied with the AC coupled LGAD structure (top left). Using simulation tools, a full 3D model (center) is studied here and can generate the time response to a MIP passing through the central (red) pixel (right).

development of special cooling systems and the use of novel materials. It is therefore fair to ask whether there could be a transformative development which would change the rules entirely? For example, are there materials or configurations with which we could operate near room temperature? Similarly, sensor mass reduction has been pursued mainly through wafer thinning. Could we integrate novel materials developed in nanotechnology or in special commercial applications in our detector design? Examples include thin film materials, organic semiconductors, and germanium. Some of these technologies and their applications are shown in Fig. 46. In this regard, a program to study and evaluate alternative materials to silicon and/or new processes or configurations could be transformative. To be scalable, it may be necessary to develop industrial partners, who can produce these materials in sufficient quantities. There are two Thrusts:

Thrust 1: Adapting non-silicon and novel-configuration sensors (diamond, large-bandgap semiconductors, thin film materials, nanotechnology, 3D sensors, new emerging materials) with new industrial partnerships

While breakthroughs such as room temperature operation would be transformative, the program already has significant precedent. For example, since the 1990s there has been an active program in diamond based sensors [288, 289]. In the 2000s, the revolutionary 3D silicon sensor was introduced [280]. And there have been modest efforts in alternative materials, such as SiC [290, 291], GaN [292], and BN [293]. But the bar is set very high. Silicon sensors and electronics are supported by one of the most highly developed technical industries ever.

Thrust 2: Development of readout electronics matched to new sensor characteristics, including new processing such as 3D-integration

For a new material or process to compete with the silicon pn diode it needs to be practical on the scale of a future tracking system and it has to be appropriately read out. So far, diamond [294–296] and 3D silicon sensors [283] have been applied only to limited coverage at small radius, and none of the exotic materials have yet found a significant niche in a physics application nor do they have a sizable industrial base yet. On the other hand, the development of new technologies which could allow “vertical 3D integration” of sensor, front-end electronics and data-processing elements utilizing novel interconnect techniques such as carbon nanotubes could allow the development of high-resolution low mass micro-pattern tracking systems. As in other applications, the use of new materials, must be considered also in a full system context covering sensors, front end electronics, power distribution, control, and thermal/mechanical management. We envision research efforts which may encompass a number of these in a coherent way.

Research Plan

To be more specific, the following areas could form the initial directions for a research program, but we must remain open to new ideas and new directions which may emerge in the future, listed in a non-ranked order:

1. Diamond: This has been an area of significant interest since the early 1990s [289]. The CERN based RD42 collaboration [289], with significant U.S. participation, has driven a steady improvement in the performance and capabilities of this material. For certain highly irradiated applications Diamond has been shown to exceed the performance of today's silicon pixel devices. But Diamond production capacity is still limited. The R&D question for far future applications is whether large scale, low-cost fabrication can be developed.

2. Large Band Gap Semiconductors: R&D has been ongoing to develop and demonstrate radiation sensitivity in a variety of these materials, including SiC, GaN, and BN. Now, more than ever, there is commercial potential in the high-power and high-temperature electronics sector. This is driven by growing markets including electric and hybrid vehicles, high efficiency batteries, solar power, long range drones, and electric trains and aircraft. If 15 years from now, sufficient industrial capacity and interest exists to serve the HEP market, that could be a significant new development.

3. Thin film materials: Thin films [297] are attractive in part because they rely on techniques developed for consumer electronics, with a solid industrial backing, and may eventually be cost effective. A number of semiconductor materials are available to construct thin, flexible detectors with integrated electronics with pixel sizes on the order of a few microns. The sensors are very thin (5-50 μm), and they allow integration of electronics with minimal radiation length. They might be used to create flexible-geometry trackers (e.g. a cylindrical sensor-electronics unit). A systematic R&D program would include an evaluation of best choice materials and processes, system issues, and radiation damage. Synergies may exist with certain large band gap materials, diamond, and germanium, which can be deposited. Similarly, new emerging nanomaterials and organics, or novel photonic materials may be relevant as well.

4. Nanotechnology: Long an emerging technology, and widely discussed as a basis for a new generation of active devices [298], there may be applications in radiation detection and signal transmission. Areas of interest include graphene and its application [299], organic semiconductors [300], and nanotube active devices and conductors [301].

5. 3D-fabricated silicon sensors and other alternative processes involving Micro-ElectroMechanical Systems (MEMs): The 3D configuration was a breakthrough for silicon sensors and has also been demonstrated for Diamond sensors [302]. In addition this technique may be used for applications where microchannels can be etched underneath integrated electronics substrates for cooling purposes, and to etch through silicon vias (TSV) in vertical sensor and electronics integration. Might this concept, or other variants, still to be found, applied to any of the materials discussed above, be a new breakthrough for large scale application?

4.6.4 PRD 20: Realize scalable, irreducible-mass trackers

The specific characteristics of a future linear or circular lepton collider suggest that dramatic reductions in detector mass may be required, as well as reduced pixel geometry. Aspects of this have been discussed for over ten years already and include pulsed power, gas cooling, and thinned monolithic sensors. As ultimately realized, this could represent a true mass-minimized, or irreducible-mass tracker, namely, a tracker whose mass budget is reduced to the active mass of the sensor, optimized for high resolution. Such a development would rely, more extensively than in the past, on commercial fabrication, and might lead to significant cost reductions and accelerated fabrication schedules. This approach, while primarily targeting lepton and

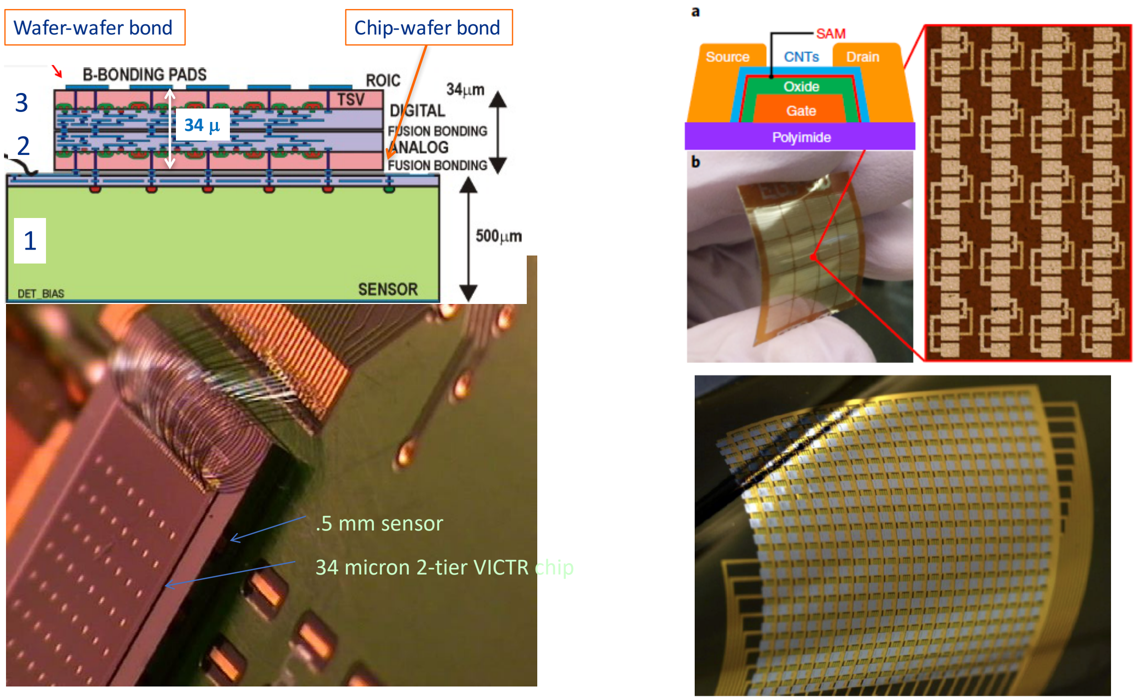


Figure 46: Examples of new integrated detector and electronics modules with transformative potential towards the goals of low-mass, high segmentation modules with reduced cooling requirements: (left) a vertical integrated sandwich encompassing one silicon sensor and two tiers of readout electronics encompassing 2-tier (analog, digital) 130 nm VIP chip and a silicon sensor array comprising 192x19, 24μm pitch pixels [303]; right: possible alternative solution for future 3D integrated devices; (top) flexible CMOS integrated circuits based on carbon nanotubes [304], (bottom) ultra-thin flexible silicon which may be substituted possibly by alternative substrates discussed in PRD 19.

heavy ion machines, would also benefit a hadron collider detector, if sufficiently fast and radiation hard, and dedicated searches for rare processes. These considerations lead to the following Thrusts:

Thrust 1: Highly integrated monolithic, active sensors

Progress on this first Thrust is very topical [305–308]. In recent years, a new generation of monolithic active pixel devices has been proposed and prototyped. These can be fabricated in certain commercially available CMOS processes. Indeed, they have been successfully deployed, as first generation devices, already in the STAR Heavy Flavor Tracker [309] at the BNL RHIC facility and are in fabrication for the ALICE ITS [310] system for use in heavy ion collisions at the LHC. ALICE employs 10 m^2 of industrially thinned sensors, comprised of 24,000 MAPS chips with 12.5 Gpixels. This shows that large scale production of irreducible mass trackers is possible. Second-generation monolithic active pixel sensors are also an area of vigorous research. Initially, by relying on charge collection by diffusion, they were not applicable to high luminosity hadron colliders. More recently, architectures based upon high voltage or high resistivity commercial CMOS have been utilized. The resulting devices already meet performance and radiation specifications for the outer radii at the HL-LHC.

Thrust 2: Scaling of low-mass detector system

This includes integrated services [311], power management [312–316], cooling, data flow, and multiplexing. Beyond the demonstration of a minimal-mass active sensor, this second Thrust addresses the remainder of the system. A substantial component of the material budget of current tracking detectors is in services, such as cables, data and power transmission, cooling and the support structure. Together with the minimization of the material in the sensors and front-end electronics, it is crucial to reduce the mass of all these components. In some cases this is only achievable by developing transformative technologies, for example embedded 3D micro-channels for cooling [317] and data transmission into the support structure, and wireless power and data transmission [318]. Some current, state-of-the-art examples are shown in Figure 47.

Thrust 3: Systems for special applications: space-based tracking detectors, and dedicated searches for rare processes and dark matter

Much of the focus on the solid state tracking technology in recent times has targeted the classical applications to hadron and lepton colliders. Concurrently, but sometimes in a niche application, solid state trackers have been used in other demanding environments. Examples are high rate fixed target or low background searches for rare processes, and space based applications. This third Thrust addresses challenges which may be faced by detectors which have to operate in demanding environments requiring special considerations. At this juncture, it is difficult to be specific but the point is to acknowledge that the technology can be adapted to a variety of different applications, such as operation in space, or detector systems emphasizing low cost with large scale.

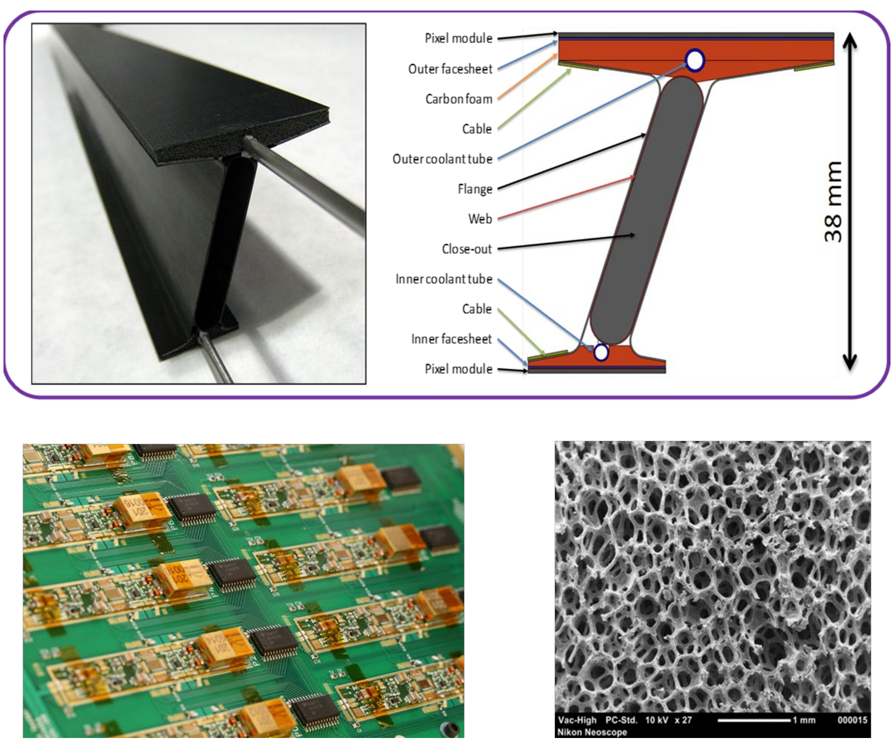


Figure 47: Top: Low mass I-beam structure designed to support two layers of pixel detectors in a cylindrical barrel geometry. Faces are made of high modulus, high conductivity carbon fiber, high thermal conductivity carbon foam fills the interior along with embedded cooling pipes carrying high pressure CO2. Entire composite is bonded using a co-curing process. Bottom Right: Thermally conductive carbon foam developed in part through the DOE SBIR program with HEP. This foam, which is machinable, has a thermal conductivity of 30-40 W/m-C at 10% the density of solid carbon. It can be used as a low mass thermal conductor and heat spreader within composite tracker support structures. Bottom Left: Low mass power regulation and control hybrid being developed for a large collider tracker. Hybrid includes DCDC conversion, HV multiplexing and filter, and monitoring and control ASICs. To produce and test thousands of hybrids, circuits are assembled, tested, and burned-in on large panels.

Research Plan

A full scale mass minimized tracker would be a significant step beyond the current examples. In any case, these developments are strongly coupled to evolving commercial IC process and their continued availability. It is critical that the community continues a vigorous program in MAPS, and related mass-minimizing technologies, going forward. While the ALICE development is tremendously impressive, the HEP community needs to demonstrate even more demanding applications of mass-minimized detector systems in running experiments before a system of several hundred square meters could be built.

As noted, a key element of a mass minimized tracker are efficient services. R&D should be supported in areas of low mass cooling methods, novel approaches to data transmission, powering, and the use of novel materials systems in electronics and opto-electronics packaging and components.

Finally, and in recognition of the role tracking plays in detectors for specialized applications and demanding environments, a robust R&D program should have a component open to new and unusual ideas or applications which may transcend traditional categories.

4.6.5 Connections Outside HEP

Solid state radiation sensors are used widely outside HEP. Applications include the fields of nuclear, astroparticle, medical, materials, and homeland security science and engineering. In particular, large scale systems which can operate at elevated temperature, without cooling, and are easily deployed can be of interest. Experiments at the planned electron-ion collider (EIC) may use ps timing to improve momentum measurements smeared by beam dispersion. In materials science atom-ion probes of surface composition may benefit from precise timing measurements. Low mass tracking systems are also of significant interest to nuclear and astroparticle physics. In the case of relativistic heavy ion colliders, low mass tracking has already been a major instrumentation focus, with some of the key breakthroughs already made there. Future tracking systems at the planned EIC facility will employ similar approaches.

4.6.6 Facilities and Infrastructure

Beyond these specific and prioritized development projects, it must be recognized that solid state tracking requires the support of specialized infrastructure and specialized electrical and mechanical engineering capabilities. While much of these exist today, and have been built up over the past 25 years, they also must be sustained and, as appropriate, modernized. This is required for any transformative, or incremental, R&D program to proceed.

The area of infrastructure includes test beam and irradiation facilities (an existing example is shown in Figure 48), silicon processing labs, electronic packaging and assembly, metrology, and composites fabrication facilities with their skilled technical staff. The area of engineering includes expertise in ASIC design and test, simulation, verification, and low power systems, and mechanical design and composite fabrication. It should be noted that an ASIC development project, from design through prototyping and production, also linked to a detector development, can easily span ten years. Maintaining engineering teams and institutional knowledge is absolutely critical.

Perhaps the most significant of the missing infrastructure is an appropriate irradiation facility.

Figure 48: Example of an existing facility for heavy ion irradiation. Beam enters from the back of the frame. Large blue vacuum chamber holds device under test. Vacuum feedthroughs are at the left of the chamber. Remote movable stages are seen on a sliding platform. Such capabilities and facilities, specifically targeting the conditions of future colliders are required going forward.

The HEP community lacks access to a long term irradiation facility with the characteristics, availability, and experimental infrastructure required to support a program of transformative R&D aimed at a future hadron collider. In fact, the development of such a facility would be transformative to the entire R&D program.

Currently, HEP uses a variety of facilities for a variety of purposes in assessing radiation damage to experimental components. Low energy electrons are used for studies of surface damage to semiconductors. X-rays are used for SEE studies. Displacement damage in structural materials can be mimicked by neutrons. Charged hadron beams are needed to replicate the effect of the charged hadrons (principally pions) that dominate the damage at a hadron collider at low radii and also for SEE studies. Considering the damage factors for various species as a function of energy, there is near-perfect overlap of pions with protons in the high energy regime relevant for our application; this motivates the use of protons to replicate pion damage conditions.

Table 21 summarizes the features of proton facilities now used, or anticipated for the near future, by particle physicists to evaluate radiation tolerance of devices.

Development and testing of detectors that will operate in the central radiation field of an FCC-hh requires anticipation of three conditions.

1. The integrated hadron fluence at the FCC-hh will be in the realm of $1 \times 10^{18} n_{eq}/cm^2$.
2. The primary pions causing the most significant damage will have energies in the realm of 0.1-1 GeV.
3. Historically the development of radiation hard devices in new regimes require a timescale on the order of a decade of dedicated, and nearly continuous, testing.

No hadron beam facility in Table 21 offers the necessary combination of the three conditions: energy, integrated fluence, and availability over the required time frame. This highlights the need for a new dedicated proton facility. Demand for electrons, X-rays, and neutrons will grow in the ramp-up to the FCC era but is second-order in urgency as existing facilities could be used. Need for a mixed beam is not anticipated at this time.

More than just a parasitic capability within a legacy accelerator, the desired high intensity facility will also benefit from critical infrastructure. Users of such a dedicated proton beam facility will require cooling, power, data acquisition, mechanical support, and storage and handling capabilities for activated samples. Cooling must be carefully considered both to control annealing in heavily irradiated silicon and to replicate the most challenging conditions for electronics. The cooling facility itself must combine guaranteed radiation tolerant components with architecture for shielding non-tolerant elements.

There are a number of modes in which the infrastructure could be supported. Users who are not local to the facility are unlikely to transport to it significant amounts of equipment that is bulky, delicate, or likely to activate. Yet at a unique facility such as this, the majority of users will be non-local. There are two ways to respond to the infrastructure needs of these non-local users:

Facility	**Species**	**Energy**	**Time to** $2 \times 10^{16} cm^2$	**Availability**
CERN	protons	24 GeV	111 hr	LS2 shutdown
Birmingham	protons	40 MeV	1 hr (*)	weekly
KIT	protons	23.5 MeV	1.5 hr (*)	4 hr/week
TRIUMF	protons	5-500 MeV	Not feasible	
FSU	protons	17 MeV	0.4 hr (*)	4 1-week runs/year
LANL	protons	800 MeV	72 hr	2 weeks/year
FNAL ITA	protons	400 MeV	0.7 hr	40 weeks/year until ~2025
UC Davis Crocker	protons	66 MeV	300 hr	weekly

(*) The ionization dose is disproportionately large for these low-energy machines.

Table 21: Summary of accelerator-based irradiation facilities currently operating

1. Anticipate and develop an infrastructure so universal that outside users can count on integrating their experiments with it smoothly and thus will bring with them little but the devices to be tested.

2. Anticipate the need for adequate numbers of permanent facility staff dedicated to designing, building, and operating custom interfaces for users' materials.

To decide between these two modes would require some further study. This could include a survey of existing facilities, inquires made to a group of potential users, and some appropriate cost benefit analysis within a funding model.

4.6.7 Solid State and the Grand Challenges

The PRDs and research plans described in this section seek to develop solid state sensors with fine spatial resolution and precise time resolution to resolve individual interactions in high-collision-density environments thereby advancing HEP detectors to new regimes of sensitivity corresponding to Grand Challenge 1, and mastering extreme environments and data rates in HEP experiments corresponding to Grand Challenge 4. The PRDs and research plans achieve this by adapting new materials and new fabrication methods corresponding to Grand Challenge 3, and integration techniques that are scalable corresponding to Grand Challenge 2, thereby allowing a significant reduction in the detector material budget. The use of novel materials and integration techniques may allow to relax cooling requirements, with broad ramifications in HEP and industry.

4.7 Trigger and DAQ

4.7.1 Introduction

Data acquisition begins at the very front-end where the detectors reside, and typically that is where the first reduction of the volume of data must be achieved with specialized algorithms running in the challenging detector environment. Many of the next generation experiments in high energy physics will generate unprecedented amounts of data. There are two approaches to pursue in order to handle and intelligently reduce these enormous data rates in real time: 1) select and store a small fraction of raw data enriched in physics content as part of a traditional "triggered" data acquisition (DAQ) system, or 2) summarize the received data by calculating higher-level quantities and storing only those at the full natural rate from the experiment. The latter is referred to as a "streaming", or "trigger-less", DAQ system.

In a triggered architecture (see Figure 49), a customized set of electronics perform the next level of processing off of the detector but still in very close vicinity for timing reasons. While based on commodity electronics components, typically the card and system designs are HEP specific to meet the data handling and latency challenges. This is followed by the collection of selected data and transmission through a commercial networking system to a very large collection of commodity computers, possibly with computational accelerators attached, to complete the data reduction processing with software-based algorithms.

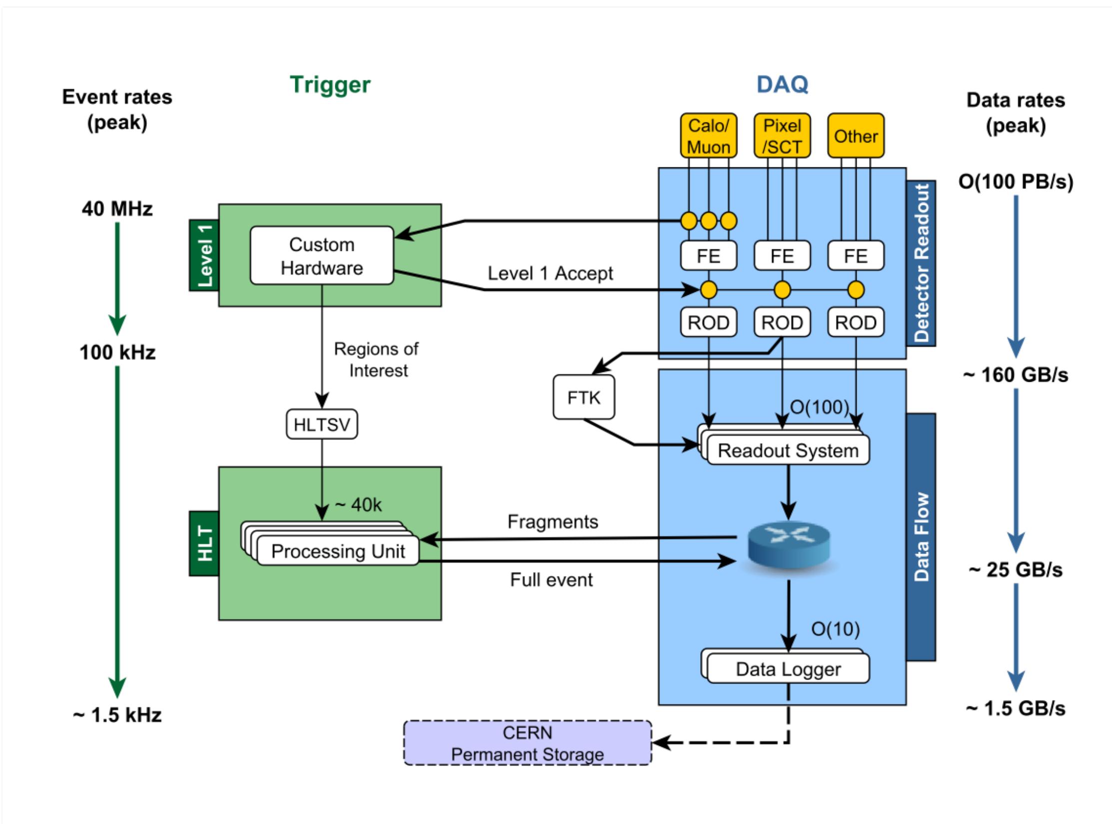


Figure 49: Data flow diagram for the trigger and data acquisition system of the ATLAS experiment at the LHC. Left axis shows the reduction in the selected event rate through each level of the trigger system, and the right axis shows the corresponding reduction in the data rate.

Both the triggered and streaming architectures require methods to move large volumes of data quickly, and real-time processing of the data at near-offline resolution to extract the physics content at every stage of data acquisition, which necessitates the use of advanced algorithms and hardware. The extreme environments of future detectors, whether exposed to high radiation, cryogenic temperatures, or remote locations, often add high robustness and low power consumption requirements.

Priority Research Directions	**Thrusts**	**Technical Requirements**
PRD 21: Achieve on-detector real-time, continuous data processing and transmission to reach the exascale	High-bandwidth, rad-hard, low-power data links; Real-time processing hardware; Online data processing on heterogeneous hardware; Fast artificial intelligence & neuromorphic computing on real-time hardware; Advanced feature extraction for trigger	TR 1.5, TR2.1, TR2.4, TR2.5, TR4.4, TR5.6, TR5.11
PRD 22: Develop technologies for autonomous detector systems	Autonomous operations; Self-calibration and alignment	TR 2.1, TR 2.4, TR 2.5, TR 4.4 TR 5.6, TR 5.11
PRD 23: Develop timing distribution with picosecond synchronization	Develop timing distribution with picosecond synchronization	TR 1.1, TR 1.2, TR 1.3, TR 1.4, TR 1.5,TR 2.1, TR 2.4, TR 2.5, TR 4.3, TR 5.11

Table 22: TDAQ. Table summarizing Priority Research Directions (PRDs), Thrusts and Technical Requirements (TRs).

Additionally, as detector systems become ever more complex to address the demands of the science, the operation of those systems similarly scales up in complexity. Often these experiments are in remote and inaccessible locations, such as the radiation environment of a collision cavern, deep underground, in remote regions of the Earth's surface, or in space. Automation of tasks like control, fault detection, and calibration is necessary to improve efficiency and reduce operations costs. Much as self-driving cars must sense their environment and take corrective actions as they travel, experiments must also develop the ability to be self-running.

Finally, trigger and DAQ (TDAQ) systems across several HEP research frontiers will require both the distribution and collection of fast timing signals at picosecond precision, over distances as much as kilometers. In comparison, light travels only 300 microns in that short amount of time. Picosecond timing precision and detector synchronization will be necessary to solve ambiguities of particle trajectories and perform particle identification in fine-grained detectors at future particle colliders, as well as maintaining coherence of detector arrays observing the sky.

Because of the challenges of and long time scales constructing large and complex detectors, many of the new technologies for improving intelligent sensing, data transmission, and fast timing will need to be developed and demonstrated well ahead of their inclusion in future experiments. Additionally, improvements in triggering and data acquisition techniques should work hand-in-hand with improvements in detector and readout electronics technologies. Development of new technologies should emphasize a systems-level approach and co-design of the entire detector readout chain, from signal generation to final storage of data, through targeted integrated solutions.

Another challenge in TDAQ research and development is anticipating improvements in commodity networking, and computing technologies developed by industry. The solutions and capabilities of today will likely look very different in ten and twenty years, when many of the next generation of HEP experiments will need the targeted research priorities described in this report. The development of the general tools and techniques to address these priorities will need to keep pace with improvements from industry in order to lay the foundation for successful application in future experiments. R&D efforts aimed for future experiments should also take advantage of the current generation of experiments as opportunities to hone and prove their benefit. Stronger R&D partnerships between industry and the HEP community will be needed to effectively adapt industry solutions to HEP application challenges.

Table 22 provides a summary of the PRDs and Thrusts for TDAQ and references them to the Technical Requirements presented in the physics sections of this report.

4.7.2 PRD 21: Achieve on-detector, real-time, continuous data processing and transmission to reach the exascale

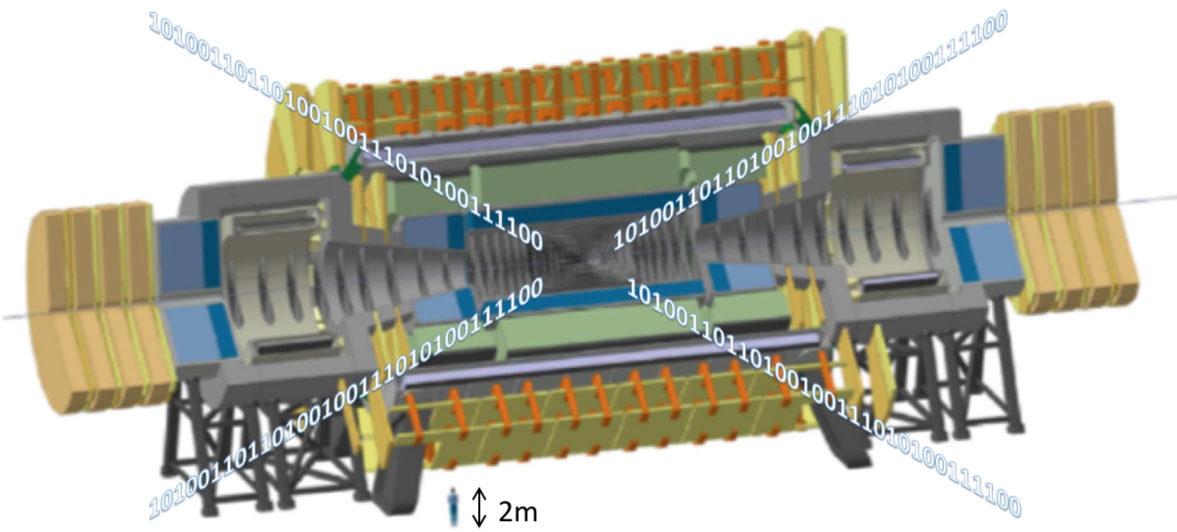


Figure 50: Next generation experiments at a future circular hadron collider will produce raw data rates from their detector systems approaching an exabyte per second (a million terabytes per second) that will need to be processed in real-time. Extracting and processing this amount of data requires significant advances in data link technology that is able to function in the extreme detector environments, picosecond precision in the synchronization of signals, artificial intelligence to quickly and efficiently extract features in the data, heterogeneous computing platforms to execute that processing, and an increased level of automation of data-taking operations.

Experiments across the Frontiers need the ability to process enormous data throughputs to reach the next energy frontier, to observe further out into the Universe, and to have sensitivity to rare signals. The rate of data to be transmitted and processed in real-time reaches exabytes per second (10^{18} bytes/sec, or a million terabytes/sec) for the unsuppressed raw data rate generated by a future hadron collider experiment (Figure 50). Likewise, the scale of the raw data rate expected from the next generation cosmology experiments operating at the 21 cm hydrogen line is expected to exceed petabits/sec with storage rates of 5 petabytes/day; this is to be compared with contemporary experiments such as Rubin Observatory (50 Gbps, 20 terabytes/day) and CMB-S4 (1 Gbps, 20 terabytes/day). Handling and processing such enormous data volumes requires advances in the data transmission capability as well as advanced algorithms and processing hardware for the data selection and reduction.

Thrust 1: High-bandwidth, rad-hard, low-power data links

For future neutrino experiments like DUNE [186], flavor physics experiments like LHCb Phase-II [145], or experiments at the future lepton colliders like FCC-ee [269], improvements in the bandwidth and performance of data links can allow the data to be streamed continuously from detector front-end electronics and processed. For future hadron colliders like FCC-hh [27], a streaming DAQ (i.e., trigger-less) system is still not viable with current technology projections. The FCC-hh silicon tracker will have $\sim$ 20 billion channels and the zero-suppressed data rate will reach 10 Pb/s. A low latency trigger will still be needed to reduce the data throughput, but it will require much better performance compared to that of the HL-LHC in order to reach the same rejection factor ($\sim$ 40) with much higher pileup, assuming a similar physics program. Therefore, other advanced techniques will be needed to help achieve the necessary data reduction, such as processing in readout chips (ASICs designed with high tolerance to the high radiation environment) and filtering with double-layer correlation (intelligent tracker design).

At the reduced rate, the data will be transferred from the readout chips electrically to a location tens of centimeters away where it will be converted optically and then transmitted out. Since this is still in the high radiation area ($1 \times 10^{17}\ n_e q/cm^2$, TID of 300 MGray), rad-hard, high rate optical links will be required, with tight constraints of low power consumption and low mass. The existing rad-hard link has a bandwidth of ∼10 Gbps (LpGBT [319] and Versatile Link PLUS [320]) and uses VCSEL technology. It will meet the needs of HL-LHC experiments, but not of FCC-hh experiments because of the power and space needed, and the dead material that would be introduced by the huge number of links. Even the planned rad-hard link R&D targeting 25 Gbps that CERN has just started will not be adequate. For FCC-hh experiments, optical links with a speed roughly matching the commercially available ones (100 Gbps or higher) will be desirable, though an intermediate step of 50 Gbps will be a critical yet challenging development for realizing the readout of the silicon tracker. Silicon photonics-based integrated optical modules and associated serializer/deserializer chipsets to support data rates of 50 Gbps or higher will be ambitious but achievable. Note that the LHCb Phase-II upgrade is proposing to stream data out at 50 TB/s at an earlier timescale (around 2030) and while this requires one order of magnitude increase of the optical link speed, even data rates of 50 Gbps will help bring the total number of links needed to a more reasonable number. This makes the R&D for rad-hard, high rate optical links more pressing.

The advantages of a wireless readout system compared to wired ones for large instrumentation systems like the silicon trackers of FCC-hh experiments, will be significant. The reduction of cables and connectors would help to reduce dead material inside the detectors as well as ease the installation and operation. New readout topologies would be possible to enable track trigger capability and fast data reduction. A 60 GHz RF demonstrator was developed with data rates of a few Gbps (cf. [318]). Transmission at a data rate of 10 Gbps was also demonstrated at higher carrier frequencies. For high density link environments like the silicon tracker, the RF signal integrity has to be ensured by exploiting directional antennas, polarization or attenuating reflections. Moreover, detailed design studies will be needed to demonstrate the full potential of wireless communication and to create a working wireless readout system in the large scale. Though the commercial chipsets can be used to construct prototypes, transceiver chips likely need to be developed suitable for high data rate and short distance applications, which can provide wireless $>$ 10 Gbps data transmission inside the extreme environment (high radiation, limited space, etc.) making readout and processing all hit data feasible. Another direction that should be investigated is line-of-sight (fiber-less) optical data transmission at high bandwidths. The same radiation, power, and space constraints apply as for RF wireless technologies, coupled with tight requirements on the alignment and light path to the receiver.

Thrust 2: Real-time processing hardware

To address the data onslaught at future experiments, localized data reduction and processing on or near the detectors is necessary. Examples include compression and zero suppression of electronics channel waveforms, clusterization of hits from tracking detectors or of energy deposits in calorimeters, and pattern-finding across multiple sensing layers for local track creation. This reduces the raw data into high-level objects of reduced size for transmission to later processing stages. For example, in future collider experiments, especially hadron colliders, more intelligence at the front-end electronics will be required to compress the data from highly granular detectors. However, since such experiments operate in extreme environments (that include radiation, magnetic fields, cold temperatures, and confined spaces) and must draw low power, the electronics will require custom development. Application specific integrated circuits (ASICs) for such processing, including general purpose RISC computers and reprogrammable logic devices should be investigated.

Analog-to-digital converters (ADCs) are one of the foundational building blocks for any DAQ system. As experiments move to higher granularity, higher sampling frequencies, and higher sampling resolution, the power consumption of ADCs can become a limiting factor. One generally-accepted figure of merit (FOM) for power efficiency is the Walden FOM [321], the energy cost per conversion per resolution step. The 2019 research state-of-the-art is ∼ 20 fJ/conversion step, with commercially-available ADCs (which comply with industry I/O standards) consuming about 100 times more power. Future astrophysical neutrino experiments with expansive arrays of autonomously-powered software-defined radio receivers distributed over 100s of km^2 and sampling clocks in the 2–4 GSa/s range will require multi-channel ADCs with at least ten times better power efficiency than the current state-of-the-art commercial off the shelf components, and must be produced on a large and economic scale not yet achieved commercially. Such ADCs will also benefit future

21-cm intensity mapping experiments which will have similar power-delivery constraints.

One of the most demanding experiments in terms of real-time processing is the proposed PUMA 21 cm intensity mapping experiment [322] slated for operations towards the end of the decade. To create a tomographic sky map, signals from >60,000 sources will be digitized at 3 GSa/s, a data throughput of one exabyte every three hours. The raw data must be processed in a correlator whose computational load is estimated to be O(100) pflops, comparable to the world record-holding supercomputer of 2019, Summit [323] (albeit running a dedicated algorithm, not to be confused with a general-purpose supercomputer). Designing a machine of this scale to operate robustly in a remote site with constraints on power consumption and maintenance will require significant R&D over the next 5–10 years.

Thrust 3: Online data processing on heterogeneous hardware

Future TDAQ architectures will need to absorb unprecedented data volumes directly into software-based triggers running on heterogeneous commodity computing resources. For example, data rates of the order of 100 terabytes/s at a future hadron collider experiment from the first level of triggering will need to be passed through a switching network to the next level of commodity computing resources for further processing before storage. This is in contrast to the state-of-the-art under implementation by the LHCb experiment for a trigger-less readout of 5 terabytes/s for Run 3 of the LHC [324]. Even for the HL-LHC, the CMS experiment foresees a data throughput of 5.5 terabytes/s in its Phase II DAQ upgrade [325], an order of magnitude less than required for a future hadron collider. As a potential step in that direction, LHCb aims for data streamed out of the detector at 50 terabytes/s by 2030 in its Phase-II proposal.

Either with streaming or at the reduced rate after the low latency trigger, the TDAQ system collects the data from the detectors, assembles the fragments into complete events (describing a collision, for example), and distributes these assembled events to a highly parallel and extensive processing farm running software algorithms on a heterogeneous, low latency computing fabric. The collection of data requires the development of HEP-specific electronics. For example, for the current generation Phase-1 upgrade of the ATLAS experiment, the PCIe-based FELIX card [326] (see Figure 51) was developed to interface the front-end detector electronics to the switching network. This technology has been adopted by other experiments, like DUNE and sPHENIX.

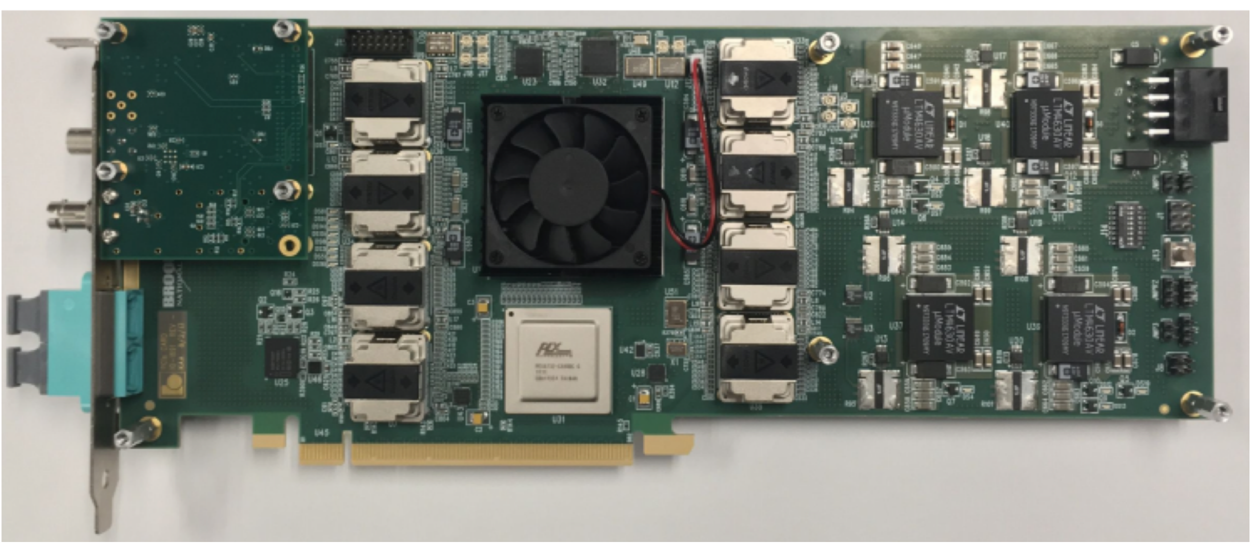


Figure 51: The PCIe-based FELIX card is a state-of-the-art detector independent readout architecture that will interface the front-end detector electronics to the trigger and data acquisition systems in a scalable and detector agnostic way. Current applications include the ATLAS Phase-1 upgrades and the DUNE experiment. It can receive data transmitted from the on-detector front-end electronics via a high-speed (4.8 Gb/s) radiation-hard optical link using the GigaBit Transceiver architecture and protocol developed by CERN. Future experiments will need electronics receiving data at even higher bandwidths.

The online processing farm is at data center scale (tens of thousands of computing cores) and will be more heterogeneous. The commodity processor technologies will include next generation central processing units (CPUs), graphical processing units (GPUs), hybrid CPUs integrated with field-programmable gate arrays (CPU-FPGA) and others (see Figure 52). Developments in the areas of the optimal data preparation and distribution using next-generation switching networks, and the execution of HEP-specific code or algorithms (including machine learning) on heterogeneous computing platforms, will be required to meet the needs of the energy, intensity, and cosmic frontier experiments.

Thrust 4: Fast artificial intelligence and neuromorphic computing on real-time hardware

Future experiments will need an unprecedented level of sophistication for the necessary data processing and data reduction. Recently the usage of machine learning algorithms, such as boosted decision trees and neural networks, for identifying particle signatures or for regressing physics quantities has moved from the offline analysis domain to online and real-time applications [327, 328], and offers great potential to increase the sensitivity of experiments. Furthermore, the reliable use of such algorithms online can be controlled by robust offline training, and through verification by measurements of the trigger performance. What is unique to the particle physics real-time applications over industrial ones running on commodity computing hardware is the very fast nature of the inferences needed: sub-microsecond versus milliseconds or longer. This emerging new direction of AI/ML and neuromorphic computing, is a potential game changer, and while major new experiments and facilities are on a longer timescale, the application of fast machine learning inferences and the FPGA-based technologies, upon which they are mainly based, are changing so rapidly it is worth investing in R&D to determine the ultimate possibilities for these future experiments. It is a new way of approaching the design of future TDAQ systems, and the electronics involved from the front-end to off-detector. Therefore, R&D is needed from the community for the development of AI/ML/neuromorphic algorithms, and the tools to deploy them, that will work with low latency (less than a microsecond) and with the large data volumes expected from high-energy physics experiments on emerging new commodity technology platforms (FPGAs, AI cores, etc.). These R&D avenues will serve to maximize the physics sensitivity of future experiments, and synergistically trains scientists as experts in this growing area of data science that extends well beyond the confines of high energy physics.

Thrust 5: Advanced feature extraction for trigger

Once data have been moved (and reduced) off the detector front-end, further processing is still necessary in order to reduce the data volume before being streamed out to a large commodity computer processing farm. Reconstruction of specific HEP objects such as electron/photon energy clusters, jets, muons, and so on must be extracted from the enormous data being sent from highly granular detectors and processed with tight timing constraints. This "feature extraction" must be achieved using specialized electronic cards (based on commodity components such as FPGAs) that implement advanced algorithms, including algorithms based on machine learning inferences as discussed above.

For example, precision timing detectors historically have been very useful for particle identification. More recently, the incorporation of timing detectors into the hadron collider experiments for the HL-LHC are planned to help mitigate the effects of pileup, adding a time dimension to the spatial tracking to further disentangle the matching of tracks to vertices at high pileup. Silicon sensor technology (e.g. LGAD) can be used for such purposes and achieve timing resolutions of less than 50 ps. A potential next leap in triggers based on semiconductor tracking systems would be to embed this timing capability into low latency trigger systems for future collider experiments, providing 4D real-time tracking information. This would further improve the online performance at high pile-up by reducing the combinatorics in building tracks in a high density environment, for example at an FCC-hh. Along with the sensor and front-end electronics R&D required to achieve this comes the need to develop methods to read out, and process, the increased amount of data from the tracking system. This may impose requirements on the design of the tracking system itself in order to reduce the amount of data to be transmitted. With silicon tracking now on the cusp of inclusion into Level-1 electronic trigger systems at the HL-LHC, the next step to extend such trigger systems to future colliders would be to leverage this 4D capability to improve the overall performance in the presence of very high pileup for the purposes of data selection and reduction.

Figure 52: Future trigger and data acquisition architectures will need to absorb and process unprecedented data volumes directly into software-based triggers running on heterogeneous commodity computing resources. The commodity processor technologies will include next generation central processing units (CPUs), graphical processing units (GPUs), hybrid CPUs integrated with field-programmable gate arrays (CPU-FPGA) and others. The recent usage of machine learning algorithms, such as boosted decision trees and neural networks, has moved from the offline analysis domain to online and real-time applications to maximize the physics sensitivity of future experiments.

Research Plan

To address the research Thrusts described above, the following approaches might prove useful to the U.S. HEP community.
For rad-hard, high-speed optical links:

- Collaborate in the planned CERN R&D on 25 Gbps optical links
- Evaluate systematically the performance (radiation tolerance, power consumption, etc.) of commercially available optical links at 40, 50, 100,iand 400 Gbps; benchmark with respect to the requirements of the future experiments; and identify and improve or replace the weak components
- Initiate R&D for 50 Gbps or higher, targeting the FCC-hh and potentially LHCb Phase-II tracker requirements

For high-speed wireless links, the community should initiate the R&D for RF wireless data transmission targeting >10 Gbps in high radiation, low power consumption, high link density environments like FCC-hh tracker. Wireless is not necessarily needed everywhere in such an experiment, but deployment with >10 Gbps would help substantially on getting some of the data bandwidth out:

- Build demonstrator with commercial hardware and identify the capability limitation
- Perform system design for reading out at a large scale
- Develop mechanism to ensure and improve the signal integrity
- Design and test transceivers with respect to FCC-hh tracker requirements

Moreover, the potential and practicality of sending line-of-sight laser signals without optical fibers and maintaining robust alignment should be investigated.

In addition, to meet real-time processing needs:

- Evaluate the power efficiency of commercial ADCs with respect to the astrophysical neutrino and 21 cm requirements; initiate the dedicated development if needed
- Follow trends in FPGA, heterogeneous computing hardware, networking technologies, and online storage systems, and develop tools to utilize them for fast machine learning and DAQ architectures for future HEP experiments needs and evaluate their capability
- Develop conceptual design and algorithm to implement a 4D capable tracking trigger based on silicon sensor technology and at scale for FCC-hh experiments

4.7.3 PRD 22: Develop technologies for autonomous detector systems

Experiments require controls for monitoring, prompt diagnosis of faults and recovery mechanisms, and calibration to correct for detector response variations. As detector size, complexity, and conditions data rates increase, it will become exceedingly challenging to maintain high detector uptime and efficient collection of physics-quality data. Future particle colliders will have billions of channels with downtime aims of the percent level or less. (Currently achieved data recording efficiencies of the CMS and ATLAS experiments are 94% and 97.5%, respectively, for 2018 [329].) Future neutrino detectors, like DUNE, will need to record data with practically 100% uptime over multiple years of operation to ensure they don't miss rare events, such as neutrinos from supernova bursts. Future cosmic spectroscopic surveys like the PUMA [322] 21-cm sky map will need precise real-time calibration to stabilize and synchronize response before data downsampling and downstream processing can be accomplished.

As an example of current capabilities, the LHCb experiment operates an automated continuous calibration and alignment system that takes in data at rates of ∼10–100 MB/s and computes a variety of necessary calibration constants on ∼ 2000 online nodes with turnaround times on the order of minutes [330]. The increased channel multiplicity of future detectors will require orders of magnitude increases in data to be monitored: for example, in the case of Phase-II proposal for LHCb, a fifty-fold increase in the data rate is expected, implying similar increases in needs for real-time calibration and alignment.

These requirements place stringent demands on control, monitoring, calibration, and alignment systems of detectors. An ultimate goal is a self-running detector system, enabled by an autonomous, self-diagnosing, and auto-correcting data acquisition system, which would collect data efficiently and reliably with negligible human intervention. The return on investment of R&D into self-running detector systems could be significant in the form of a large reduction in costs of the operation of future detectors. This will take the form of increased productivity of science operations, reduction of frequency of intervention and control contact and cycles of command communication for remote detector systems, and prompt and efficient recovery due to unexpected conditions or faults.

Thrust 1: Autonomous operations

Autonomous operations will require the development of new technology and algorithms for fast collection and processing of conditions data, in order to enable health monitoring and detection of problems as they appear. Increasing automation in the detection of anomalous conditions and performing corrective measures, rather than relying on manual interventions, will also be needed to improve data-taking efficiency, and it requires key development efforts both in performing real-time or near-real-time detection of anomalies and problems (*anomaly detection*), and quickly determining and executing an appropriate response for recovery (*fault recovery*). This is in many ways similar to the problems faced in PRD 21, for data selection and triggering, except that in many cases automation of a self-running system may need to be more contextually adaptive: continually collecting and analyzing data, making appropriate adjustments, and reevaluating under new operating conditions. Advances in AI and ML (e.g. applications of unsupervised and reinforcement learning) will enable new types of algorithms to be put in use for improving the performance and stability of automatized error detection and prevention. Furthermore, high-performance distributed databases and messaging that can scale to increasing detector complexity, granularity, and extent, will be needed to facilitate self-diagnosis and recovery.

Thrust 2: Self-calibration and alignment

Many current experiments have automated calibration routines that provide reasonably fast feedback to data collection. For example, LHCb has developed an almost fully-automated system for alignment and calibration that can be applied to data on timescales of the order of minutes [330]. However, self-calibration of increasingly complex, granular, and extensive detector systems will require a significantly greater level of processing power and buffering capabilities in order to keep pace with data rates, and thus the development of improved methods and technologies is important. Applications of above methodologies, e.g. unsupervised and reinforcement learning, may be further applicable to self-calibration of detectors in terms of calorimetric response, timing, alignment, etc. In particular, as complexity of trigger decision/data selection/data reduction increases, there will be greater demands on calibrated detector stability.

Many of these same ideas may be applied to improved control of other complicated systems, like particle accelerator operation, and present an opportunity for cross-cutting initiatives.

Research Plan

Developing technologies for self-running DAQ systems will be an ongoing and cumulative process, building off advances in processing hardware technologies (including ASICs, FPGA, GPU, heterogeneous computing, etc.), high bandwidth links, fast-access memory, and increased fault tolerance strategies. Research into hardware systems now will both benefit the operations and performance of current detectors as well as pave the way for the needs for future detectors that are larger and more complex. It is important to invest in directions early and over time, to keep-up with the pace of changes and standards in cutting-edge computing driven by other industries.

An early need is investigations into the basic infrastructure and software tools required for collecting and temporarily storing large amounts of diverse monitoring data (at the many GB/s scale) and accessing it for fast processing to determine operating conditions. Additionally, solutions for low-latency distributed messaging and data distribution that can be operated at the scale of future detectors needs to be researched and demonstrated.

Development of monitoring and calibration/alignment algorithms will need to keep synchronized with detector developments, including detector and readout design, detector conditions monitoring, and real-time data selection algorithms. In many cases these algorithms and their performance requirements will be domain specific, but general tools in fast, intelligent anomaly detection and fault recovery should be pursued. Research on the development and performance of such tools should take advantage of data from currently operating detectors, and target successful applications to them while also considering their application to future detectors in the next 10 years.

Ultimately, research should be targeting the design and development of fully autonomous data acquisition and detector controls systems by 2030 that would directly support the physics goals of next generation detectors operating "streaming" data acquisition systems. This includes, but is not limited to, the proposed LHCb Phase-II upgrade and future collider detectors, DUNE with its full complement of detector modules, G3 dark matter detectors, and the PUMA [322] 21-cm intensity map.

4.7.4 PRD 23: Develop timing distribution with picosecond synchronization

Future high energy physics experiments in all Frontier areas emphasize pushing towards the 1-picosecond timing range. For example, in future Energy Frontier experiments extreme pile-up and occupancy must be mitigated with high-granularity tracking detectors and calorimeters capable of precise measurements of particle time-of-arrival (ToA). The trend towards triggerless or "streaming" DAQ will bring new challenges for synchronization and event tagging.

Collider detectors have traditionally derived timing references from the machine RF signals which in turn are synchronized to a master oscillator with exceptionally high stability. Derived clocks from the central machine timing are used to generate the detector timing and synchronization messages which are then distributed as needed to the front- and back-end electronics over optical fiber links. In next-generation colliders, the timing precision required to disambiguate interactions will go down to 25 ps in e^+e^- machines, and better than $\sim$5 ps in hadron colliders (see Section 3.1.2). For events that are registered on different detector elements, it follows that the difference in clock propagation delays must be matched (or measured) to similar precision. The adjustable delays, voltage controlled oscillators, jitter attenuators, and other on-detector synchronization circuitry must be able to survive the radiation environment and may require custom implementation.

Detectors for Cosmic and Intensity/neutrino frontier experiments face different issues. In the absence of a signal from machine RF systems, the detectors will be responsible for defining their own master timing reference. Many proposed experiments involve arrays of detector stations spread over kilometer distances, including hostile/remote (underwater, desert, under-ice etc.) environments. Timing distribution over cables (copper or optical) subject to temperature variation will suffer phase drifts and timing systems will need to develop compensating techniques to preserve synchronicity. For multi-messenger studies, where e.g. detection of a transient astrophysical event (gravitational wave, supernova, ultra high-energy cosmic ray) in one detector initiates followup observations at other sites, it will be essential to make accurate absolute timestamps available across networks that may span thousands of kilometers. Difficulties may be faced by underground/underwater/under-ice detectors that cannot easily access the international time reference signals broadcast from the atomic clocks aboard navigation satellites.

Future cosmology and neutrino experiments will use software-defined radio techniques, enabled by the rapidly advancing COTs hardware being developed for communications applications, to build arrays of interferometers. Receivers in the array will incorporate front ends that capture GHz signals with Nyquist-rate digitizers. The sampling clocks for these GSa/s digitizers must be phase-coherent (or calibrated) to within $< 1\%$ of the RF period, or around 1 ps. Since optical fibers have thermal coefficients of delay of around 35 ps/km/°C, phase drifts due to diurnal temperature variations in outdoor environments will need to be continuously compensated or monitored. Two-way time-frequency transfer methods have achieved sub-ps synchronization in a number of laboratories, but advances will be required to develop practical systems for cost-effectively synchronizing thousands of clocks across kilometer scales (Figure 53).

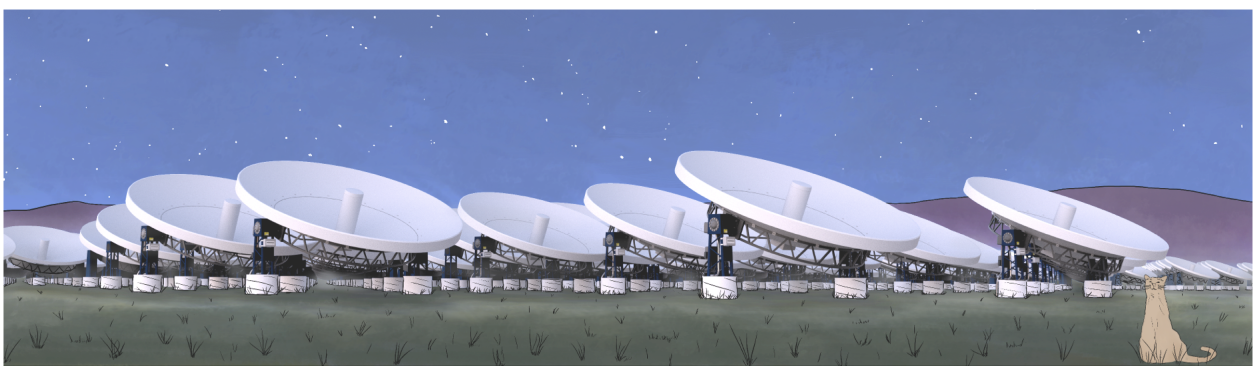


Figure 53: Trigger and data acquisition systems across several frontiers will require both the distribution and collection of fast timing signals at picosecond precision, over distances as much as kilometers. In comparison, light travels only 300 microns in that short amount of time. Picosecond timing precision and detector synchronization will be necessary to solve ambiguities of particle trajectories and perform particle identification in fine-grained detectors at future particle colliders, as well as maintaining coherence of detector arrays observing the sky, such as for the proposed PUMA radio telescope array shown here.

Research Plan

The following approaches should be taken by the U.S. HEP community to meet the goals for future experiments.

- As a first step, define the system requirements for the various use cases and then develop laboratory test stands for quantitative studies of synchronization techniques
- Follow with a multi-year task to demonstrate 25 ps synchronization across tens of meters distance scales under laboratory conditions

- Refine the technique above to achieve the goal of robust synchronization of 5 ps or better
- Achieve the ultimate goal of robust synchronization of 1 ps over 1 km in an outdoor environment for the PUMA [322] experiment requirement

4.7.5 Connections outside HEP

These developments will be beneficial to other scientific fields. The applications of machine-learning and the technologies for implementation overlap with those of the technology industry for latencies larger than milliseconds. Additionally, there may be synergies with the need for streaming data and feature extraction from AFM microscopy.

There are potentially strong connections here to real-time and near real-time data distribution and control systems in industries like aeronautics, smart power grids, and autonomous vehicles. There are also many connections to machine learning and fast inference for developing more intelligent data acquisition systems.

Examples of systems with similarly stringent synchronization requirements are free electron lasers (FELs), which require precise and deterministic time relations for the electron bunch and RF field interaction, and large radio telescope arrays such as the Square Kilometer Array and the Event Horizon Telescope. There are potential benefits to working with DOE Basic Energy Sciences, National Institute of Standards and Technology, National Radio Astronomy Observatory, and international standards labs with experience in these techniques. Small business partnerships may also be appropriate.

4.7.6 Facilities and Workforce

To accomplish the TDAQ R&D described above effectively and cost efficiently will require partnerships between U.S. national laboratories and universities for tool development, ASIC development, and TDAQ development in general. For example, universities have access to engineering expertise in Electronics and Computer Engineering departments, and some have launched institutes in artificial intelligence. Similarly, partnerships with the international community such as with the CERN laboratory should be encouraged, and industrial partnerships in the technology sector should be explored.

TDAQ R&D in rad-hard components requires irradiation facilities (see Section 4.6.6 for further details). Also, facilities that can accommodate integration tests of detector readout chains are important for finalizing systems-level designs. Examples include test beam facilities for integration with solid state tracking detectors and readout, and cryogenic platforms for integration with cold readout electronics in noble liquid detectors (see Section 4.2.5). A more complete list of current and future facilities can be found in Section 5.

4.7.7 TDAQ and the Grand Challenges

The PRDs and research plans described in this section seek to process data rates reaching exabytes per second corresponding to Grand Challenge 4, sometimes in extreme environments, in order to pursue elusive phenomenon. Advances in detector technology are also needed to achieve new regimes of sensitivity, which require picosecond timing precision and detector synchronization corresponding to Grand Challenge 1. As the complexity of detector systems increases, autonomous operations and the integration of intelligent computing with sensor technology become critical areas of R&D corresponding to Grand Challenges 2 and 4.

4.8 Cross-Cutting Priority Research Directions

4.8.1 Introduction

Cutting across many of the specific technologies discussed above are a set of Priority Research Directions that encapsulate needs in a multitude of areas. Recognition of the cross-cutting nature of these needs may spur collaboration between different technology groups to pursue them and may motivate funding agencies to identify new ways to sponsor work on these broad needs. Given the cross-cutting nature of these Priority Research Directions, no explicit association with individual Technical Requirements has been made. It is understood that these PRDs support the totality of the program.

4.8.2 PRD 24: Manipulate detector media to enhance physics reach

The development of new materials and media has always been a key component of HEP detector R&D, yielding, for example, a zoo of scintillating crystals, plastics, and liquids. This work has required a deep coupling to allied fields such as materials science, condensed-matter physics, and chemistry. Such new materials and media can have impact across a wide range of technologies and fields. This topic is therefore identified as a cross-cutting PRD. Below are a number of Thrusts, many of which are also themselves cross-cutting:

Thrust 1: Doping or enrichment to enhance interaction rate

For detectors in which the detection medium also acts as the source of, or target for, the particles to be detected, doping/mixtures or enrichment can be used to extend the physics reach of the experiments by, respectively, the introduction of the element or enhancement of the abundance of the particular isotope that provides the physics reach. Examples include the addition of hydrogen or deuterium to liquid xenon detectors to provide additional sensitivity to both spin-dependent and spin-independent dark matter interactions at for masses below 1 GeV (PRDs 4, 5), the dissolution of quantum dots with isotopes interesting for neutrinoless double beta decay (e.g., ^{116}Cd) in liquid scintillators, and isotopic enrichment of germanium, xenon, and other materials for both neutrinoless double beta decay and spin-dependent dark matter scattering. Isotopic enrichment is discussed in more detail in the context of separation of undesirable isotopes in PRD 25.

Doping/mixing can present new R&D challenges beyond the development of the dopant/mixture itself: stability of the doping or mixture, characterizing the proportions, modifications to detector operation, etc. Isotopic enrichment can require R&D to demonstrate enrichment of new isotopes or enhance enrichment efficiency and/or reduce cost.

Thrust 2: Doping and new materials for enhanced or more radiation-hard light or charge production

Doping, or embedding, can be used in a variety of ways to enhance light production in materials that scintillate in pure form, and new materials are constantly being explored. Examples of the former include the doping of LYSO with cerium and of garnet with cerium or praseodymium to enhance radiation tolerance (effectively preventing a degradation of light production; PRD 2), the doping of water and liquid scintillators with specific elements, or with quantum dots containing specific elements, to provide or enhance neutron capture cross-section and thus light production for neutrino detectors using inverse beta decay, the doping of gallium arsenide to achieve enormous IR scintillation yields, and the doping of wide band-gap semiconductor-based inorganic scintillators with nano-crystals (another name for quantum dots) for ultra-fast scintillation (noted in the context of PRD 3; see also PRD 2). Examples of the latter include the perovskite ceramics as scintillators (PRD 2) as well as diamond and other wide band-gap materials for ionization-based tracking (PRD 19). R&D challenges include, besides identification of potential dopant-material combinations and new materials, the same operational considerations as for Thrust 1.

Thrust 3: Doping for enhanced light or charge collection

Mixtures, or doping, can improve sensitivity by changing the characteristics of the detector response in a beneficial way. Liquid argon scintillation light with 1 μs-scale emission at 128 nm can be shifted to 10 ns scale and 178 nm by xenon doping, enhancing timing information while also making the light easier to collect (PRDs 4, 5). Quantum dots can absorb a broad spectrum above a cutoff and reemit at a characteristic wavelength, making it possible to tune the reemission to the peak efficiency of photodetectors and also enhance separation of scintillation and Cherenkov light. Gaseous time projection chambers for directional dark matter searches have been doped with CS_2 to implement negative ion rather than electron drift, which can reduce diffusion and also slow down the arrival of the track information at the readout, thus improving charge collection and track reconstruction. Such negative ion doping may be beneficial for noble liquid detectors for the same reasons.

Thrust 4: Doping to improve event localization

The same techniques noted above can also improve event localization by increasing signal-to-noise for position reconstruction via enhanced light production, faster generation of light from particles produced in interactions before they can move significantly away from the creation site, or reduced diffusion of ionization tracks.

Thrust 5: Metastable systems; see also PRDs 4, 5

It is conventional to consider the target or detector medium as "passive" in the sense that its properties are only weakly dependent on operating conditions and evolve slowly over time: i.e., drifts to be taken out by calibration. But there is growing interest in "active" media, in the sense that quantities like physical parameters can be tuned to adjust performance parameters like threshold and background rejection.

This strategy has been demonstrated in bubble chambers using superheated liquids, notably the PICO dark matter experiment [214] and its predecessors. Bubble chambers provide intrinsic, noise-less amplification of small heat signals, as once the bubble exceeds a certain critical size determined by thermodynamic conditions, it grows to macroscopic size. Various fluids have been explored to date, providing varying thresholds and sensitivities, and there are certainly more materials to be studied. Bubble chambers using noble liquids hold the promise of extending the intrinsic background rejection of such devices to energy thresholds as low as a few tens of eV [215] because electronic excitation is efficiently radiated away from an interaction site by charge and light while nuclear interactions deposit most of their energy as heat. Hydrogenated liquids and liquid nitrogen are also interesting targets for this approach because of their greater sensitivity to spin-dependent interactions (higher abundance of unpaired spin isotopes).

Research Plan

Given the large range of possibilities, the vast majority of the Thrusts above begin with small-scale experimentation, and they can benefit from highly multidisciplinary environments such as is present in universities and the multi-purpose national labs. It is important to recognize that a diversity of approaches is beneficial given the wide range of parameter space to explore, and thus these small-scale investigations should be given appropriate support. This support can be incredibly cost-effective given the possible long-term physics impact of these individual R&D efforts.

Facilities and Capabilities

Hand-in-hand with support for small-scale experimentation on ideas in the vein of this PRD, support is also needed for the small-scale testing infrastructure, at universities and national labs, for the necessary measurements. Once an investigator determines how to make a measurement of a particular property of a detection medium and develops the test infrastructure, it would be cost-effective for that infrastructure to be used for multiple developments. There may be multidisciplinary efforts the Office of Science can encourage between its various subprograms to enhance this R&D effort.

4.8.3 PRD 25: Advance material purification and assay methods to increase sensitivity

Experiments that search for particle dark matter and neutrinoless double-beta decay can be limited in sensitivity by radiological backgrounds, i.e. adding more detector mass or running the experiments longer can reach a point of diminishing returns. As these experiments scale up to reach greater sensitivity, they also must significantly reduce radiological backgrounds. External backgrounds are controlled through shielding. For instance, the most sensitive systems are installed deep underground (4000+ feet) to shield them from cosmic rays and suppress cosmogenic activation of detector materials. External backgrounds also come from the surrounding rock that emits both gamma rays and neutrons from naturally occurring radioactivity, primarily originating from ^{238}U, ^{232}Th, and ^{40}K in the rock. Low radioactivity shielding, typically lead and copper for gamma rays and polyethylene and water for neutrons, can be used to mitigate these external backgrounds. A particularly pernicious background for such experiments is radon, a radioactive gaseous daughter product of ^{238}U, ^{232}Th decay, which can migrate in the environment and plate out on surfaces of detectors or become entrained in liquid detector media. Radon emanation is greater at these underground sites.

In addition to radioactive contaminants that can limit detector sensitivity, other impurities can also limit performance. Impurities can limit charge carrier lifetimes and photon attenuation lengths in gaseous and liquid detectors while isotopic impurities can add degrees of freedom that spoil quantum system performance. In the case of neutrinoless double-beta decay, only specific isotopes can decay through this process and enrichment of targets in the relevant isotope, *e.g.* ^{76}Ge or ^{136}Xe, is used to increase the mass of the relevant isotope without increasing the total target mass required (see also PRD 24).

As experiments continue to grow in physical size and in sensitivity, and with them the channel count and mass, so do the challenges related to material purity and requirements for screening, background reduction, and purification systems.

Thrust 1: Radiologically pure materials

Radiological purity includes control of naturally occurring ^{238}U, ^{232}Th, and ^{40}K which are present in nearly all materials at some level as well as other naturally occurring and anthropogenic radioisotopes. The timely procurement and clean storage of large quantities of pure materials is an emerging need of future experiments. Historically important materials for the community have included low radioactivity lead, low radioactivity commercial copper, and ultra-low-background electroformed copper, low radioactivity polymers such as polyethylene for neutron shielding, Teflon used for light reflectors and PCTFE used for electrical insulation; photomultiplier tubes and vessels for bubble chambers fabricated with low radioactivity fused silica; low background cables; and carefully screened electronics components. In many cases, these materials are identified by screening commercially available products to identify suitable sources, but in other cases dedicated manufacturing is required to control backgrounds in the source materials.

Cosmogenic activation is a significant concern for both targets and surrounding detector materials. In many cases there is inherent purification of the radioactive contaminants during processing, whether that is electrorefinement in the case of copper or crystal growth in the case of silicon and germanium, and it is important to manage surface exposure from this manufacturing step onward. For targets pursuing low-energy phenomena, underground target storage will eventually be required to control the production of cosmogenically-produced tritium and, for argon, long-lived radioactive ^{37,39,42}Ar isotopes. Cosmogenically-produced ^{60}Co in copper has driven electroformed copper production and storage underground for the past decade.

Target materials of high radiopurity are central to any low background experiment. These include noble elements (*e.g.* Xe, Ar, He) as gasses, liquids, or solids, semiconductors (*e.g.* Si, Ge), scintillators (*e.g.* NaI, CsI), bolometer materials (*e.g.* Si, Ge, TeO2), and bubble chamber fluids (*e.g.* Freon, noble liquids). For many of these materials there is inherent purification in the production process that has made them suitable target candidates, including processes such as cryogenic distillation, zone refinement, and crystal growth. Some unique low background materials are sourced from materials that have been shielded from cosmic rays for many decades allowing the radioactive isotopes produced by cosmogenic activation to decay away, *e.g.* lead from the keels of sunken Roman ships and low radioactivity argon gas sourced from deep underground gas wells.

Sourcing and clean and/or underground storage of radiopure materials will continue to be a hallmark need for particle-like dark matter and neutrinoless double-beta decay searches.

Thrust 2: Enhanced capability for measurement and control of surface backgrounds

Surface backgrounds originate from deposition of radioactive particulates (dust) and plate-out of radon daughters. Advances in cleaning techniques are needed for surface background reduction of various detector components, both metals and plastics. For smaller components and systems, these techniques can be performed in highly controlled environments such as glove boxes or clean rooms with radon-reduced air. But as detectors scale up to kiloton class it is no longer feasible to require all handling to be done in tightly controlled environments and in-situ surface cleaning techniques are required.

More sensitive measurement techniques are needed to assay for radon and radon daughters. These include large area surface alpha (and beta) screening, assay of daughters such as ^{210}Pb, and radon emanation measurements.

Thrust 3: Purification and storage of noble liquids

Noble liquids are an attractive detector medium for scaling both neutrino and dark matter detectors to kiloton scale. Noble liquid detectors employ recirculating purification systems that can continuously remove radioactive and chemical impurities, including electronegative impurities. Scaling up to the next generation of dark matter (DARWIN, GADMC) and neutrino (DUNE) experiments will require sourcing and storage of high purity noble liquids and the development of industrial-scale cryogenic and purification systems, including cryogenics purification (N_2, O_2, H_2O removal, etc.) and removal of noble backgrounds (Kr, Rn, ^{39}Ar).

Understanding and characterizing the impacts of impurities on ultimate detector performance through experimental and computational techniques will be essential to realizing the science goals of future noble liquid detectors.

Thrust 4: Isotopic enrichment or rejection

Isotopic separation is used to produce enriched sources for neutrinoless double-beta decay, including ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te and ^{136}Xe. The principle enrichment techniques used have been electromagnetic or centrifuge separations. Most, if not all, recent experiments have sourced enriched material from Russia.

Isotope separations can also be used to reduce the amount of unwanted isotope, for example the radioactive isotope ^{32}Si, in silicon for dark matter detectors or ^{29}Si in silicon for quantum devices.

Production strategy and supply of enriched/depleted isotopes for the U.S. is overseen by the Isotopes Program in the DOE Office of Science. There is an active program to re-establish domestic isotope production through electromagnetic and centrifuge separators targeting stable isotope production at ORNL (in this context neutrinoless double-beta decay isotopes are considered stable). There are also emerging technologies such as microchannel distillation under study for isotope separation. The HEP community could benefit greatly from initiatives that lead to reduced cost.

Research Plan

1. Developing new solutions for screening and procurement of low-background detector materials, including electronics components such as cables, and understanding how those backgrounds generate signals in sensitive detectors.

2. Developing strategies for storage and transportation of large quantities of noble liquids with minimal exposure to cosmogenic activation.

3. Developing strategies to further reduce surface backgrounds and for commensurate assay sensitivity.

4. Developing methods for scale-up of purification solutions for the removal of both electronegative species and radioactive contaminants, including radioactive noble elements.

5. Leveraging developments in isotope separation solutions being pursued by other disciplines.

Beyond these identified activities, novel uses of high-purity materials for particle detection should be strongly encouraged to fully explore and advance the range of experimental techniques.

Facilities and Capabilities

There are a number of existing facilities supporting R&D on ultra-pure materials and low-level assay. These efforts require cross-disciplinary input, *e.g.*, from chemists and materials scientists as well as physicists. Training and retaining the requisite expert workforce is an important component of maintaining these facilities. Similarly, these activities require specialized equipment operating in clean room environments.

Low background and ultra-pure materials capabilities utilize a range of purification techniques from distillation and cryogenic separations to zone refining and crystal growth to electrochemical refinement. In many cases, the facilities and infrastructure are significant and the unique processes utilized have been developed over many years by the subject matter experts. These capabilities largely reside within the national lab complex. Some efforts at commercialization have been made, but there is not a sufficient need to maintain an industrial base in most cases.

Low-background screening capabilities are an essential component of rare event searches. This includes traditional radiometric measurements with high-purity germanium (HPGe) spectrometers and alpha/beta counters, as well as mass spectrometer techniques primarily Inductively-Coupled Plasma Mass Spectrometery (ICPMS). Screening at many levels of sensitivity is required during development of materials sources, while high-throughput screening material is needed during construction to validate detector components. Complementarity of methods is essential to the program. HPGe spectroscopy provides a broad analysis of all gamma ray and X-ray emitting radionuclides present in a material but requires significant mass of material (of order kg) and long measurement times (up to a month), whereas ICPMS has outstanding sensitivity to specific isotopes (typically targeting ^{238}U, ^{232}Th and ^{40}K) and provides results in minutes rather than weeks, but provides no sensitivity to masses that are not specifically interrogated. Similarly, alpha counters directly measure surface alpha contamination while alternatives such as assay of ^{210}Pb using ICPMS measure contamination throughout the material if the entire sample is digested.

Improving both sensitivity and throughput across all modalities is critical to meet the future dark matter and neutrinoless double beta decay science goals. Given the wide range of modalities and sensitivity needs, a distributed screening model, making use of expertise at facilities and national labs as well as at universities, has been successful to date and continues to be promising for the future.

4.8.4 PRD 26 Addressing challenges in scaling technologies

Scaling of technologies permeates nearly every aspect of high energy physics experiments and squarely belongs in the category of cross-cutting PRDs. The challenges range from the required scaling in detector size and mass, number of readout channels, purity and radiopurity, sensitivity, and being able to operate in unprecedented regimes of temperature or radiation environments. Some experiments also aim at spanning large geographic areas. In many future experiments, multiple scaling challenges have to be faced simultaneously. A number of Thrusts have been identified in this PRD:

Thrust 1: Detector mass

The challenges in scaling detector mass occur at many different levels. One primary reason for scaling up in mass is to increase total interaction rate, and the challenges in scaling detector mass occur at many different levels. The use of CCDs for dark matter detection requires scaling up the detector mass into the kilogram regime. In the area of noble element detectors, the magnitude of the scaling is into the many ton (for dark matter) to many kilo-ton (for neutrinos) regime. Scaling up in size leads to several technological challenges. Larger detector volumes call for longer drift distances for the collection of signals. Signal degradation due to diffusion, scattering, and impurities are significant challenges. The latter necessitates scaling of purification systems. Larger detector volumes can also impose increasingly stringent requirements on radiopurity of the materials to limit background signals, as described in the previous PRD.

Thrust 2: High voltage delivery

Larger detector volumes call for longer charge drift distances in TPCs, which in turn require higher drift voltages than achieved in the current experiments. Delivery of voltages exceeding 600 kV without electrical breakdown are required for the current set of experiments. Upgrades of these experiments and future experiments may have even higher voltage requirements. The development of clean and robust high voltage feedthroughs and high-voltage distribution systems is a clear area of research. Advances in this area will benefit greatly from the emergence of facilities to test future high-voltage solutions as well as from the coordination of currently available expertise.

Thrust 3: Fundamental material properties

Related to the requirement of very high voltages in noble liquids is the need for improved understanding of field emission and electric field properties of electrodes in noble elements. Similarly, for the next collider, the detectors are exposed to extreme radiation environments paralleling exposures seen in nuclear reactors or tokamaks. Two orders of magnitude increase in radiation flux is anticipated, in which sensors and active electronics need to perform for well over a decade. A thorough understanding and characterization of material and device properties needs to be gained to enable these experiments. A whole class of experiments calls for operation at very low temperatures, below 100 mK. Enhanced understanding of material and device properties at these temperatures will be crucial to achieve the science goals.

Thrust 4: Large-volume magnetic fields

In a wide range of experiments, new physics opportunities are enabled by immersing detectors with tracking capability in magnetic fields to boost particle identification performance. In some specific cases, enhancing field strength increases potential event rates. In order to magnetize future large-volume detectors, be it for dark matter searches, neutrino detection or for future colliders, non-trivial challenges need to be addressed that will require further development of large-scale superconductors. Scaling the use of high-temperature superconductors to these large volumes would have transformative impact.

Thrust 5: Channel count

Future experiments will enhance their sensitivity partly by increasing the granularity with which the data is recorded; that is, with a larger number of readout channels. Data volumes exceeding many tens of terabytes per second will have to be transmitted. This brings enormous challenges in electro-optical data transmission, clock distribution and synchronization of signals, power management, and front-end data processing in FPGAs. For example, the presently used data link architecture in which front-end ASICs communicate electrically to optical converters does not scale to arbitrary data rates. For future collider environments 10 Gbps/cm^2 of output data rate is anticipated. Projected improvements in both channel bandwidth and on-chip data compression will fall short, even before considering the need to reduce mass.

Thrust 6: Data volume

Finally, larger detectors will produce a large quantity of data that, without advances in triggering, data acquisition, and data analysis, threaten to overwhelm existing computational capabilities.

Research Plan

The enormity of the challenge in scaling technologies to the next generation projects is such that a collaborative effort between the multi-program national laboratories, universities, and industry is required. This reports clearly describes the areas where scaling is a major factor in achieving the science goals. Scaling is not new to high energy physics, but to achieve the maximum benefit an understanding of the research directions at the various national labs and industry can lead to a promising, collaborative and cost-effective approach to start tackling scaling problems for the next generation experiments. Once the research program has been defined and prioritized, small-scale collaborative experiments should be initiated that will benefit from the different environments and backgrounds present in the collaboration. In the area of high-voltage delivery, for example, novel ideas are beginning to be explored, including the use of resistive materials, the study of the properties of surface treatments in different purity environments, and the improved understanding of the dielectric properties of noble elements. The need to develop the capability to trigger, handle, process, and analyze the exponential increase in data volumes that will come with future large-scale detectors is common to many areas of science and the industrial cloud. Synergies exist with light and neutron scattering sources; addressing the challenges through a common project would benefit the broader science community. In the area of radiation damage, close collaboration with the fusion energy efforts, which face some of the same problems, would accelerate progress.

Facilities and Capabilities

To rapidly advance the research required for scaling technologies, support for multi-disciplinary efforts across the Office of Science and access to the facilities and capabilities needs to be provided. PRD 25 outlined the needs for scaling of radiopurity screening. In the area of high-radiation environments, the fusion energy community is building the Material Plasma Exposure Experiment (MPEX), to study the characteristics of materials that have been exposed to the plasma. These materials will be exposed to high-energy neutrons, ions, and electrons that damage and degrade materials. These studies could inform the radiation tolerance of materials used in targets for neutrino production and in collider experiments. In the area of high data volumes, access to the national leadership computing facilities will provide critical links to existing programs that will help expedite progress. For example, to emulate the Western Australian portion of the Square Kilometer Array (SKA) experiment, researchers at leadership computing facilities ran simulations that mimic the SKA's data collection. Data was generated at 247 GBps and using the Adaptable IO System (ADIOS) software platform, successfully demonstrated handling such large amounts of date in real time. Across the Thrusts of this PRD, strategic partnerships, combined with support for small-scale experimentation at the traditional high energy universities and laboratories, will enable swift and efficient progress in addressing technological barriers in scaling existing technologies.

4.8.5 Cross-Cutting Priority Research Directions and the Grand Challenges

The PRDs and research plans described in this section address the Grand Challenges in a variety of ways. PRD 24 seeks to advance HEP detectors to new regimes of sensitivity, corresponding to Grand Challenge 1, by promoting the development of novel materials and operating modes, corresponding to Grand Challenge 3, specifically by manipulating detector media to increase interaction rates, enhance the production, collection, or localization of the relevant signal modality, or to actively tune the medium's performance. PRD 25 addresses Grand Challenge 3 by seeking to develop materials that are novel in their chemical, radiological, and/or isotopic purity and that require advanced techniques for purification and storage. It addresses Grand Challenge 4 by mastering the production and maintenance of these extremely pure environments. These advancements in purity will enable HEP detectors to reach new regimes of sensitivity corresponding to Grand Challenge 1. PRD 26 seeks to address challenges in scaling technologies to diverse new regimes, many of which involve extreme environments or data rates or both. In some cases (channel count and data volume), integration is a key tool to enable scalability corresponding to Grand Challenge 2. In other cases, material properties must be better understood and advanced construction or operation techniques or both must be employed to enable scalability, corresponding to Grand Challenge 3.

5 Facilities in Support of HEP

Progress in particle physics depends on a multitude of unique facilities and capabilities that underpin the advanced detector R&D program see Table 23. There is terrific infrastructure in place in various user facilities and centers at national labs and universities that are being used already by the HEP community. These are, for example, the various light sources to study the photon response of detectors, DOE and university centers for nano-scale materials and high-field magnet labs. The field, however, also needs specialized, dedicated facilities for their detector development. It is critical that these core facilities continue to be supported and that new capabilities required for testing and evaluation of detectors for future experiments be created. The value of the facilities can be gauged by the number of users and the number of scientific publications as is done for official DOE user facilities.

	Higgs and Energy Frontier	**Neutrinos**	**Dark Matter**	**Cosmic Acceleration**	**Unknown**
Irradiation, ionizing and non-ionizing	✓	✓			✓
Test Beams	✓	✓			✓
Test Stands at Ultra-low Temperature			✓	✓	✓
Calibration Facilities	✓	✓	✓	✓	✓
Low Background Materials and Assay		✓	✓		✓
Ultra-light Composites	✓				✓
Novel CCD Development			✓	✓	
Superconducting Detector and Device Foundry			✓	✓	
Microelectronics Engineering and Foundry Access	✓	✓	✓	✓	✓
Simulation Framework	✓	✓	✓	✓	✓

Table 23: Facility and capability needs for the five Science Drivers.

5.1 Existing Facilities

The availability of dedicated, specialized facilities has contributed immensely to the success of HEP. These facilities will continue to be critical for future instrumentation research and development. The following are a few important examples.

- **SiDet**: The Silicon Detector Center (SiDet) at Fermilab has been a pioneer in the development of large-scale silicon tracking detectors. Cleanroom space is dedicated to the fine-scale assembly of detector modules, microbonding, testing, and large-scale assembly of complete silicon trackers. The facility provides for close daily interaction between physicists, engineers, and technicians that has enabled an accelerated development of these detectors and a fertile, hands-on training ground for the next generation of practitioners. Because of the existing capabilities, the facility was also engaged in the R&D, CCD packaging, and focal plane assembly for dark matter and cosmological survey experiments.
- **Noble Liquid Development Facility**: The noble liquid testing facility at Fermilab is located at the Proton Assembly Building (PAB) and consists of five liquid argon cryostats, three of which can be booked by members of the community for tests. It also offers working areas for smaller temporary setups, including several open dewars. The three test stands available for booking focus on specific

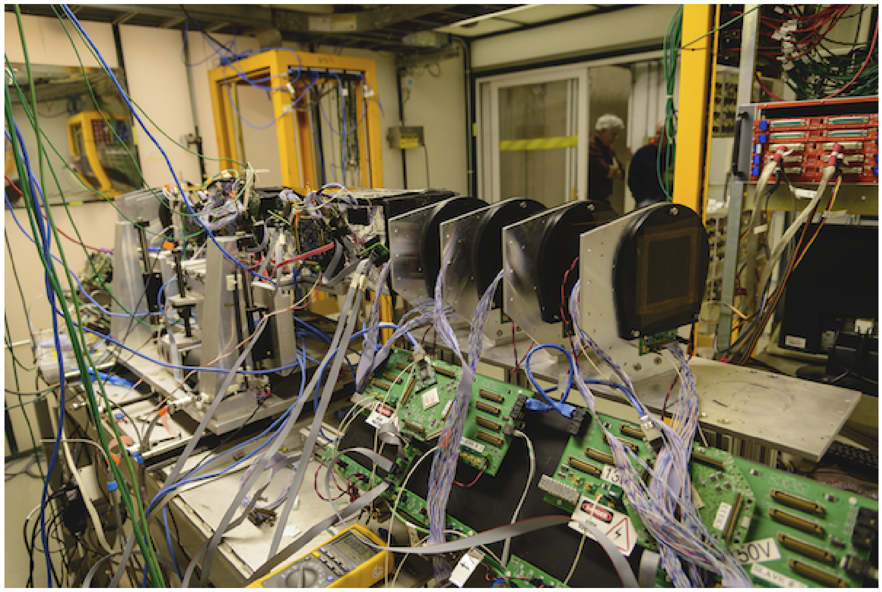


Figure 54: Experimental setup in the Fermilab Test Beam Facility (photo credit: Fermilab).

research topics: one, known as the Material Test Stand, is used to study the impact of materials on the electron lifetime; one is used for developing scintillation light collection technologies; and a multipurpose cryostat is mainly used for studying high-voltage breakdown in noble liquids.

- **MSL**: The Micro-Systems Laboratory (MSL) at LBNL is a semiconductor processing facility specializing in the fabrication of various types of radiation detectors and integrated electronics on high-resistivity silicon. Devices are fabricated using common process techniques including high-temperature oxidation, thin-film deposition, diffusion of impurity dopants, dry plasma etching, and photolithography. The back-side illuminated fully-depleted CCD was developed by MSL in 1996. They have been deployed on many telescopes world-wide, and their use has expanded beyond astronomy. New devices are now being developed for X-ray detection at light sources and for dark matter detection.

- **FTBF**: The Fermilab Test Beam Facility (FTBF) is a User Facility whose goal is to provide flexible and open access to test HEP detector concepts (see Figure 54). The facility consists of two versatile beamlines in which users can test equipment or detectors with the only high energy, hadron test beam in the U.S. This facility has been invaluable to demonstrate detector concepts. The FTBF is located in the Meson Detector Building and services users for approximately eight months per year whenever the Fermilab accelerator complex is operating outside the summer shutdowns. A typical year sees 20 different experimental efforts with more than 200 users from CMS, ATLAS, sPHENIX, collider physics, muon and neutrino experiments, general R&D, and outreach. The facility offers a number of experimental areas to accommodate both short-term runs of several weeks and longer duration experiments. Multiple groups often run simultaneously. A new area is under construction, the Irradiation Test Area, to support sample irradiation.

- **Test Beams at SLAC**: The End Station Test Beam at SLAC concluded its operations in 2019. It provided primary electrons with energies up to 15 GeV and secondary beams that were produced by using a Be target. Presently, the XTA (X-band Test Accelerator) can supply primary beams of electrons with energies up to 100 MeV. Additionally, FACET-II will enable access to up to 13 GeV beams of electrons after its commissioning in 2020. The proposed Sector 30 Transfer Line (S30XL) will provide near-CW beams of 4 GeV electrons at currents of pA to μA to End Station A; the beam energy will be increased to 8 GeV by the LCLS-II High Energy Upgrade project.

In addition, there exist other facilities including the Precision Metrology Facility, Rapid Prototyping and

Lithography Etching Film Deposition CCD Wafer

Figure 55: Photographs of the various processing bays of the Micro-Systems laboratory at LBNL with a picture of a fully processed CCD wafer. (photo credit: LBNL).

Special Materials Facilities, and Custom Detector Technologies Facility at Fermilab and Noble Liquid Test Stands at BNL and SLAC. These facilities provide unique opportunities for training students and young researchers. They also train the technical experts needed to design, build and operate such facilities.

5.2 Facility Needs

To support an advanced detector R&D program to execute the next generation of particle physics experiments, the following facility needs have been identified in the preceding technology sections and are summarized here.

Irradiation and post-irradiation evaluation

Future particle accelerator-based experiments will experience unprecedented radiation exposures of 10 GigaGray ionizing dose and 10^{18} 1 MeV-equivalent neutrons/cm^2 over their lifetimes. Detectors, support structures, electronics, data transmission components, and on-board data processing units will all need to be evaluated for performance at these dose rates and integrated doses two orders of magnitude greater than systems operating today. This will require new high-dose-rate environments for accelerated testing so that the anticipated integrated dose can be delivered in days rather than months or years. Activation of the detector materials will limit facility throughput unless remote material handling techniques are implemented. Such techniques are already employed for irradiation and post irradiation evaluation (PIE) of accelerator components such as targets and windows for neutrino beam lines, but many of the irradiation facilities are at capacity.

Facilities for long-term irradiation at lower dose rates are employed for outer detector components, such as calorimeters, where accelerated testing at high dose rates has been found to underestimate damage. Some of today's high dose rate facilities are representative of the dose rates required, but lack the availability and duty cycle needed to support next-generation and beyond detector development.

Test beams

CERN, the center for HEP in Europe, has exemplary test beam facilities with superb user support. A significant revitalization of U.S. facilities is needed to enable the detailed tests required. This effort should be executed holistically by evaluating all facilities in the country. For example, multiple electron beams are available at the light sources and at JLab and SLAC, and a 2.8 MW proton driver will soon be available at ORNL. In the next decade a rapid cycling synchrotron will be available as part of the Electron Ion Collider at BNL that might provide operation modes that could provide electron test beams. These facilities are complementary to other facilities around the world. Among the future needs will be very precise test beams (spatial, energy spread, timing, intensity) and potentially a new facility that can provide very high energy (TeV) test beams. JLab and SLAC may be suitable for the former as they offer very high quality electron beams at energies up to 12 GeV. The only accelerator that could host a TeV-scale test beam is the accelerator complex at CERN.

Simulation framework

Equally important is the capability to perform detailed, reliable, and predictive simulations of new detector technologies. This will be critical for any new detector proposal, especially those at future colliders. Although test beams provide valuable reference points, the full phase space can never be covered and accurate simulations are required to understand the performance under realistic running conditions. The field is currently already facing significant computing challenges, since the current simulation platforms are not adequate to carry out reliable simulations in a timely manner. To take advantage of next generation high performance computing platforms, significant research needs to be carried out, bearing in mind that the current simulation tools were developed over a period spanning at least three decades within large teams of physicists and software engineers.

Ultra-low temperature test stands

As described in the dark matter and quantum sensor sections, these areas of research will impose exacting requirements on ultra-low temperature (mK) environments and significant testing will be required to realize future experiments. Yet, test stands for operating at these temperatures are costly and limited in number. These high value assets are dispersed throughout the community, primarily at national labs and large research universities. Some were funded by HEP while many have been funded by institutional investments and other government agencies.

The expansion of interest in such facilities is a relatively recent phenomenon, driven largely by the quickly growing HEP-QIS overlap, and thus there is not yet a consensus on the scale of community need and what siting and operating models ensure appropriately broad access and sustainable operation. Hand-in-hand with facilities supply and access is the question of what explicit efforts ought to be made to disseminate expertise in areas relevant to work that use such facilities—in particular device design and fabrication and experimental techniques—and to facilitate access. Further study by the relevant communities would clarify the situation and better define a path forward. Such study would also determine the potential impact of technical or manufacturing advances that reduce the cost of such test stands, though it is not clear that direct HEP funding for such work would substantially augment the much larger commercial and governmental interest driven by quantum computing.

Specialized calibration facilities

There are a number of specialized calibration facilities that will be needed to characterize detectors in new regimes. Low-energy neutron beams are needed to calibrate direct dark matter search detectors. Facilities for preparation and calibration of low-level and specialized radioactive calibration sources are needed to support a variety of detectors for neutrino physics and dark matter. Facilities such as the Radiochemical Processing Lab at PNNL and in C-division at LANL have expertise in this area, but have not traditionally worked with the HEP community. RF and microwave test facilities are essential for calibration of axion-like dark matter detection systems. These varied capabilities reside at specific institutions with the unique infrastructure needed, most of them not at the traditional high energy physics laboratories.

Low-background materials and assay

Central to the development of any low-background detector system is an accurate background model and validation of that model with assays and identification or development of alternative materials with greater radiopurity as needed. The techniques employed are varied and the assets to perform assay at the required sensitivities are distributed throughout the U.S. and overseas, both at national laboratories and universities. Examples include the facilities at underground labs at SNOLAB in Canada, LNGS in Italy, SURF (see Figure 56), PNNL, and LBNL in the U.S., Boulby in the U.K., MPIK in Germany, and HADES in Belgium. A robust program in basic R&D is invaluable for pushing the sensitivity limits of assay techniques, identifying promising new materials for use in low-background detectors, and developing the radiochemical purification and materials handling.

Besides access, there would also be greater efficiency in having a community-wide coordination element that includes maintaining supply chain information, papers on production and measurement techniques, and a database of results. For example, SNOLAB currently hosts radiopurity.org that maintains a database of assay results. This is a hugely valuable service to the community, but it is in danger of becoming obsolete due to inadequate support.

Figure 56: Left: Low background counting clean room facility on the 4850' level of the Sanford Underground Research Facility (SURF). The detectors from left to right around the room are the Mordred, SOLO, Morgan, Maeve and Twins detectors, all HPGe spectrometers. Right: Copper electroforming facility at the 4850' level of SURF. The electroforming process removes radioactive constituents including naturally occurring uranium and thorium as well as the activation product Co^{60}. The process is done underground to suppress reintroduction of the latter. The part shown is for the Majorana Demonstrator project.

Microelectronics capability and foundry access

The use of application specific integrated circuits (ASICs) is ubiquitous in particle physics experiments. The drivers for in-house capability include the harsh environments in which the devices have to operate (radiation, temperature) and the need to tailor electronics to specific detector outputs, data rates, etc. There are many elements required to support this capability.

Personnel with requisite skills in electrical engineering, device design, layout, and familiarity with the design and validation tool suites is essential. Such skilled personnel are highly sought after by industry and maintaining a pipeline of students and early career engineers and scientists with these skills is essential. Enabling continued participation of university groups will be critical.

The design and validation tools are unique to each foundry process and are increasingly more expensive as technology moves to smaller feature sizes. HEP has unique needs for process and device models both at low (down to 4K) temperatures as well as under high radiation dose rates and integrated dose. Experimental data is needed to build these models that can then be integrated with the design and validation software. This must be redone for each new foundry process and feature size.

Given the escalating costs of the design and validation tools, wafer processing, and device characterization to build models for extreme environments unique to HEP, and the high cost of having to port designs, it would be prudent for HEP to work with other U.S. government agencies and CERN to identify foundries and processes that will be more enduring, from an industrial obsolescence standpoint with regard to access by the HEP community, as well as focus R&D activities on those processes. To further realize cost savings, many institutions rely on building blocks that can be used in multiple System On Chip (SOC) designs. University consortia with implicit lab and U.S. foundry access could be used to help support basic research, create a pipeline for lab staff (and U.S. industry), support this critical U.S. technology sector, shore up lab programs, and build a foundation for the future.

There is no access to research lines in U.S. foundries where process parameters can be varied. This is in stark contrast to the situations in Europe and Asia where there are often multiple industrial partners who open their research processing lines for collaboration with the scientific community to develop new devices or optimize processes.

Ultra-light composites

Carbon fiber composites are used to minimize scattering in tracking detectors. These structures provide precise and stable positioning of detector elements at the level of 10-20 μm, and often have integrated cooling for the detectors and electronics. The structures built by HEP typically use some of the thinnest and highest stiffness materials available commercially and are much thinner and more precisely manufactured than those produced in industry. The capability to design and fabricate these structures has been developed in the U.S. national labs over the past few decades, primarily for collider experiments. Because HEP needs are a significant departure from industrial ones, it has proven difficult, nearly impossible, to transition this work to industry. Adding to the challenge in the future will be radiation levels that may impact the structural integrity of the polymers used in commercial materials. As plans for a very large hadron collider emerge, the impact of the intense radiation environment on the structural integrity of composites may require additional R&D. Ongoing support for in-house fabrication capability will be needed to support advanced detector R&D.

Novel CCD manufacturing and development

Ongoing work on CCDs using current technology is threatened by the choice by commercial foundries to terminate support for non-standard processes crucial to the HEP community, such as thick, fully depleted silicon CCDs on 200 mm wafers. Sourcing of high-resistivity wafers has also become challenging. A variety of potential future R&D paths for CCDs are discussed in this report. Pursuing them would require upgrades to existing facilities for post-processing of Si CCDs as well as new infrastructure to pursue new Si CCD post-processing methods and Ge CCD development. In both cases, continued support for engineers for the fabrication and for technicians for the assembly and testing of prototype CCDs is a necessity.

Superconducting detector and devices foundry

The fabrication and development of superconducting detectors is a critical capability that crosses multiple technologies (e.g. photodetectors, quantum sensors), with applications across multiple science thrusts (e.g. cosmic acceleration, dark matter). While various national labs and universities have developed such facilities based on local needs, the potential growth in this area motivates consideration of a more systematic approach. Fabrication facilities focused on materials and processes dedicated to high impact applications would be an important resource for successful development of many of the technologies discussed in this report. Relevant facilities would require cleanroom space equipped with thin film growth and processing tools. Such facilities would need to be staffed and operated with both controlled processes and scalable capabilities to provide a reliable resource to the community. Commercial options for such facilities are becoming more viable as the need for superconducting devices, both inside and outside of HEP, grows.

As noted, most facilities with their unique expertise are not run as a traditional Office of Science user facility. An issue facing the community is how to facilitate and coordinate access to these limited resources to enable smaller research groups to participate in new burgeoning areas of detector R&D, where the initial investment costs far exceed their budgets. A possible model is a distributed national user facility, such as the DOE Atmospheric Radiation Measurements (ARM) facility. Another option is to structure some facilities as a user facility, open to the larger user community where utilization is prioritized based on a user proposal-based review process. In some cases, it should be studied if certain capabilities cannot be integrated in the existing five DOE nanoscience centers.

6 Definitions of Technical Terms and Acronyms

4D	Four dimensional
4MOST	4-meter Multi-Object Spectrograph Telescope
AAO	Australian Astronomical Observatory
AC-LGAD	AC-coupled Low-Gain Avalanche Detector
ADC	Analog-to-digital Converter
ADIOS	Adaptable Input Output System
ADMX	Axion Dark Matter eXperiment
ADMX-G2	ADMX-Generation 2
AFM	Atomic Force Microscope
AI	Artificial Intelligence
AIM-CO	ASIAA Intensity Mapping for CO
ALD	Atomic Layer Deposition
ALICE ITS	A Large Ion Collider Experiment Inner Tracking System
ALP	Axion-like Particle
AMS-II	Alpha Magnetic Spectrometer-II
APD	Avalanche Photo Diode
ArgoNeuT	The Argon Neutrino Test
ARIADNE	Axion Resonant InterAction DetectioN Experiment
ARM	Atmospheric Radiation Measurements facility
ASIC	Application Specific Integrated Circuits
ATLAS	A Toroidal LHC ApparatuS
ATLAS IBL	Insertable B Layer
BaF2	Barium fluoride
BAO	Baryon Acoustic Oscillation
$^{9}Be^{+}$	Singly charged beryllium ion
BES	Basic Energy Sciences, DOE Office
BGO	Bismuth germanate
BNL	Brookhaven National Laboratory
BRN	Basic Research Needs Study
BSM	Beyond the Standard Model
CAD/EDA	Computer-Aided Design/ Electronic Design Automation
CASPEr	Cosmic Axion Spin Precession Experiment
CC	Charged-current
CCAT-Prime	Cerro Chajnantor Atacama Telescope-prime
CCD	Charge-coupled device
CEBAF	Continuous Electron Beam Accelerator Facility
CEPC	Circular Electron Positron Collider
CERN	European Laboratory for Particle Physics
CEvNS	Coherent Elastic Neutrino-Nucleus Scattering
CHIME	Canadian Hydrogen Intensity Mapping
[CII]	Singly-ionized Carbon
CLFV	Charged Lepton Flavor Violation
CLIC	Compact Linear Collider (a proposed particle accelerator at CERN
CMB	Cosmic Microwave Background
CMB-S4	Cosmic Microwave Background-Stage 4 experiment
CMOS	Complementary Metal–Oxide–Semiconductor
CMS	Compact Muon Solenoid experiment
CNB	Cosmic Neutrino Background
CNO	Carbon-Nitrogen-Oxygen
CO	Carbon Monoxide
CO2	Carbon Dioxide

Codex-B	Compact Detector for Exotics at LHCb
COMAP	Carbon Monoxide Mapping Array Pathfinder
COMET	COherent Muon to Electron Transition
COSY	Cooler Synchrotron a partcile accelerator at Forschungszentrum Jülich
COTs	Commercially Off The shelf
CP	Charge-parity
CPAD	APS-DPF Coordinating Panel for Advanced Detectors
CPU	Central Processing Unit
CsI	Cesium Iodide
CsTe	Cesium Telluride
CTE	Coefficient of thermal expansion
CVD	Chemical vapor deposition
DAMA/LIBRA	DArk MAtter/Large sodium Iodide Bulk for RAre processes
DAQ	Data Acquisition
DarkSide-50	Physics detector in the Darkside program
DarkSRF	Dark Superconducting Radio Frequency
DARPA	Defense Advanced Research Projects Agency
DARWIN	DARk matter WImp search with liquid xenoN
DBD	Double beta decay
DC	Direct current
DC/DC	Direct Current to Direct Current
DEAP-3600	Dark matter Experiment using Argon Pulseshape Discrimination
DESI	Dark Energy Spectroscopic Instrument
DFSZ	Dine–Fischler– Srednicki – Zhitnitsky axion model
DLL	Delay-Locked Loops
DM	Dark matter
DOE-SC	U.S. Department of Energy, Office of Science
DRC	Design Rule Checking
DUNE	Deep Underground Neutrino Experiment
E	Electron
ECAL	Electromagnetic Calorimeter
ENC	Equivalent Noise Charge
EDM	Electric Dipole Moment
EIC	Electron Ion Collider
EM	Electromagnetic
ER	Electron Recoil
ERDM	Electron Recoil Dark Matter
eV	Electron Volt
FACET-II	Facility for Advanced Accelerator Experimental Test-II at SLAC
FASER-II	ForwArd Search ExpeRiment II
FCC-ee	Future Circular Collider e+e- a proposed accelerator at CERN
FCC-hh	Future Circular Collider hadronic a proposed accelerator at CERN
FEL	Free Electron Laser
FELIX	FrontEnd LInk eXchange
FES	Fusion Energy Science, DOE Office
FNAL	Fermi National Accelerator Laboratory
FOA	Funding Opportunity Announcement
FOM	Figure-of-Merit
FPGA	Field-Programmable Gate Array
FTBF	Fermilab Test Beam Facility
G2	Generation-2
G3	Next-Generation Dark Matter Experiments
G3Xe	Next-Generation LXe Observatory for Dark Matter Neutrino Physics
GADMC	Global Argon Dark Matter Collaboration

GaInP	Gallium Indium Phosphide
gamma ray	Electromagnetic radiation
Gbps	Giga bits per second
GEANT4	GEometry ANd Tracking
GEM	Gammas, Electrons, and Muons
GHz	Gigahertz
GRad	Giga Rad
GSa/s	Giga Samples per second
GPU	Graphics Processing Unit
HADES	The Belgian Underground Research Laboratory
HAWC	High Altitude Water Cherenkov Observatory
HAYSTAC	Haloscope At Yale Sensitive To Axion CDM
HCAL	Hadron calorimeter
HE-LHC	High Enery Large Hadron Collider a proposed accelerator at CERN
HEP	High Energy Physics, Department of Energy Office of Science
HEPIC	High Energy Physics and Instrumentation Center in Brazil
HFIR	High Flux Isotope Reactor
HGCAL	The endcap calorimeter for the Phase-2 upgrade of the CMS experiment for the HL-LHC
high-Q	High-Quality factor
HL-LHC	High-Luminosity LHC
HPGe-	High-Purity Germanium
HPHT	High-pressure high-temperature
HTS	High Temperature Superconductor
Hz	Hertz
HV	High Voltage
IAXO	International Axion Observatory
IC	Integrated Circuits
ICARUS	Imaging Cosmic And Rare Underground Signals experiment
ICPMS	Inductively-Coupled Plasma Mass Spectrometry
IFU	Integrated Field Unit
I/O	Input/Output
IoT	Internet of Things
IP	Intellectual Property
IR	Infrared radiation
JSCPAEP	Joint Stock Company Production Association Electrochemical Plant
JLab	Thomas Jefferson Laboratory
KID	Kinetic Inductance Detector
K	Kelvin
kHz	Kilohertz
KSVZ	Kim–Shifman–Vainshtein– Zakharov
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science CEnter
LAPD	Liquid Argon Purity Demonstrator
LAPPD	Large Area Picosecond Photodetector
LArIAT	Liquid Argon In A Testbeam
LArTPC	Liquid Argon Time-Projection Chamber
LC	Inductor(L) and Capacitor(C) electronic circuit
LCLS-II	Linac Coherent Light Source-II
LDMX	Light Dark Matter eXperiment
LEP	Large Electron-Positron collider
LGAD	Low Gain Avalanche Detectors
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty experiment

LIDAR	Light Detection and Ranging system
LIGO	The Laser Interferometer Gravitational-Wave Observatory
LISA	The Laser Interferometer Space Antenna
LN	Liquid Noble
LNGS	Laboratori Nazionali del Gran Sasso, Italy
LS4	Fourth Long Shutdown of the LHC
LSST	Vera C. Rubin Observatory Legacy Survey of Space and Time
LUX	Large Underground Xenon experiment
LXe	Liguid Xenon
LXeTPC	Liquid Xenon Time Project Chamber
LYSO	Lutetium-yttrium oxyorthosilicate
LZ	LUX-ZEPLIN experiment
M	Million
MAPS	Monolithic Active Pixel Sensor
MARK-II	An experiment at the Stanford Linear Accelerator
MATHUSLA	MAssive Timing Hodoscope for Ultra Stable neutraL pArticles
MBE	Molecular beam epitaxy
MCP	Microchannel Plate
mCP	Milli-charged particle
MEG II	The Mu to E Gamma II experiment
MEM	Micro-ElectroMechanical system
mHz	MegaHertz
MIP	Minimum Ionising Particle
MKID	Magnetic Kinetic Induction Device
ML	Machine Learning
MOSIS	Metal-Oxide Semiconductor Implementation Service
Mpc	Megaparsec
MPEX	The Material Plasma Exposure Experiment
MPIK	The Max Planck Institute for Nuclear Physics, Germany
MRad	MegaRad
MSL	Microsystems Laboratory at LBNL
Mu2e	Muon-to-Electron-conversion experiment
Mu3e	Muons (Mu) to an electron and two positrons (3e) experiment
N	Nucleon
NASA	National Aeronautic and Space Administration
NDA	Nondestructive Assay
NIST	National Institute for Standards and Technology
NLDBD	Neutrinoless double beta decay
NMOS	N-type metal-oxide-semiconductor
NMR	Nuclear Magnetic Resonance
NNSA	U.S. National Nuclear Security Administration
NOL	Nanostructured-Organo-silicon-Luminophores
NQI	National Quantum Initiative
NRDM	Nucleon Recoil Dark Matter
NRAO	The National Radio Astronomy Observatory, USA
NSF	National Science Foundation
NV	Nitrogen Vacancy
[OII]	Singly-ionized oxygen
P5	2014 Particle Physics Prioritization Panel
PAB	Proton Assembly Building
PB	Peta-byte
PCB	Printed Circuit Board
pCT	Proton radiography and Computed Tomography
PCTFE	Polychlorotrifluoroethylene

PET	Positron Emission Tomography
PF	Particle Flow
pflops	petaflops
PFS	Prime Focus Spectrograph
PICO	Pacific Institute for Community Organization
PIE	Post-irradiation evaluation
PLL	Phase-Locked Loops
PMNS	Pontecorvo-Maki-Nakagawa-Sakata
PMT	Photomultiplier tube
PN junction	a boundary between p-type and n-type semiconductor material
PNNL	Pacific Northwest National Laboratory
pp	Proton-proton
PRD	Priority Research Direction
PROSPECT	Precision Oscillation and Spectrum Experiment
ps	Picosecond
PFS	Prime Focus Spectrograph
pT	Particle transverse momentum
PUMA	Packed Ultra-wideband Mapping Array
QCD	Quantum Chromo Dynamics
QIS	Quantum Information Science
QND	Quantum Non-Demolition
QuantISED	Quantum Information Science Enabled Discovery program
R	Recoils
RD	Research and Development
RAM	Random Access Memory
RF	Radio Frequency
RHIC	Relativistic Heavy Ion Collider
RICH	Ring Imaging Cherenkov detector
RISC	Reduced Instruction Set Computer
S30XL	Sector 30 Transfer Line at SLAC
SBIR	Small Business Innovation Research
SBN	Short-baseline neutrino
SEB	Single Event Burnout
SEE	Single Event Effects
SEL	Single Event Latch-up
SENSEI	Sub-Electron-Noise SkipperCCD Experimental Instrument
SET	Single Event Transient
SEU	Single Event Upset
SHiP	Search for Hidden Particles
SiDet	Silicon Detector Center
SiPM	Silicon photomultiplier
SIS	Superconductor-insulator-superconductor
SKA	Square Kilometer Array
SKIROC2-CMS	A front-end readout ASIC for the CMS HGCAL calorimeter
SLAC	Stanford Linear Accelerator Center
SM	Standard Model
SNe Ia	Type Ia supernova
SNOLAB	Sudbury Neutrino Observatory (SNO) Laboratory
SNS	Spallation Neutron Source
SNSPD	Superconducting Nanowire Single Photon Detector
SoC	System-on-Chip
SPAD	Single-photon Avalanche Diode
SQL	Standard Quantum Limit
SQUID	Superconducting Quantum Interference Devices

SSA	Silicon Strip ASIC
SSC	Superconducting Super Collider
STAR	Solenoid Tracker at RHIC
STEM	Science, Technology, Engineering, and Mathematics
SuperCDMS	Super Cryogenic Dark Matter Search
SURF	Sanford Underground Research Facility, South Dakota
T	Time reversal symmetry
TAPO	Trusted Access Program Office
TC	Critical Temperature
TCSPC	Time Correlated Single-Photon Counting
TDAQ	Triggered Data Acquisition
TDC	Time to Digital Converter
TES	Transition Edge Sensor
tHz	teraHertz
TIM	[CII] Terahertz Intensity Mapper
TIME (CO/CII)	Tomographic Ionized Carbon Intensity Mapping Experiment
ToF	Time-of-Flight
ToA	Time-of-Arrival
TORCH	Time Of internally Reflected CHerenkov light
TPB	Tetra-phenyl butadiene
TPC	Time Projection Chamber
TR	Technical Requirement
TSMC	Taiwan Semiconductor Manufacturing Company foundry
TSV	Through Silicon Via
TUNL	Triangle Universities Nuclear Laboratory
UHE	Ultra-high-energy
UV	Ultraviolet
VCSEL	Vertical-cavity Surface-emitting Laser
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VRO	Vera C. Rubin Observatory Legacy Survey of Space and Time
VUV	Vacuum Ultraviolet
W	Watt
WIMP	Weakly Interacting Massive Particle
X-ray	Electromagnetic radiation
XTA	X-band Test Accelerator at SLAC

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8 Acknowledgements

Many people contributed at various stages of the Basics Research Needs study that led to this report. We are grateful to those who played roles beyond the report authors. The Report's ”readers” gave us critical feedback and provided fact checking during the final stages of preparation. Many thanks for this to Dan Akerib (SLAC National Laboratory), Myron Campbell (University of Michigan), Andy Lankford (University of California Irvine), Ritchie Patterson (Cornell University), Steve Ritz (University of California Santa Cruz) and Heidi Schellman (University of Oregon). Our report benefited enormously from professional editing assistance by Tiffani Conner, (Oak Ridge Associated Universities). DOE staff and contractors were always responsive to logistical requests. We especially thank Donna Nevels and Christie Ashton who provided outstandingly professional support at the workshop and contributed importantly to the immensely positive and constructive atmosphere that was highly conducive to productivity.

9 Basic Research Needs Study Participants

Twenty four Panel Leads, thirty six Panel Members, five Cross-cut Panel Members and two Co-Chairs participated in the Basic Research Needs Workshop.

Co-Chairs

Bonnie Fleming	Yale University
Ian Shipsey	Oxford University

Cross-Cut Panel

Marcel Demarteau	Oak Ridge National Laboratory
James Fast	Thomas Jefferson National Laboratory
Sunil Golwala	California Institute of Technology
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Panel Leads

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10 Basic Research Needs Study Charge

Department of Energy
Office of Science
Washington, DC 20585

10 July 2019

MEMORANDUM FOR HELMUT MARSISKE

FROM: GLEN CRAWFORD
DIRECTOR, RESEARCH AND TECHNOLOGY DIVISION
OFFICE OF HIGH ENERGY PHYSICS (HEP)

SUBJECT: Basic Research Needs Study on HEP Detector Research and Development

I request that you organize and carry out a Basic Research Needs (BRN) study to assess the present status of the HEP technology landscape, and to identify strategic technology areas, aligned with the strengths of the US community, that future long-term research and development (R&D) efforts should focus on in pursuit of the HEP science drivers identified in the P5 report. For each of these areas, the study should articulate and justify a set of Priority Research Directions (PRDs) to push the technology well beyond the current state of the art, potentially leading to transformative advances with broad-ranging applicability in HEP and beyond. Furthermore, the study should identify a small set of high-impact instrumentation "Grand Challenges" where technological breakthroughs could lead to game-changing experimental capabilities in pursuit of HEP science goals.

You should select co-chairs to lead the study and work with them to select the core group of working group leads to carry it out. The study encompasses responses to the specific charge elements elucidated below and is expected to take several months to complete. A focal point of the study should include a workshop, with attendance beyond the core group, expected to be held in December 2019 time frame in the Washington, DC area. The study participants are to serve by invitation only.

The HEP Detector R&D program aims to develop cutting-edge, novel instrumentation to enable scientific leadership in a worldwide experimental program that is broadening into new research areas with ever increasing demands in sensitivity, scale, and cost. To meet this challenge, HEP aims to execute a program appropriately balanced between incremental, near-term, low-risk detector R&D and transformative, long-term, high-risk detector R&D.

With the near-term technical challenges of current high-priority P5 projects subsiding, the HEP Detector R&D program aims to shift more emphasis towards building a long-term, high-risk high-reward ("Blue Sky") R&D portfolio that holds the promise of transformative advances with broad-ranging applications across HEP as well as other fields of science, medicine, and national security. Crucially, the program must take full advantage of the major advances happening in other scientific disciplines such as materials science, photonics, nanotechnology, and QIS, as well as innovations in the commercial sector such as in microelectronics and telecommunications. In light of constrained budgets, the Detector R&D program must optimize the use of human and technical resources through collaboration and equipment sharing.

Following the 2013 Snowmass Community Planning Exercise, the P5 Report emphasized the importance of instrumentation development for the long-term advancement of the field. In response, the DPF's Coordinating Panel for Advanced Detectors (CPAD) has organized since 2015 a series of "New Technologies for Discovery" annual community workshops that aim to "…explore and evaluate detector R&D opportunities, the critical needs of the field, and the challenges that lie ahead for HEP in the US within the context of the P5 plan and beyond". These workshops provide a broad survey of the detector technologies the US community is currently engaged in. Moreover, CPAD is using them to conduct a study to identify "research directions in instrumentation in support of the HEP science mission within the twenty-year P5 vision" where the US community can play a leadership role. The results of the CPAD study are summarized in a report available at https://anl.app.box.com/v/CPADReport2016. For this BRN study, the 2016 CPAD report together with any near-term updates and other workshop materials will provide the primary input for the assessment of the present state of the technology landscape relevant for HEP, summarized in a Technology Perspectives Factual Document.

In carrying out the BRN study, the following specific charge elements should be addressed:

- Survey the present state of the HEP technology landscape.
- Identify key enabling capabilities and associated performance requirements.
- Identify technologies to provide/enhance such capabilities.
- Articulate PRDs to push well beyond the current state of the art, potentially leading to transformative technological advances with broad-ranging applicability. Flesh out the required R&D efforts with deliverables with notional timelines and key technical milestones along the way. Elucidate the technical infrastructure required to support these efforts.
- Formulate a small set of instrumentation Grand Challenges that could result in game-changing experimental capabilities.

The study results should be described in a report delivered within two months following the completion of the workshop. DOE will use the study results to inform Detector R&D program planning, which may include a call for proposals to support new technology developments and capabilities that address the study priorities.

cc: James Siegrist, SC-25
Michael Procario, SC-25

11 Basic Research Needs Study Process and Organization

The Basic Research Needs (BRN) Study on HEP Detector Research and Development (R&D) was announced by the DOE HEP at the APS-DPF meeting in Boston in August, 2019. The co-Chairs had been appointed some months earlier.

The charge states that the Detector R&D BRN Study will:

- Survey the present state of the HEP technology landscape.
- Identify key capabilities and associated performance requirements to enable HEP Science Drivers.
- Identify technologies to provide or enhance such capabilities.
- Articulate long-term Priority Research Directions to push well beyond the current state of the art, potentially leading to transformative technological advances with broad-ranging applicability; flesh out the required R&D efforts including deliverables with notional timelines and key technical milestones along the way; and elucidate the technical infrastructure required to support these efforts.
- Formulate a small set of instrumentation Grand Challenges that could, if addressed successfully, result in game-changing experimental capabilities.

The co-Chairs met weekly with the DOE liaisons Glen Crawford and Helmut Marsiske in the months leading up to the announcement. The co-Chairs determined the BRN Study structure that would most effectively address the charge after considering several possibilities. The structure chosen diagonalises the field of HEP instrumentation first by physics and then by technology. The physics diagonalization identifies physics objectives and the Technical Requirements (TRs) to meet them. The technology diagonalization determines the Priority Research Directions (PRDs) and actionable research plans to meet the TRs.

Explicitly the structure consists of five Physics Panels based on the five P5 Science Drivers: the Higgs as a tool for discovery, the physics of neutrino mass, the new physics of dark matter, cosmic acceleration: inflation and dark energy, and exploring the unknown: new particles, new interactions and physical principles; and seven Technology Panels in alphabetical order these are: Calorimetry, Nobel Liquids, Photodetectors, Quantum Sensors, Readout and ASICs, Solid State and TDAQ (including Machine Learning).

Each Panel was led by two conveners. In addition to the conveners, the Physics Panels had two members and the Technology Panels had four members. There was also a Cross-cut Panel tasked with identifying synergies and cross-cutting themes both within and outside of HEP, and with elucidating the facilities and infrastructure needed to underpin the field.

In September regular telecons began to conduct the ground work for a productive and conclusive workshop in December that would lead to a report that is a crisp and compelling articulation of the essential enabling power of instrumentation to deliver the U.S. High Energy Physics program in a global context over the next twenty years.

A hallmark of the BRN Study was the very close interaction between the Physics Panels and Technology Panels and with the HEP community. The initial community input to the BRN Study was the DPF Coordinating Panel on Advanced Detectors (CPAD) 2018 Report "New Technologies for Discovery". Following on from this, the BRN Panels identified a number of experts and engaged in outreach to the relevant communities. This led in some cases to small targeted workshops.

A BRN website http://doe-brn-hep-detectorrandd.physics.ox.ac.uk provided email addresses of the conveners and co-Chairs and we encouraged the community to contact any convener or the co-Chairs with comments, ideas, suggestions or questions. The website also had portals to communicate with the BRN Study. In addition, many BRN Study members attended the CPAD Workshop in Madison, Wisconsin December 8-10, 2019 where each BRN Panel gave a plenary status report https://wp.physics.wisc.edu/cpad2019/.

The report took its final shape at a BRN Workshop in December 11-14, 2019 in the Washington D.C. area. The workshop was attended by all BRN Study members and a number of observers: DOE Program Managers from HEP and related programs, and from NSF. The plenary talks on the first day were live-streamed to the community. After the workshop BRN Study members continued to work on the report. A draft was circulated to designated readers and feedback was incorporated before transmission to HEPAP in July, 2020.

12 Basic Research Needs Study Workshop Agenda

Basic Research Needs Workshop on HEP Detector R&D
Hilton, Rockville, December 11-14, 2019

Wednesday, December 11, 2019
https://indico.cern.ch/event/870453/

8:30 – 9:10 a.m.	DOE Introduction *Helmut Marsiske (DOE)*
9:10 – 9:40 a.m.	Higgs and Energy Frontier *Gabriella Sciolla (Brandeis), James Hirschauer (Fermilab)*
9:40 – 10:10 a.m.	Neutrinos *Amy Connolly (OSU), Kate Scholberg (Duke), Ornella Palamara (Fermilab)*
10:10 – 10:40 a.m.	Dark Matter *Daniel Mckinsey (UC Berkeley), Jodi Cooley (SMU)*
10:40 – 11:00 a.m.	BREAK
11:00 – 11:30 a.m.	Cosmic Acceleration *Clarence Chang (ANL), Brenna Flaugher (Fermilab)*
11:30 a.m. - 12:00 p.m.	Explore the Unknown *Monica Pepe-Altarelli (CERN), Sarah Demers (Yale)*
12:00 - 1:00 p.m.	LUNCH *Presidential Foyer*
1:00 - 1:30 p.m.	Quantum Sensors *Andrew Geraci (Northwestern), Kent Irwin (Stanford)*
1:30 - 2:00 p.m.	Noble Elements *Jocelyn Monroe (University of London), Roxanne Guenette (Harvard)*
2:00 - 2:30 p.m.	Calorimetry *Francesco Lanni (BNL), Roger Rusack (UMN)*
2:30 - 3:00 p.m.	Solid State Vertexing and Tracking *Carl Haber (LBNL), Marina Artuso (Syracuse)*
3:00 - 3:30 p.m.	BREAK
3:30 - 4:00 p.m.	Photodetectors *Lindley Winslow (MIT), Peter Krizan (Jozef Stefan Institute)*
4:00 - 4:30 p.m.	TDAQ *Darin Acosta (UF), Tulika Bose (UW Madison)*
4:30 - 5:00 p.m.	Readout and ASIC *Gabriella Carini (BNL), Mitchell Franck Newcomer (Penn)*

5:00 - 5:30 p.m.	Cross Cutting Topics *Abraham Seiden (UCSC), Marcel Demarteau (ORNL)*

Thursday, December 12, 2019

8:00 – 9:00 a.m.	Continental Breakfast *Presidential Foyer Area*
9:00 – 12:00 p.m.	Parallel Working Sessions Between Groups
12:00 – 2:00 p.m.	Working Lunch: Key Challenges Across Groups *Moderator: Cross Cutting Group* *Eisenhower Room*
2:00 – 5:00 p.m.	Parallel Working Sessions Continue
5:00 – 6:00 p.m.	Wrap up Key Challenges Across Groups *Moderator: Cross Cutting Group* *Eisenhower Room*
6:00 p.m.	DINNER

Friday, December 13, 2019
https://indico.cern.ch/event/870928/

1:00 - 1:20 p.m.	Higgs and Energy Frontier *Gabriella Sciolla (Brandeis), James Hirschauer (Fermilab)*
1:20 - 1:40 p.m.	Neutrinos *Amy Connolly (OSU), Kate Scholberg (Duke), Ornella Palamara (Fermilab)*
1:40 - 2:00 p.m.	Dark Matter *Daniel Mckinsey (UC Berkeley), Jodi Cooley (SMU)*
2:00 - 2:20 p.m.	Cosmic Acceleration *Clarence Chang (ANL), Brenna Flaugher (Fermilab)*
2:20 - 2:40 p.m.	Explore the Unknown *Monica Pepe-Altarelli (CERN), Sarah Demers (Yale)*
2:40 - 3:00 p.m.	BREAK
3:00 - 3:20 p.m.	Quantum Sensors *Andrew Geraci (Northwestern), Kent Irwin (Stanford)*
3:20 - 3:40 p.m.	Noble Elements *Jocelyn Monroe (University of London), Roxanne Guenette (Harvard)*

3:40 - 4:00 p.m.	Calorimetry *Francesco Lanni (BNL), Roger Rusack (UMN)*
4:00 - 4:20 p.m.	Solid State Vertexing and Tracking *Carl Haber (LBNL), Marina Artuso (Syracuse)*
4:20 - 4:40 p.m.	Photodetectors *Lindley Winslow (MIT), Peter Krizan (Jozef Stefan Institute)*
4:40 - 5:00 p.m.	TDAQ *Darin Acosta (UF), Tulika Bose (UW Madison)*
5:00 - 5:20 p.m.	Readout and ASIC *Gabriella Carini (BNL), Mitchell Franck Newcomer (Penn)*
5:20 - 6:00 p.m.	DINNER
5:40 p.m.	Cross Cutting Topics *Abraham Seiden (UCSC), Marcel Demarteau (ORNL)*
6:00 - 7:30 p.m.	Discussion with Cross Cutting Group *Conveners Only* *Eisenhower Room*

Saturday, December 14, 2019

8:00 – 9:00 a.m.	Continental Breakfast *Presidential Foyer Area*
9:00 – 10:00 a.m.	Cross Cutting Group: Key Challenges *Eisenhower Room*
10:00 am – 12:00 p.m.	Writing Key Recommendations and Takeaways
12:00 p.m.	Adjourn