The Path to Global Discovery

U.S. Leadership and Partnership in Particle Physics

A REPORT FROM THE HEPAP INTERNATIONAL BENCHMARKING SUBPANEL

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EDITING AND COPY EDITING
HOLLY HOLT
OAK RIDGE INSTITUTE FOR SCIENCE AND EDUCATION (ORISE)

ART DIRECTION AND DESIGN
SANDBOX STUDIO, CHICAGO

ILLUSTRATION
KIMBERLY BOUSTEAD

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In February 2022, HEPAP, the High Energy Physics Advisory Panel to DOE (Department of Energy) and NSF (National Science Foundation), was charged with forming a subpanel to conduct an international benchmarking study to evaluate U.S. leadership in particle physics in a global context (Appendix D). HEPAP formed an International Benchmarking Subpanel and gathered qualitative and quantitative data from the international particle physics community to 1) determine how the U.S. particle physics program can maintain critical international cooperation in an increasingly competitive environment for both talent and resources, 2) identify key areas where the U.S. has or could aspire to leadership roles, and 3) determine how programs and facilities can be structured to attract and retain talented people.

This report also serves as input to P5 (Particle Physics Project Prioritization Panel), a subpanel of HEPAP that defines the strategic scientific direction for the U.S. particle physics program.

Respectfully submitted,
2023 HEPAP International Benchmarking Subpanel

CO-CHAIRS

Patricia McBride
Fermi National Accelerator Laboratory

Bonnie Fleming
Fermi National Accelerator Laboratory and University of Chicago

SECTION AND CONTENT LEADS

Mei Bai
SLAC National Accelerator Laboratory

Andrew Lankford
University of California, Irvine

Sekazi K. Mtingwa
U.S. Nuclear Regulatory Commission

Ian Shipsey
Oxford University

MEMBERS

Marcela Carena
Fermi National Accelerator Laboratory

Scott Dodelson
Carnegie Mellon University

Daniel Dwyer
Lawrence Berkeley National Laboratory

Tova Holmes
University of Tennessee, Knoxville

Tsuyoshi Nakaya
Kyoto University

Wim Leemans
Deutsches Elektronoen-Synchrotron

Reina Maruyama
Yale University

Brian Nord
Fermi National Accelerator Laboratory

Stefan Soldner-Rembold
University of Manchester

Lindley Winslow
Massachusetts Institute of Technology

JoAnne Hewett (ex-officio)
former HEPAP Chair

Sally Seidel (ex-officio)
present HEPAP Chair

RESPECT
sense of ownership
SCIENTIFIC OBJECTIVE
decision making
GOVERNANCE
AUTHORSHIP
SHARED
culture
sense of success
CREDIT
PROBLEM SOLVING

“By working together across borders, international collaborations have delivered the ideas, instrumentation, and major facilities that have yielded groundbreaking discoveries.”

Particle physics strives to discover and understand the world around us—from the smallest elementary particles to the largest scales in the universe—and, in doing so, to deliver paradigm-shifting ideas and to contribute to technologies that transform daily life.

Over the last century, particle physics ideas and discoveries have led to a remarkably beautiful and consistent picture of the fundamental building blocks of matter and laws of nature. This framework, known as the Standard Model, has come together through a continuing interplay between new theoretical ideas and experiments using state-of-the-art, pioneering technologies. The field's innovative spirit and transformative findings also yield technologies and discoveries that advance other fields of science, medicine, and national security, impacting society, and more broadly, the human condition.

The field's most challenging endeavors, be they large or small, can require garnering the expertise and resources of many countries, leading to multi-national collaborations. The most important and pressing particle physics questions are being approached, essentially, as a global enterprise. By working together across borders, international collaborations have delivered the ideas, instrumentation, and major facilities that have yielded groundbreaking discoveries. To continue uncovering the mysteries of the universe, the field must build state-of-the-art precision experiments coupled with the world's most powerful accelerators. Particle physicists must peer into the universe with the most advanced telescopes, and they must analyze the biggest datasets by developing and using the most advanced computational architecture and algorithms.

The U.S.'s current leadership in particle physics derives from a storied and successful history of international cooperation. However, the U.S.'s success in the next century in a global leadership role is not guaranteed. To be a leader as a partner abroad and a host at home, the U.S. must engage as a trailblazer in experiments of all scales (from small to mega scale). The U.S. must harness its expertise in areas where the country already excels, rekindle expertise in areas where the country has fallen behind, and engage strategically in new areas. The U.S. must also compete in an escalating pursuit of scientific talent and resources. Finally, to succeed in achieving world-class science, the U.S. must inspire the public as well as attract, train, and retain a diverse workforce of outstanding scientists and engineers. In doing so, the U.S. will continue to impact society more broadly as new technologies and new research areas, born from these endeavors, are applied to sectors beyond particle physics.

International benchmarking of the U.S. particle physics program

HEPAP (High Energy Physics Advisory Panel)—which offers input to HEP (Office of High Energy Physics) in DOE (Department of Energy) and to the Division of Physics in NSF MPS (National Science Foundation Directorate for Mathematical and Physical Sciences)—was among the DOE and NSF advisory committees to be charged with an international benchmarking exercise.[a] This report is preceded by those from the Basic Energy Sciences Advisory Committee (2021),[1] the Biological and Ecological Research Advisory Committee (2022),[2] the Advanced Scientific Computing Advisory Committee (2023),[3] and the Fusion Energy Sciences Advisory Committee (2023).[4]

HEPAP's charge broadly seeks international benchmarking of U.S. particle physics across three topics: 1) international collaboration, 2) enabling capabilities and technologies, and the 3) workforce. The charge underscores the unique international nature of particle physics and specifically requests consideration of U.S. leadership in this context.

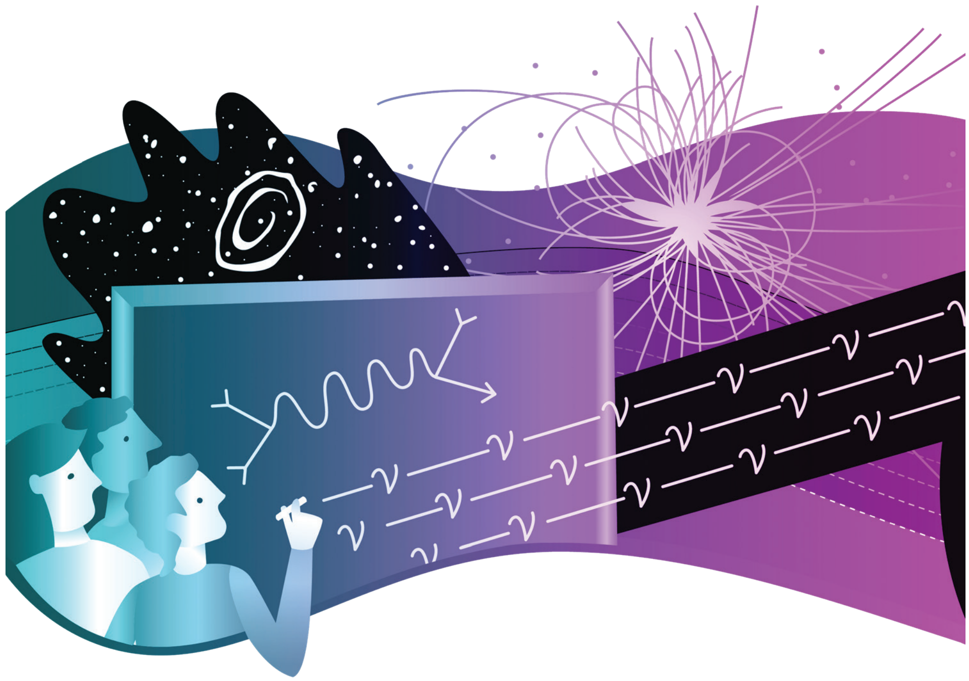
The U.S. particle physics program is primarily supported by DOE HEP and NSF Division of Physics. DOE HEP and NSF Division of Physics are advised by HEPAP. HEPAP, in turn, engages with the U.S. and the international particle physics community through a formal long-range planning activity that culminates in recommendations issued by P5 (Particle Physics Project Prioritization Panel), a subpanel of HEPAP. P5 and associated community activities are convened on a decadal basis and set the field's research directions and project priorities for the next 10 years within a 20-year context. Thus, P5 science drivers are the product of the community's expertise, and P5's priorities represent a cohesive vision for U.S. investment, innovation, and leadership in the global particle physics arena. The U.S. has made excellent progress on the last set of P5 priorities issued in 2014 and is preparing for the next P5 report, with release anticipated in December 2023. The field's longer-term vision is addressed by the National Academies' consensus studies, with the next study, *Elementary Particle Physics: Progress and Promise*,[5] expected to be released in mid-2024. This HEPAP international benchmarking report highlights the areas of U.S. leadership but does not attempt to prioritize among them or to make specific budget recommendations; these activities are the purview of P5.

Defining and obtaining metrics of international leadership in a field distinguished by international collaboration is a challenge. Leadership in particle physics is not always about being first and is not just about setting the direction that others follow. Leadership takes on a different meaning in collaborative research. Leadership means having the capabilities, experience, and infrastructure to contribute to a research direction in a significant way. This report assumes there is usually more than one leading group or nation within a collaboration or in an area of research.

In generating this report, this HEPAP subpanel gathered both qualitative and quantitative data. Interviews with national and international leaders in experiment and theory offered expert perspectives and were coupled with feedback from surveys and townhalls. Key points emerged from the convergence of outlooks and opinions. Traditional and more readily accessible quantitative metrics, such as publications and citations, are not a meaningful proxy for leadership in this collaborative context. Where appropriate, this subpanel obtained numerical figures, such as programmatic investments or educational metrics.

Key findings and recommendations

This report identified seven key findings and recommendations that speak to the impact of particle physics, the complex landscape of ongoing efforts (which vary in size and maturity), and the international nature of the field, where forging successful collaborations is facilitated by having a good reputation as a partner or host nation. Key U.S. strengths and opportunities for leadership encompass technical capabilities in particle physics, and the field plays an important role in ongoing national initiatives. Importantly, U.S. strengths and leadership are predicated on a strong workforce.



Scientific breadth and application

KEY FINDING

Particle physics theory and experiments address deep mysteries of the universe while advancing concepts and technology that are vital to other research fields as well as society at large.

KEY RECOMMENDATION

Strengthen investments to advance particle physics discoveries as well as benefits to other scientific disciplines and society.

Diversity across scales and stages

KEY FINDING

The field of particle physics is a vibrant research ecosystem, built by an international network of partnering nations, facilities, experiments, and people. To be a leader, the U.S. must continuously produce scientific results, build facilities and experiments for the future, and advance new ideas and technologies that enable the discoveries of tomorrow.

KEY RECOMMENDATION

Maintain a comprehensive program at home and abroad, with a range of experiment scales and strategic balance among construction projects, operations of experiments and facilities, and core research activities, including the development of future facilities.

Collaborating across the globe

KEY FINDING

Frontier research in particle physics necessitates international collaboration and cooperation. The combined expertise and resources from nations around the world enable discoveries and technological advances impossible to achieve by any single nation. It is the global particle physics program that collectively addresses the burning scientific questions across the breadth of the field.

KEY RECOMMENDATION

Continue support for and actively seek engagement with international collaborations and partnerships of all sizes.

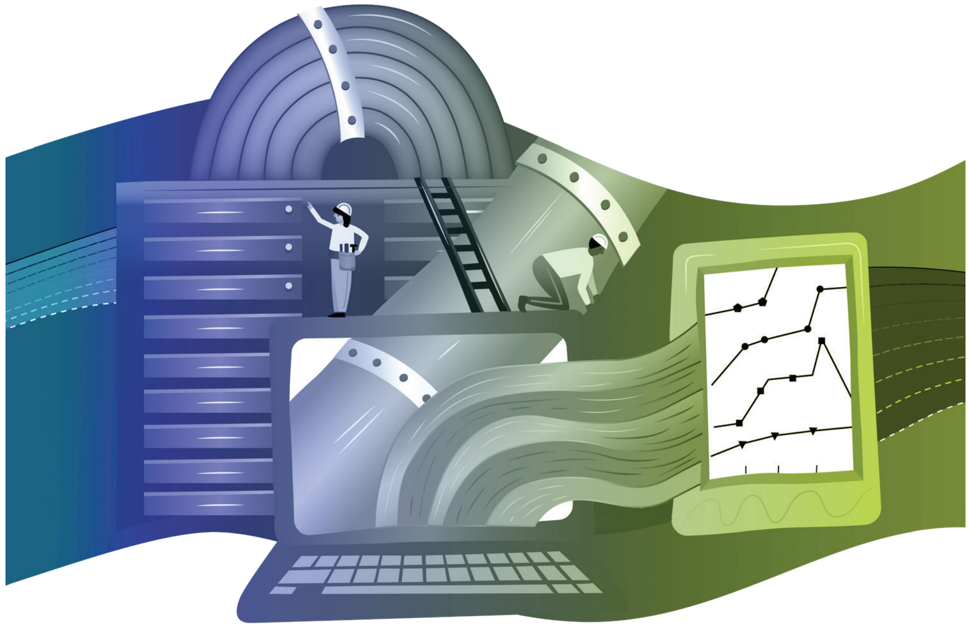
Being a partner of choice

KEY FINDING

Success in hosting and participating in international collaborations requires tailored approaches to collaboration governance and project management, host lab environments that are conducive to international research teams, and the ability to make reliable agreements with international partners.

KEY RECOMMENDATION

Implement structures for hosting strong international collaborations, act with timeliness, consistently meet obligations, and facilitate open communication with partners.



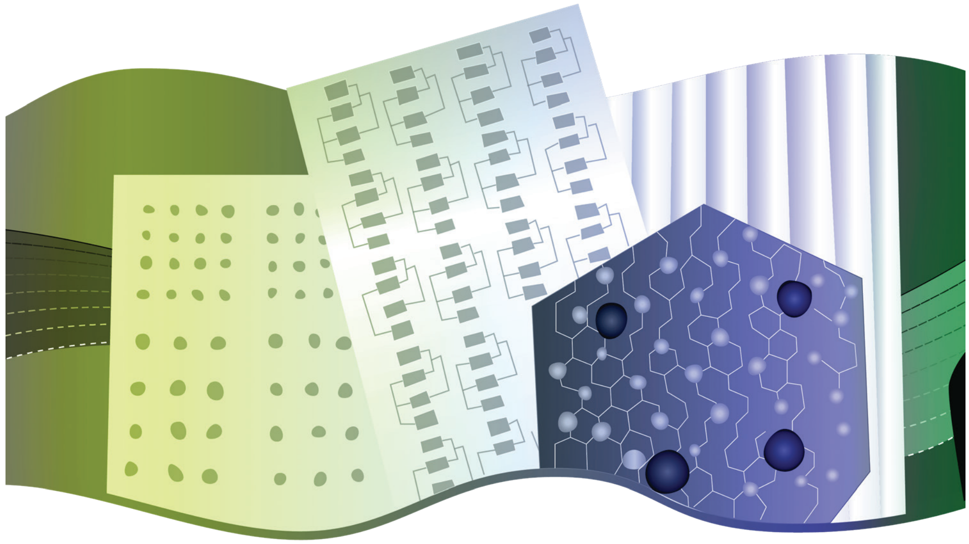
Strengthening critical capabilities

KEY FINDING

It is our state-of-the-art expertise in the tools, technology, and techniques of particle physics that makes the U.S. a sought-after partner and gives us the ability to impact future experiments at home and abroad.

KEY RECOMMENDATION

Continuously develop critical technologies to maintain and grow U.S. leadership in particle physics at home and abroad.



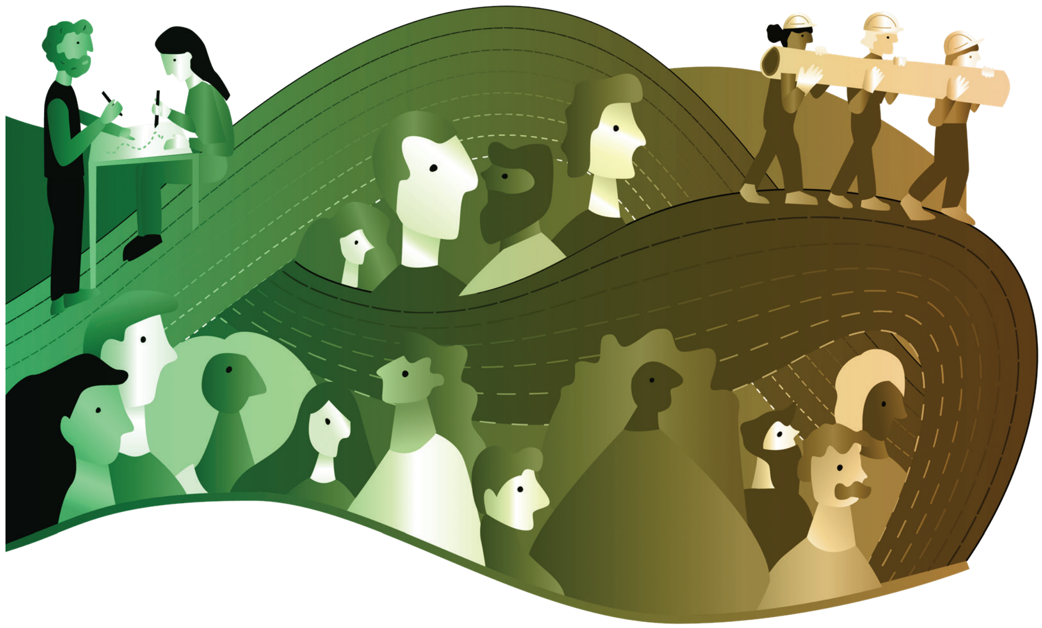
Advancing national initiatives

KEY FINDING

The national initiatives in artificial intelligence and machine learning, quantum information science, and microelectronics are accelerating new research avenues in particle physics, and particle physics contributions to these initiatives are bringing new ideas and new technologies to a range of disciplines.

KEY RECOMMENDATION

Enhance and leverage the innovative role that particle physics plays in artificial intelligence and machine learning, quantum information science, and microelectronics to advance both particle physics and these national initiatives.



Building a robust workforce

KEY FINDING

Attracting, inspiring, training, and retaining a diverse workforce is vital to the success of all particle physics endeavors and more broadly to U.S. science and technology. A robust particle physics workforce will both leverage and be representative of the diversity of the nation.

KEY RECOMMENDATION

Explore frontier science using cutting-edge technologies to inspire the public and the next generation of scientists while opening new pathways to diversify the workforce and realize the full potential of the field.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A REPORT FROM THE HEPAP INTERNATIONAL BENCHMARKING SUBPANEL

1 Introduction

A history of the global endeavor of particle physics

The field of particle physics was built on the principles of open science, and its history is a story of international collaboration. Theorists and experimentalists work together to understand the basic nature of matter, energy, space, and time by defining the elementary constituents of the universe and their interactions. International cooperation spans research endeavors of all sizes and durations—from small group efforts lasting less than a decade to those of the size of CERN (European Laboratory for Particle Physics Research), which was established in 1954 and currently engages 23 member states, employs >2,600 staff members, and attracts ~12,000 users worldwide.[6] These collaborations serve as the training grounds for the next generation of scientists, engineers, and technicians. Bespoke technology, built to test new particle physics ideas, fuels discoveries and advances scientific capabilities in other research fields. These capabilities are also adopted by society for use in medicine, finance, security, and other sectors.

Particle physics research is carried out at universities, national laboratories, accelerator facilities, telescopes, and underground facilities around the world (Appendix E explains how this report uses terms in a field-specific context). Characteristics of particle physics experiments vary widely, particularly depending upon whether they study particles produced at accelerators, search for rare particles underground, or observe the cosmos (Appendix F describes the nature of particle physics experiments). Experiments push the boundaries of state-of-the art instrumentation and computation for data collection and analysis, contributing to vital U.S. initiatives in AI/ML (artificial intelligence and machine learning), QIS (quantum information science), and microelectronics. Skills gained from work in these areas contribute to a robust U.S. workforce.

The U.S. particle physics program and community is primarily supported by DOE (U.S. Department of Energy) HEP (Office of High Energy Physics) and the NSF (National Science Foundation) Elementary Particle Physics and Particle Astrophysics programs in the Division of Physics.

Though overall U.S. particle physics funding has grown over the past decade, investments in core research have not kept pace with inflation. Core research supports the scientists who utilize particle physics infrastructure. If core research funding continues to decline, the U.S. will lack a qualified workforce to commission projects, operate experiments, and produce the results that advance theoretical understanding. Maintaining and building core research strengths will ensure the U.S. particle physics community 1) maintains forefront domestic facilities and continues as a sought-after partner in international endeavors, 2) retains a competitive edge in key technologies and capabilities, and 3) continues to develop a workforce with competitive skills that advance particle physics and other fields.

1.1 Particle physics is a global field for discovery

Why do particle physicists collaborate, and why are the collaborations international? P5 (Particle Physics Project Prioritization Panel) is tasked by DOE and NSF each decade to develop a strategic plan for U.S. leadership in the global context of the field. In 2014, P5 eloquently summarized the importance of international collaborations in its report titled, *Building for Discovery*.[7]

Particle physics is global. Nations pursue particle physics because the questions are profound and provocative, and the techniques are beautiful and useful. The countries that lead these activities attract top minds and talent from around the world, inspire the next generation of scientists and technologists, and host international teams dedicated to a common purpose. The scientific program required to address all of the most compelling questions of the field is beyond the finances and the technical expertise of any one nation or region; nonetheless, the capability to address these questions in a comprehensive manner is within reach of a cooperative global program.

International collaboration is a decades-long tradition of particle physics. In the past, regions could mount competing efforts, but the complexity and costs of facilities and experiments are growing. The scope of the field's fundamental science questions is broad, as is the variety of the scientific techniques, both invented in particle physics and imported from other fields, to answer these questions. Consequently, the required expertise, resources, and facilities are often not available in a single nation. Thus, U.S. scientists often seek to collaborate on experiments being mounted abroad, particularly if comparable experiments are not being mounted in the U.S. The reverse is true for international scientists seeking to collaborate on experiments hosted in the U.S. This is true for experiments at all scales. International collaboration also has an intrinsic value by furthering the peaceful cooperation of scientists from different cultures and by enabling the participation of regions with less developed research infrastructure in frontier science.

Illustrating the international exchange of ideas and concept of hosting, the CDF (Collider Detector at Fermilab, Fermi National Accelerator Laboratory) collaboration was founded during the early 1980's as the Tevatron collider's first experiment. At the time, the Tevatron was the world's highest energy particle accelerator. The Tevatron was used to discover two fundamental particles: the top quark and the tau neutrino. From the experiment's earliest days, important collaborating groups from Italy and Japan brought major detector contributions to this U.S.-hosted effort. Additional international collaborators joined CDF in subsequent years.

The following decade, when there was no comparable experimental facility available in the U.S. for the detection of solar and atmospheric neutrinos, U.S. university groups became important collaborators on the Super-Kamiokande (Super-Kamiokande Neutrino Detection Experiment) at a deep underground facility in Japan. The U.S. groups brought not only their expertise from a predecessor experiment (IMB, Irvine-Michigan-Brookhaven experiment) but also brought significant portions of the IMB detector itself.

In the last two decades, international partnerships to construct and operate experiments have reached a new scale with proportionately impactful findings. For instance, two experiments at the LHC (Large Hadron Collider) at CERN—1) ATLAS (A Toroidal LHC ApparatuS) and 2) CMS (Compact Muon Solenoid)—were each constructed and are operated as international partnerships of dozens of nations, of nearly 200 institutions, and of thousands of scientists from around the globe. While hosted at CERN, these collaborations are largely self-governing. The huge scientific success of these international efforts, including their simultaneous discovery of the Higgs boson, the subject of the 2013 Nobel Prize in physics, makes these experiments role models for future partnership and collaboration.

Meanwhile, the U.S. is collaborating with international partners to develop a coherent short- and long-baseline neutrino program hosted at Fermilab. The international collaboration that is designing and executing the long-baseline program is called LBNF/DUNE (Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment). Fermilab's proton accelerator complex is being upgraded to produce higher intensity beams in part to support DUNE; this facility upgrade has been named PIP-II (Proton Improvement Plan-II). The DUNE experiment is being developed by an international collaboration of institutions from 36 partner nations plus the U.S. and CERN, much in the model of the LHC collaborations. Meanwhile, the PIP-II project is benefitting significantly from accelerator components from France, India, Italy, Poland, and the U.K. (United Kingdom). With these initiatives, the U.S. has formed international partnerships to construct international facilities hosted in the U.S. In the future, particularly as projects grow in scale and in complexity, one can expect to see increased degrees of partnership, particularly on accelerators and other facilities. The next generation of energy frontier machines will certainly require significant international partnership. One notable example of such a project is the proposed FCC (Future Circular Collider) program at CERN or a high energy muon collider.

International partnership, however, is not limited to the largest experiments involving the most complex equipment and facilities. International partnerships as small as two individuals, sharing ideas across borders, have delivered important findings. For example, the DONUT (Direct Observation of the Nu Tau) collaboration that announced the discovery of the tau neutrino in 2000 was a collaboration of 54 physicist from the U.S., Japan, Korea, and Greece. A more recent example is the similar-scale CCM (Coherent CAPTAIN Mills) collaboration. CCM is a collaboration of scientists from institutes in the U.S., U.K., and Mexico that is searching for dark matter in a neutrino beam at Los Alamos National Laboratory.

1.2

U.S. particle physics

The 2014 P5 report highlights the international nature of many of the U.S.'s high-priority particle physics programs. Notably, the highest priority U.S. programs—the neutrino program (LBNF/DUNE) at Fermilab and the LHC program at CERN—are both international programs at the forefront of the field and where the U.S. remains a leader.

Five intertwined science drivers,[7] listed below, guide the 2014 P5 priorities and are connected through the backbone of theory. U.S. contributions to and notable research opportunities for each of the drivers are presented in the next chapter.

1. Use the Higgs boson as a new tool for discovery;
2. Pursue the physics associated with neutrino mass;
3. Identify the new physics of dark matter;
4. Understand cosmic acceleration: dark energy and inflation; and
5. Explore the unknown: new particles, interactions, and physical principles.

The U.S. has both space and resources available to host and support international experiments. Furthermore, the scale and cohesiveness of the U.S. program makes it resilient and able to tackle major long-term programs. The combination of NSF investigator-driven research and the DOE mission-driven programs complement each other and add to the overall strength of the U.S. program.

DOE supports particle physics programs and projects in university groups and at the DOE national laboratories. Among the DOE national laboratories, Fermilab is dedicated to particle physics, but other laboratories have strong participation in the program, particularly Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory and SLAC National Accelerator Laboratory.[b] NSF supports university groups, facilities, and centers in a program that complements that of the DOE. The NSF MREFC (Major Research Equipment and Facilities Construction) program enables the building of major facilities and research infrastructure. The complementarity of DOE and NSF funding models fosters a particle physics program that supports experiments of all scales.

Close collaboration between university groups and the U.S. national laboratories has been a successful model for the U.S. particle physics program. The laboratories provide facilities and are a source of R&D (research and development), technical expertise, and project management and oversight. The universities provide essential ideas, R&D, cross-disciplinary activities, and most importantly, training for students. This research ecosystem has worked well but has been stressed by tight budgets for research and operations over the last decade.

Investing in long-term, large projects pays dividends in paradigm-altering findings while ground-breaking science attracts the brightest minds from around the world. However, reduced core research funds not only threaten the ability of U.S. scientists to exploit the scientific potential of these projects but also have made the U.S. program less nimble in starting other new initiatives and smaller projects. Consequences of this reduction include limited U.S. participation in R&D for the next generation of experiments or facilities.

In addition, the year-to-year uncertainty of the U.S. funding process has led to misunderstandings and a diminished reputation with international partners in the past, although the U.S. has proven to be a strong and reliable partner in the LHC program at CERN for more than two decades.

The fundamental questions of particle physics are attractive to students and researchers around the world. Within the U.S., the country's history as a melting pot of cultures and ideas has lent itself to international collaborative discovery. The workforce, both at the universities and laboratories, has historically been international. However, barriers to international participation in the U.S. program have increased over the last decade because of research security concerns, visa issues, and more restricted access to the national laboratories. Meanwhile, the number of particle physics researchers in China has doubled, and the number of researchers in Indian institutes entering the field is also growing. These effects combine to make it increasingly challenging to recruit the best international collaborators to U.S.-based positions.

Despite widespread effort, recruitment of a diverse workforce within the U.S. continues to be a challenge. There has been little change over the last decade in participation from underrepresented groups in particle physics. Recent DOE Office of Science and NSF programs to broaden and diversify the U.S. workforce, such as RENEW-HEP (Reaching a New Energy Sciences Workforce-Office of High Energy Physics) and LEAPS-MPS (Launching Early-Career Academic Pathways-Directorate for Mathematical and Physical Sciences) are commendable. However, broadening diversity in the field will require a more sustained and targeted effort to provide opportunities and a welcoming, inclusive environment within the field.

1.3

Evaluating U.S. leadership through an international lens

Given particle physics' highly collaborative and topically diverse nature, leadership takes many forms. Traditional benchmarks, like highly cited papers from individuals or small groups, do not adequately measure important contributions to this field. Instead, leadership is better defined by influence: the extent to which individuals, organizations, or countries are able to set scientific priorities and accelerate progress towards results.

Within particle physics collaborations, the high level of organizational structure makes leadership evident. However, it is not just top-level management positions that indicate success. Intellectual leadership comes from all levels, from spokespersons to shift leaders, with involvement across levels indicating a healthy workforce pipeline. Within collaborations, convenership roles in physics, operations, and computing serve as a measure of leadership for many early career scientists. To achieve global standing, the U.S. must produce individual leaders at all levels. Thus, a large number of individual U.S. leaders in particle physics is both indicative of and a prerequisite for U.S. leadership at a global scale.

In shaping this assessment, the subpanel considered a series of questions that address U.S. leadership in theory and practice. The order in which questions are presented reflects the dimensions of U.S. leadership discussed in this report. These questions consider the collaborative global context of the field and traverse leadership indicators across research scales that range from the individual to large facilities.

Chapter 3, Collaboration: At large research scales, to what extent do global projects line up with the interests of the U.S. particle physics community as outlined by the P5 process? Does the output of this process guide the direction of global efforts? Is the U.S. able to take ownership of key elements of projects overseas and successfully facilitate global engagement in its hosted projects? Is the U.S. able to react in a timely way to new ideas and new initiatives?

Chapter 4, Enabling capabilities and technologies: Which critical capabilities are needed to advance the field of particle physics and drive innovation? How does the U.S. program fit into the global context? Does the balance of blue sky research and strategic initiatives lead to technologies that enable discoveries? What is the U.S. role in international initiatives? What are the synergies with other fields?

Chapter 5, Workforce: Ultimately, it is the people composing the U.S. particle physics workforce that make leadership possible. Is the workforce pipeline sufficiently robust to train enough students in the key areas required to meet national and international goals? Can universities and laboratories attract and retain experts? Relatedly, is the U.S. particle physics program sufficiently stable that individuals can grow their expertise over the length of a full career? Does U.S. training enhance the skills needed to evolve as research needs change?

1.4

Benchmarking methodologies

In February 2022, HEPAP was charged by DOE and NSF to write this report. The subpanel that formed was divided into four separate areas: 1) Large experiments, 2) Small experiments and enabling technologies, including national initiatives, 3) Accelerators and accelerator technology, and 4) Workforce. Theory was considered by all the subgroups. The division between experimental sizes was meant to reflect the presumed formality of governance structures for each. Compared to small experiments, large experiments tend to have a more formal governance structure and more international connections.

The subpanel was asked to evaluate what leadership means in the international context of particle physics. The subpanel reviewed the status of the major projects recommended by the 2014 P5. These projects reflect the strategic scientific directions of the U.S. program. They are part of the global particle physics ecosystem and most, if not all, benefit significantly from international collaboration. The subpanel examined the importance of these collaborations, the characteristics of a successful collaboration, the role of the U.S. in these collaborations, and their value to the U.S. program.

The subgroups also weighed many other possible metrics of leadership, including publications, Nobel Prizes, investment per capita, and leadership roles. However, these figures are often not readily available, as is the case with investment per capita. Moreover, extracting meaning from such metrics would be confounded by the international nature of efforts and the diverse approaches to issuing credit. For example, author lists on publications follow different conventions depending on the field and/or collaboration (some lists are alphabetical, some emphasize contributions of first authors, *etc.*). In addition, the boundaries of the field are defined differently in different countries.

To address the charge, each subgroup conducted a series of interviews with leaders in the field, including several current and past laboratory directors and heads of both present and recent experiments and accelerator projects of varying size. Both U.S. leaders and non-U.S. leaders were consulted for U.S.-hosted activities and those hosted abroad. Experts in enabling technologies, such as instrumentation, AI/ML, QIS, software and computing, and microelectronics, were also interviewed. These experts were both from the U.S. and from abroad. The interviews were semi-structured with questions prepared in advance. In some cases, input was solicited through an email questionnaire. The subpanel also held a town hall during the Snowmass Community Planning Workshop in Seattle in 2022 to receive community input.

The subpanel presented a status report at the Snowmass meeting and presented several interim status reports at HEPAP meetings and at an open meeting of the National Academy of Sciences panel that is conducting the consensus study for elementary particle physics. The extensive Snowmass Community Planning Exercise report[8] and various other public reports such as *DOE Basic Research Needs for High Energy Physics Detector Research & Development*[9] were taken into account.

Data on workforce demographics were compiled primarily from information from the American Institute of Physics Statistical Research Center[10] and the NSF National Center for Science and Engineering Database.[11] In addition, the subpanel requested demographic data from DOE national laboratories and select major international experiments.

1.5 Report Outline

Following this introduction, Chapter 2 explains the big science questions in the field, putting the report in context. Chapter 3 addresses the first element of the HEPAP charge, focusing on the U.S. as a leader and a partner in a field driven by international collaboration. Chapter 4 describes the innovative and transformative capabilities that are critical to advance the field, responding to the second charge element. Chapter 5 addresses the third charge element, analyzing the strength of the particle physics workforce. The Key Findings and Recommendations are integrated into report chapters: Chapters 3, 4, and 5 develop Key Findings and Recommendations 1–4, 5–6, and 7, respectively. Within chapters, explanatory discussion of Key Findings and Recommendations gives rise to specific Findings and Recommendations (see Appendix G for a complete list of the report’s findings and recommendations). Appendices B and H–K summarize interview and data collection methods, contain workforce data, and offer additional explanatory or contextual information for topics discussed in this report.


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Science Drivers

Exploring the mysteries of the quantum universe

Because particle physics is driven by collaboration, community consensus on scientific priorities is essential. When HEPAP (High Energy Physics Advisory Panel) last convened P5 (Particle Physics Project Prioritization Panel), P5 was charged to "Identify key areas where the U.S. currently has or could aspire to leadership roles in particle physics via its unique or world-leading capabilities." P5 answered this charge in its 2014 report[7] by distilling the community's most pressing questions into its *science drivers*. These five subjects define the key scientific goals that have pushed particle physics forward for the last decade. They are as follows: 1) Use the Higgs boson as a new tool for discovery, 2) Pursue the physics associated with neutrino mass, 3) Identify the new physics of dark matter, 4) Understand cosmic acceleration: dark energy and inflation, and 5) Explore the unknown: new particles, interactions, and physical principles.

This section provides a brief outline of past and present U.S. leadership in the context of each of these goals and discusses opportunities and challenges for the future. A final section focuses on the role of particle theory in guiding, connecting, and interpreting these seemingly disparate experimental strategies. Guidance from the forthcoming 2023 P5 report will build on the outcomes of the 2014 P5 efforts and poise the U.S. for continued leadership.

2.1

Use the Higgs boson as a new tool for discovery

The Higgs boson particle offers a unique portal into the laws of nature, and it connects several areas of particle physics. Any observed small deviation in its expected properties would be a major breakthrough.[7]

The Higgs boson is the elementary particle that confers mass to all other particles. Predicted by British theorist Peter Higgs in the early 1960s, the

Higgs boson was observed by the ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) experiments at the LHC (Large Hadron Collider) accelerator complex at CERN (European Laboratory for Particle Physics Research) in 2012, with key contributions across accelerator, detector, and analysis techniques coming from the U.S. The intervening 50-year campaign between prediction and discovery demonstrates both the predictive power of particle theory and the value of international collaboration.

U.S. expertise played a leading role in the Higgs boson discovery. For instance, U.S. labs partnered with Japan to provide the high-field superconducting magnets that focus the LHC beams at their interaction points inside the experiments, and U.S. labs and universities partnered with those of other nations on nearly every particle detector system of both ATLAS and CMS.

P5's ongoing vision to unlock the secrets of the Higgs boson relies on six decades of U.S. leadership in energy frontier colliders and associated technologies. The U.S. constructed several prior colliders on U.S. soil, leading to the discovery and characterization of other elementary particles, including new leptons and new quarks.[c] Along the way, the U.S. developed advances in accelerator technology. At present, the U.S. is contributing to the upgrade of the LHC to the High-Luminosity LHC (HL-LHC) and upgrades to the ATLAS and CMS detectors, which will provide a new dataset with more than ten times the number of Higgs bosons that have been produced to date. Experimental operations are anticipated in 2028–2029.

While the HL-LHC will provide increased precision on many Higgs boson properties, a Higgs factory, a collider tuned to produce huge quantities of Higgs bosons with very little background, could drastically improve these measurements. Designs for these Higgs factories typically involve electron and positron beams with energies on the scale of hundreds of GeVs (gigaelectron volts) in a compact linear configuration such as that of the ILC (International Linear Collider) or with a larger circular footprint such as that of the FCC-ee (Future Circular Collider for electron-positron collisions).

Directly studying the underlying physics that produces a Higgs boson requires a higher energy collider, which could be accomplished using proton beams in a large circular machine (potentially reusing a tunnel from a circular Higgs factory), or by using muon beams to make a more compact circular collider.

The U.S. is the recognized leader in a number of accelerator and detector capabilities that will be key to future collider designs for this high-priority research area; for example, superconducting radio frequency accelerating technology, high-field superconducting magnets, production of cooled beams of muon particles, and development of highly granular precision timing detectors. At present, the level of U.S. investment in future collider and experiment design and in underlying accelerator and detector technology is a barrier to full and effective U.S. engagement.

2.2

Pursue the physics associated with neutrino mass

Physicists now know that neutrinos exist in three types and that they oscillate, i.e.*, they change type as they move in space and time. The observed oscillations imply that neutrinos have masses, but these masses have yet to be directly measured. Many aspects of neutrino physics are puzzling, and the experimental picture is incomplete.*[7]

Since neutrinos were first postulated in the 1930s by the Austrian theoretical physicist Wolfgang Pauli, the U.S. has played a leading role in understanding this notoriously difficult-to-detect sector of the Standard Model. All three neutrino species were discovered at U.S. laboratories: the electron neutrino in 1956 at the Hanford Site nuclear reactor in Washington State, the muon neutrino in 1962 at Brookhaven National Laboratory on Long Island, and the tau neutrino in

2000 at Fermilab (Fermi National Accelerator Laboratory) outside of Chicago. An underground experiment in the Homestake gold mine in South Dakota made the first observation of neutrinos produced in the Sun in the late 1960s, providing the first evidence that neutrinos oscillate between these different species as they propagate through space. Three Nobel Prizes have been awarded to U.S. scientists for these breakthroughs in understanding the neutrino sector.

Experiments in the U.S. and Japan made the first observation of neutrinos from a source outside the solar system in 1987 when they observed neutrinos streaming from a nearby supernova. This marked the beginning of “multi-messenger astrophysics”, the first time scientists were able to observe the cosmos using something other than light. Today, astrophysicists are building a global network of alert systems which rely on early neutrino detection to point telescopes toward upcoming supernovae.

Beginning the 1990s, the largest neutrino facilities were hosted by other nations. The Super-Kamiokande (Super-Kamiokande Neutrino Detection) project in Japan and the SNO (Sudbury Neutrino Observatory) in Canada benefitted from U.S. involvement at the construction, operation, and analysis stages. Nonetheless, it was Japanese and Canadian leadership teams that won the Nobel Prize for the discovery of neutrino oscillations in 2015.

In subsequent years, the U.S. reinvigorated its local neutrino program, building experiments to study neutrinos produced at Fermilab and detected on site (SBN, Short-Baseline Neutrino program) as well as beams traveling over long baselines to far detectors both at the surface and underground (MINOS, Main Injector Neutrino Oscillation Search and NOvA, NuMI Off-axis ν_e Appearance). In addition, the U.S. continued to play a leadership role abroad, most notably in the Daya Bay experiment in China and in continuing collaborative experiments in Japan and Europe.

A new generation of international mega-scale underground neutrino oscillation experiments is now in construction, both in the U.S. and in Japan. The U.S. program has several parts: PIP-II (Proton Improvement Plan-II) which provides a new, high intensity, and reliable front end to Fermilab’s particle accelerator complex; LBNF (Long-Baseline Neutrino Facility) which produces the world’s most intense high energy neutrino beam; and DUNE (Deep Underground Neutrino Experiment) at Fermilab and at SURF (Sanford Underground Research Facility) in South Dakota, where detectors will observe the LBNF beam’s neutrinos. DUNE will detect neutrinos using precision liquid argon technology, capitalizing on the ambitious U.S. program, underway since 2000, to take liquid argon detectors from table-top size to the enormous scale of the DUNE far detector. DUNE’s signature measurement searches for differences between matter and anti-matter in the neutrino sector. In addition, the facilities will determine the mass ordering of the neutrino species, search for proton decay and neutrinos from astrophysical sources, measure neutrino cross sections, and look for new physics.

This project is the first U.S.-hosted large-scale international project with broad international participation and notably, the first time the CERN laboratory has contributed to an external project. While LBNF/DUNE and the Hyper-Kamiokande experiment in Japan take advantage of different experimental setups, their physics goals are similar and in some ways complementary. To be competitive, the U.S. must work effectively with its international partners to construct this project on schedule and produce timely results. To further advance the understanding of neutrino properties in the future, the capabilities of this line of experimentation must be extended.

2.3

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. Dark matter is presumed to consist of one or more kinds of new particles. The properties of these particles, which are all around us, are unknown.[7]

The evidence for the presence of dark matter in the universe is incontrovertible but indirect. Gravitational measurements of the cosmos spanning different length scales all indicate the need to extend the Standard Model to explain how one or more species of dark matter particles came to dominate the material universe. Strategies to study dark matter rely on techniques from particle physics and astrophysics. For example, dark matter particles bound in the halos of galaxies could annihilate with one another or decay, producing detectable particles such as gamma rays, cosmic rays, and neutrinos. Dark matter particles in the solar vicinity could be directly detected via their scattering in terrestrial detectors. Alternatively, high energy accelerators such as the LHC or high luminosity fixed-target facilities could produce dark matter, whose presence could be inferred from measurements of visible particles. Finally, properties of dark matter could be inferred by combining astronomical observations with improved modeling of galaxy formation.

The P5 2014 strategic vision advised using all these technological approaches to search for dark matter. U.S. physicists have led the development of many technical capabilities seeking candidate dark matter particles across a range of masses and with the full set of approaches. For example, the U.S. has led development of large liquid xenon detectors to investigate WIMPs (weakly interacting massive particles) as well as resonant cavities to characterize ultra-light dark matter like QCD (quantum chromodynamics) axions. Recent U.S. advances in quantum sensor technology allow for new detector concepts based on scintillating crystals, semiconductors, and superfluids that are sensitive to the scattering or absorption of dark matter in the mass gap below WIMPs and above axions. The 2018 DOE study titled *Basic Research Needs for Dark Matter Small Projects New Initiatives*[12] identified three promising avenues where dark matter searches could be fruitfully expanded. Subsequent R&D funding has supported demonstrator-level projects for each strategy. Further funding is required to realize this set of initiatives to search for dark matter. Ultimately, when dark matter is discovered, next-generation experiments to identify the new physics associated with dark matter will be needed. The U.S. is well positioned continue to lead this campaign.

2.4

Understand cosmic acceleration: dark energy and inflation

A primordial epoch of acceleration, called inflation, occurred during the first fraction of a second of the Universe's existence. The cause of this inflation is unknown but may have involved fundamentally new physics at ultra-high energies. A second distinct epoch of accelerated expansion began more recently and continues today. This expansion is presumed to be driven by some kind of dark energy, which could be related to Einstein's cosmological constant, or driven by a different type of dark energy that evolves with time.[7]

Albert Einstein's theory of relativity predicts that the universe is expanding, but the nature of the expansion—whether its rate is increasing or decreasing—depends on the constituents of the universe. The discovery that the expansion of the universe is accelerating earned the 2011 Nobel Prize in Physics for two U.S. scientists and a U.S.-born Australian scientist. The expansion rate of a universe populated with ordinary protons, neutrons, and electrons, even taking into account dark matter, would slow down over time. To describe the observed accelerated expansion, another component of energy in the universe is required. This unknown component is called dark energy.

In 1980, the U.S. theoretical physicist Alan Guth hypothesized that, if the universe had undergone a brief period of accelerated expansion when it was very young, a number of cosmological conundrums would be solved. This idea, called inflation, has survived extensive scrutiny, again often led by U.S. scientists, and it has emerged as the dominant model of the early universe. Evidence of inflation would be imprinted on the cosmic microwave background, which was discovered by two American radio astronomers in 1965.

One of the deepest questions in physics remains: what sources of energy powered these two separate epochs of cosmic acceleration? The answer in either case will point to new fundamental physics that is likely not accessible at colliders like the LHC.

Although the history above is abbreviated, U.S. leadership in the discovery of accelerated expansion and the pursuit of the energy responsible is clear. In recent years, the U.S. has probed dark energy with a cosmic survey known as DES (Dark Energy Survey) and probed the cosmic microwave background with a set of surveys collectively known as CMB-S2 and CMB-S3 (Cosmic Microwave Background-Stage 2 and Cosmic Microwave Background-Stage 3). The 2014 P5 report strongly endorsed three cosmic surveys that would deepen our understanding of cosmic acceleration and retain leadership in ground-based cosmic surveys studying dark energy: 1) DESI (Dark Energy Spectroscopic Instrument) now in operation, 2) LSST (Legacy Survey of Space and Time), now being commissioned, and 3) CMB-S4 (Cosmic Microwave Background-Stage 4) now in design. All these surveys have international partners but are U.S. led. The results of this generation of cosmic surveys will guide the next generation. To maintain U.S. leadership, R&D across multiple technologies is needed, even as scientists await findings from the current generation of cosmic surveys, to enable the community to move quickly once science points to the right direction.

2.5

Explore the unknown: new particles, interactions, and physical properties

There are clear indicators of new phenomena awaiting discovery beyond those motivating the other four drivers. Particle physics is a discovery science defined by the search for new particles and new interactions, and by tests of physical principles.[7]

Advances in particle physics are frequently driven by the discovery of new particles and new interactions, and by tests of physical principles. Sometimes, as in the case of the Higgs boson, a robust theory precedes experimental discovery. In other cases, like the discovery of the muon, wholly unexpected particles are found, and theory must catch up to the new reality. Searches for new phenomena take two basic forms: 1) production of new particles via controlled experiments at accelerators or by interactions with cosmic rays and 2) detection of the quantum influence of new particles, where the properties of lower energy particles are modified due to the existence of new particles at an inaccessible energy scale. There is an interplay between these two forms of experiments, described via theoretical interpretation and speculation about novel mechanisms. For example, the type of radioactivity called beta decay of atomic nuclei, discovered in 1896, was eventually understood to be the discovery of the quantum influence of a new particle, the electrically charged W boson, and the mediator of the weak force. In 1973, using neutrino beams at CERN, scientists discovered the quantum influence of the electrically neutral quantum of the weak interaction, the Z boson. Then, in 1983, both W and Z bosons were produced in real non-virtual states, thanks to the high energy provided by the beams of a proton-antiproton collider at CERN.

The mysteries not explained by the Standard Model necessitate a broad program exploring potential extensions. While predictive, the Standard Model was built in an *ad hoc* way, relying on unlikely coincidences with no fundamental explanation. Additional mathematical structures have been proposed to provide explanations for its behavior, including theories to unify fermions and bosons (Supersymmetry) or to describe the internal structure for particles currently assumed to be fundamental. Exploration of these possible extensions is interconnected with the other P5 drivers. For example, Supersymmetry could provide an explanation for dark matter, explain neutrino mass, or create detectable modifications to the Higgs sector, and its particles could be identified directly at the LHC or indirectly through precision measurement of Standard Model particles. A comprehensive program searches both for these theory-driven scenarios and for unexpected hints of new physics, covering as much territory as possible to seek out discovery. These and other theoretical speculations extend the particle content of the Standard Model, providing an opportunity for discovery.

Today's experiments, many led or supported by the U.S., are searching for new particles directly as well as particle interactions via quantum influence, pushing beyond the boundaries of the Standard Model. The LBNF/DUNE neutrino facility and experiment will not only pursue the physics associated with neutrino mass but also search for signs of proton decay, which would signal a new particle interaction. Similarly, the forthcoming Fermilab Mu2e (Muon-to-Electron experiment) will search for muons that spontaneously turn into electrons without involving neutrinos in the final state, a process forbidden in the Standard Model but possible given many possible extensions. Fermilab's Muon g-2 experiment also uses muons to search for non-Standard Model interactions via hyper-precise measurement of the muon's magnetic moment.

Meanwhile, at the LHC, ATLAS and CMS have performed and published >600 unique searches for new physical phenomena and >900 measurements of Standard Model processes. These experiments not only use the Higgs boson as a new tool for discovery but also search broadly for the production of new particles in all their forms, continuously building novel tools to access new potential signatures of unknown particles. A comprehensive measurement program, spanning nearly every particle of the Standard Model, looks for signs of new particles via quantum influence with increasingly precise techniques. LHCb (Large Hadron Collider beauty), a third international particle physics experiment at the LHC, searches for signs of as yet unknown signals of quantum influence in the decays of particles containing bottom quarks while also adapting its unique detector to look for new particles.

The breadth of the U.S. program probably places it at the forefront of exploration of the unknown. However, in individual domains, there is competition from other programs. For instance, Japan currently has world-leading programs in searches for proton decay in large-volume neutrino detectors, as well as experiments targeting precision muon measurement. The challenges for future scientific advances, and for leadership, are new ideas for experiments which can be guided by theory and new experimental techniques which could exploit advancements in instrumentation and quantum sensors.

2.6

Particle theory

Theoretical research provides the conceptual framework that binds together all the areas of experimental particle physics and opens portals to other realms of science and mathematics. Theorists synthesize existing knowledge, identify gaps in our understanding, and imagine ways to advance the scientific frontiers of particle physics. They work to create a universal scientific language that encompasses the full panorama of experimental and observational campaigns to yield insights that enable both explanatory and predictive power.

Theoretical research takes several overlapping forms, each rich and diverse. Exploratory ("formal") theory probes our understanding of the theoretical principles and mathematical structures that underlie our modern conception of nature. Particle phenomenology engages closely with experiment and observation by analyzing and interpreting their results and by proposing new studies as well as creating many of the tools that experiments use for their own interpretation. Phenomenologists elaborate the consequences of established or conjectured theories and seek to incorporate new findings by inventing models to explore "if this, then what?" questions. Computational theory advances our science by developing new algorithms and by shaping or adapting novel computing architectures. Large-scale simulations and other machine-based techniques make explicit the implications of theory for experiments and illuminate the structure of theories to a degree impossible by other means.

There is a long history of U.S. leadership in particle theory, with many Nobel Prize-winning discoveries made by particle theorists at U.S. institutions. Within the past decade alone, U.S.-based theorists have discovered new generalized symmetries of nature, revealed profound connections between quantum gravity and quantum information science, created new frameworks for physics beyond the Standard Model, broadened the search for dark matter over orders of magnitude of energy, expanded the LHC's reach with proposed synergistic detectors, spearheaded progress in quantum field theories, and unleashed the transformative potential of machine learning for computations in high energy physics from the lattice to colliders and from neutrinos to cosmology. Theorists also play a key role in motivating future experiments by predicting and comparing their potential reach.


UP
STRANGE
ELECTRON

3

Collaboration

Science enabled by partnerships, experiments, and facilities

Particle physics experiments and theory address the deep mysteries of the universe. Understanding the smallest scales in nature often requires the largest experimental efforts. Experiments of all scales accomplish impactful science and experiments at different scales frequently complement one another. Using accelerators, telescopes, and detectors large and small, particle physicists strive to probe the elementary constituents of matter and energy.

The U.S. has a long history of hosting and conducting some of the most successful projects in particle physics covering a range of scales and methodologies. The U.S. continues to host projects today at national laboratories and also at universities for many of the smaller projects.

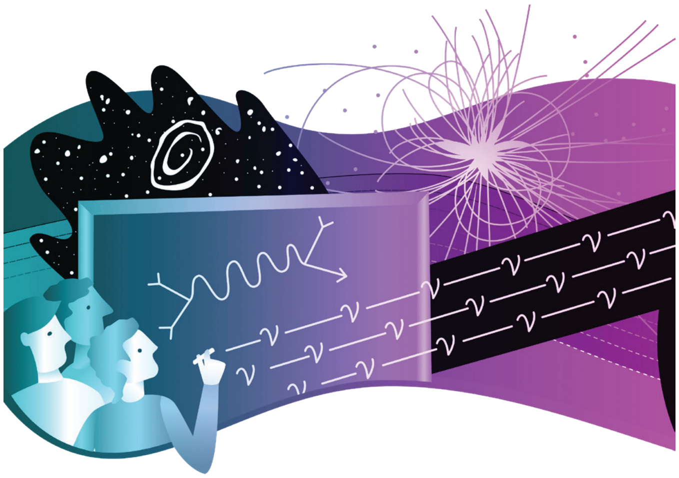
Over time, the experiments and instruments of particle physics have become more complex, and the facilities have become much larger, leading to more international collaboration and cooperation to achieve the field's scientific goals. The combined expertise and resources from nations around the world enabled the technological advances at the LHC (Large Hadron Collider) and the discovery of the Higgs boson (see Chapter 2). Such accomplishments would have been impossible to achieve by any single nation.

The large particle physics laboratories in the U.S. and CERN (European Laboratory for Particle Physics Research) and others in Europe facilitate the strong interplay between pure and applied research. The fundamental understanding of the universe is pure research, but the technology needed to enable it creates broadly applicable innovations—better magnets, faster electronic circuits, large global computing systems, big data techniques, and new sensors.

While many factors go into a decision to pursue a career in science, certainly one is excitement about the big fundamental questions waiting to be answered. Particle physics stimulates that excitement, and in the process, draws people to the physical sciences and helps fill the education pipeline with talent.

3.1

Key scientific areas and U.S. leadership



Scientific breadth and application

KEY FINDING

Particle physics theory and experiments address deep mysteries of the universe while advancing concepts and technology that are vital to other research fields as well as society at large.

The primary goal of particle physics is discovery science, and the U.S. has had a leadership role in the field. Strong strategic planning, investments in facilities, and world-class research infrastructure have led to discoveries and innovations in technology and have attracted researchers from around the world.

KEY RECOMMENDATION

Strengthen investments to advance particle physics discoveries as well as benefits to other scientific disciplines and society.

Planning foundations of discovery

FINDING

The strategic plan for particle physics is developed through a community planning process culminating in the report of the HEPAP subpanel called P5.

The roadmap for U.S. particle physics begins with a community planning exercise organized by the American Physical Society's Division of Particles and Fields. The most recent planning exercise "Snowmass 2021" brought together scientists from all areas of the field and closely associated fields[d] in a two-year study of the major questions in particle physics and the underlying technology and infrastructure needed to answer them. The Snowmass report[8] gives a comprehensive overview of the challenges and opportunities in particle physics in the future.

P5 (Particle Physics Project Prioritization Panel), a subpanel of HEPAP (High Energy Physics Advisory Panel), defines the strategic plan for U.S. particle physics. The 2014 P5 report[7] set the direction for the U.S. program in particle physics over the past decade, focusing investment in the science drivers (see Chapter 2). A new P5 panel will update this strategic plan in 2023 for the coming decade, positioning the U.S. for continued leadership in answering the most pressing questions of the field.

The 2014 P5 report enabled the U.S. to advance a set of construction projects in the U.S. and to continue its successful partnership in the LHC program at CERN. There was consensus at Snowmass 2021 that the science areas outlined in the 2014 P5 report were still appropriate for the next decade. Based on the success of the 2014 report, the U.S. should aspire to leading roles in the key areas identified by the new strategic plan in the 2023 P5 report.

RECOMMENDATION

The U.S. should continue to play leadership roles in the key scientific areas defined as science drivers by P5.

The 2014 P5 strategic plan put the U.S. program in a strong leadership position. Most of the construction projects recommended by the 2014 P5 panel have made significant progress, and many are already in operation. These projects reflect the priorities of the field and have in many cases already begun producing scientific results. They will shape the particle physics landscape over the next decade and beyond.

The neutrino program with the associated LBNF (Long-Baseline Neutrino Facility) and PIP-II (Proton Improvement Plan-II) construction projects is key to the 2014 strategic plan. Both projects are clear priorities for the U.S. program, are progressing, and are on track for completion as U.S.-hosted international facilities dedicated to particle physics. Science with DUNE (Deep Underground Neutrino Experiment) will begin at the South Dakota site in 2029, with the detectors at Fermilab (Fermi National Accelerator Laboratory) complete in 2031 and with PIP-II complete in 2033.[8] These projects will enable ground-breaking neutrino physics in the 2030s and beyond. As host of these projects, the U.S. should see additional economic benefits, particularly in the host states of Illinois and South Dakota.[13] This will likewise be true for the next major particle physics facility the U.S. will host.

The U.S. LHC program and HL-LHC (High-Luminosity LHC) upgrade projects, both high-priority programs with support from DOE (Department of Energy) and NSF (National Science Foundation), have enabled strong U.S. participation in the international energy frontier at the LHC at CERN.[e] The participation of five DOE national laboratories and over 65 U.S. universities continues to be essential to the LHC. An NSF MREFC (Major Research Equipment and Facilities Construction) award is critical to the upgrades of the ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) detectors and enables major roles by numerous U.S. universities in the upgrades. Overall, the U.S. plans to deliver major portions of the detector upgrades and key parts of the HL-LHC accelerator in preparation for a new era of exploration at the energy frontier that will commence in 2029 and is foreseen to last about a decade.

The construction of the DESI (Dark Energy Spectroscopic Instrument) survey instrument has been completed as an international project hosted in the U.S. with data-taking and data analysis underway. The collaboration plans to deliver its initial cosmology results and catalogs to the public next year.

Fermilab's accelerator infrastructure has been a key enabler of world-leading intensity frontier small- and medium-scale experiments such as Fermilab's Muon g-2 and Mu2e (Muon-to-Electron experiment) which squarely address the physics of the P5 science driver "Explore the Unknown". These experiments were conceived and approved before the 2014 P5 but were recommended to continue.

The U.S.-hosted experiment Fermilab Muon g-2 leads the world in measuring the magnetic strength (estimated as "g-2") of the muon particle. The experiment recently completed its target goal of collecting 21 times the statistics of its predecessor experiment at BNL (Brookhaven National Laboratory), and data-taking is now complete. In August 2023, Muon g-2 announced a new measurement of g-2,[14] which comes from analyzing the first three years of data, with a precision of 0.20 parts per million, the most precise measurement to date. This measurement is in tension with one of the two leading Standard Model theoretical predictions of muon g-2 but in agreement with the other, which is based on a different theoretical approach.

The Fermilab Mu2e Project received DOE Critical Decision-0 in November 2009, is fully funded, and 85% complete as of mid-2023. Mu2e is expected to take data for six months in 2026, collecting 10% of the total dataset envisaged and at a 1000x improvement in sensitivity over the present world-best experimental limit. However, this project has been considerably delayed even though it has competition. A rival experiment, COMET (Coherent Muon to Electron Transition) at J-PARC (Japan Proton Accelerator Research Complex), will commence Phase 1 data-taking *in 2025 and is expected to achieve a 100x improvement in sensitivity over the present world-best experimental limit.*

Fermilab also hosts SBN[f] (Short-Baseline Neutrino program), which is a unique probe of the P5 science driver for the physics of neutrinos. One of the physics targets of SBN is to investigate the evolution of neutrino oscillations over a short time and distance for evidence of a Beyond the Standard Model mysterious fourth neutrino (also known as a sterile neutrino) and other Beyond the Standard Model phenomena. SBN, a suite of short-baseline neutrino experiments in operation at Fermilab, is an excellent training ground for DUNE, because the same detector technology is used on a much earlier timeline than DUNE. MicroBooNE (Micro Booster Neutrino Experiment), one of the SBN experiments, has found no evidence for a sterile neutrino with the data analyzed so far.[15]

The Sanford Laboratory in South Dakota hosts another of the mid-scale projects, the cosmic frontier experiment LZ (LUX-ZEPLIN), which searches for dark matter in the galactic halo as it passes through the Earth. As recommended by P5, LZ is part of a staged suite of complementary generation 2 direct detection experiments with multiple technologies to search for the two most favored dark matter candidate particles, the WIMP (weakly interacting massive particle, LZ) and axion (ADMX-G2, Axion Dark Matter Experiment-G2). ADMX-G2 is currently operating at the University of Washington, Seattle. DOE also supports the low mass WIMP search SuperCDMS-SNOLAB (Super Cryogenic Dark Matter Search-Sudbury Neutrino Observatory) project in Canada.

ADMX-G2 2021 results[16] reached a milestone for global axion searches, reporting they had achieved a five-order-of-magnitude improvement over previous limits, ruling out the KSVZ[17,18] axion dark matter hypothesis in the 3.3 to 4.2 μeV (microelectron volt) mass coupling range.

LZ data-taking started at the end of 2021; the experiment is now in its second run. World-leading results were published in Physical Review Letters in 2023.[19] LZ is in direct competition with XENON-nT (Direct Search for Dark Matter with Liquid Xenon Deep Underground) at LNGS (Laboratorio Nazionale Gran Sasso) in Italy. The two collaborations have joined forces to propose a more sensitive third-generation dark matter experiment.

The SuperCDMS-SNOLAB project is in the fabrication phase; DOE Critical Decision-4 was approved in March 2023. Data-taking with one production tower of sensors will occur in 2023 and with all four towers in 2025.

The Vera C. Rubin Observatory will probe the nature of dark matter and dark energy. The observatory is preparing for LSST (Legacy Survey of Space and Time) operations, and the survey is scheduled to start operations in 2025. DESC (Dark Energy Science Collaboration) is well prepared to carry out a full spectrum of cosmology analyses that will illuminate dark energy, dark matter, neutrinos, and inflation.

The U.S. has been a leader in ground-based cosmic microwave background research. The CMB-S4 (Cosmic Microwave Background-Stage 4) experiment, recommended by the 2014 P5 report and the National Academy of Sciences decadal survey on astronomy and astrophysics 2020,[20] has achieved DOE Critical Decision-0, and the conceptual design is moving forward.

Enabling other fields of science and society

FINDING

Particle physics pushes the boundaries of technology in ways that enable research in other fields of science and that benefit society at large.

Particle physics research activities facilitate the interplay between pure and applied research. The dependence of applied research on the pure research that precedes it is well illustrated by an NSF study[21] that found that 73% of the papers cited in industrial patents were published as “public science” and were overwhelmingly basic research papers.

Tools developed for particle physics experiments now power next-generation technologies with diverse applications. These technologies enable cargo screening for safer borders, monitoring the cores of nuclear reactors, advancing computing technology for pattern recognition, and enabling microelectronics to function in ultracold environments. Crystal growth methods developed for particle detectors later found use in and a large commercial market for these crystals in medical imaging.[22] 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.[23]

Intense particle beams eliminate harmful chemicals in wastewater, while compact mobile superconducting accelerators extend the life of highway surfaces.[24] In medicine, particle physics technologies operate at the core of imaging devices (*e.g.*, the PET or Positron Emission Tomography scanner), and are used in manufacturing customized medical implants and the treatment of cancer. For example, software developed to model particle detectors has been adapted to plan radiation therapy for cancer patients, and accelerator technologies are used to deliver these treatments. Particle physics has also been instrumental to drug discovery; researchers use light sources, powered by next-generation superconducting accelerators, to understand the molecular structure of biological targets that are key to designing new pharmaceuticals.

Particle physics experiments that detect neutrinos have also provided valuable data to other scientific fields. For example, precise measurements of neutrinos from radioactive isotopes deep inside the earth have been informative to geoscience. 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, thereby enabling detailed reconstruction of paleo-climate records.[25]

Today’s R&D (research and development) advances will enable new ways to apply particle accelerator, instrumentation, and computing technologies to serve the environment, industry, medicine, and much more. The advances needed for the particle physics experiments and facilities currently under construction hold the promise of revolutionizing several fields in the coming years. For example, scientists working on LBNF, DUNE, and PIP-II push the boundaries of technology to build powerful accelerators and massive and intricate ultracold detectors. Researchers at the LHC are pushing the boundaries of data-intensive computing for science.

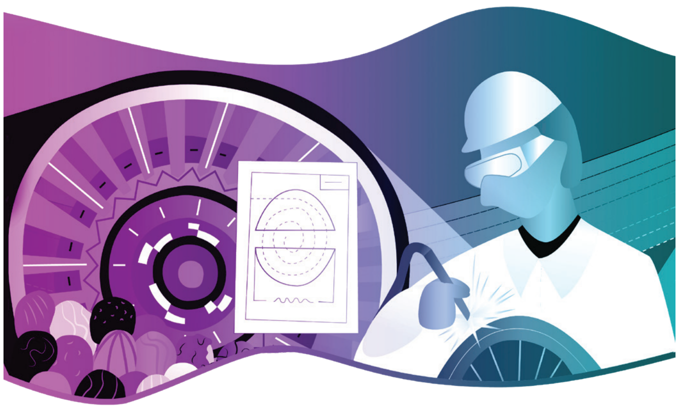
DOE HEP (DOE Office of High Energy Physics) has been the steward for accelerator R&D in the U.S. The outcomes have not only benefited DOE HEP missions but also the missions across the DOE SC (DOE Office of Science) as well as other funding agencies. For example, research on high brightness electron sources has enhanced X-ray free-electron laser performance and could result in cost reductions in LINAC-based (linear accelerator-based) discovery science facilities.

RECOMMENDATION

Continue to invest in technology R&D that enables new discoveries in particle physics and other scientific fields and that will lead to applications that benefit society at large.

3.2

Particle physics as an ecosystem



Diversity across scales and stages

KEY FINDING

The field of particle physics is a vibrant research ecosystem, built by an international network of partnering nations, facilities, experiments, and people. To be a leader, the U.S. must continuously produce scientific results, build facilities and experiments for the future, and advance new ideas and technologies that enable the discoveries of tomorrow.

KEY RECOMMENDATION

Maintain a comprehensive program at home and abroad, with a range of experiment scales and strategic balance among construction projects, operations of experiments and facilities, and core research activities, including the development of future facilities.

Particle physics in the 21st century is a global scientific ecosystem, and the U.S. program is an integral part of the field. The field advances through sharing ideas and by developing, constructing, or adapting tools needed for accelerators, detectors, and computing. New technologies and new ideas can lead to breakthroughs at all scales. Understanding the smallest scales drives the development of high energy accelerators, instrumentation, large underground facilities, and experiments of all sizes. These experiments can generate massive collections of data, and advanced computing tools are required to uncover the physics hidden within them.

The Snowmass Community Planning Exercise[26] highlighted the many strengths of a comprehensive and diverse global field that crosses many frontiers. During the Snowmass 2021 study, the U.S. community examined the most promising opportunities in the field along its many focuses: energy frontier, neutrinos, rare and precision measurements, cosmic frontier, theory, accelerators, instrumentation, computation, underground facilities, and community engagement. The frontiers are largely distinguished by the tools they use and by the questions they address. These interconnected frontiers cannot operate as research silos. They support and complement each other to address the big questions in the field and aim to generate a comprehensive and balanced research program with a continuous stream of compelling science.

A diversity of project scales is just as important to the particle physics ecosystem. Experiments from small to mega scale are able to address unique scientific goals, with small-scale experiments being especially impactful in the cosmic and intensity frontiers. This variety of scale—in size, complexity, and length of time between the idea and the scientific results—helps drive innovation and keeps the field on the human scale. The continuity of such a diverse program enables more training opportunities and the development of broader capabilities and expertise. In the end, a well-balanced program enables the field to address more questions and to advance in a way that is attractive and better matched to scientific career development.

The global ecosystem is based on principles of balanced strategic competition and collaboration. Essentially, the field has established a federated portfolio of research investments and facilities hosted in various countries and regions. Open science and the expectation of fair-share contributions from each country or region underlie the system. Given the scale of many current large projects, a healthy ecosystem can be achieved when global regions are each able to host local facilities and also participate in the construction and operations of many complementary facilities hosted abroad. Partner participation in facilities hosted abroad involves intellectual contributions as well as material deliverables, typically in the form of components of the facility fabricated in the partner's own country delivered to the international host laboratory for integration into the overall facility.

Because the lifecycle of many experiments can be decades long, it is essential for the health of the field and for workforce development to have a portfolio of projects that are at different phases of development at any given time. For example, the energy frontier experiments at the LHC, ATLAS, and CMS were conceived in the early 1990s, constructed in the 2000s, began operations around 2010, and plan to operate until around 2040. The ongoing upgrade projects for ATLAS and CMS for the HL-LHC will enable the collaborations to produce compelling discovery science well into the 2040s. U.S. universities have continued to train students in the LHC research program throughout the entire lifecycle. During the construction and commissioning of the LHC facility and experiments, many students analyzed data from the Fermilab-based Tevatron program while commissioning the new detectors at the LHC at CERN. The training and experience gained at the Tevatron and at previous high energy colliders were essential for the Higgs discovery at the LHC. A similar synergy exists between the ongoing SBN program at Fermilab and the DUNE experiment that is currently under construction and that will begin operations at the end of the decade.

A sustainable and balanced program should support projects in all phases: in planning, in construction, and in operation. The Snowmass Community Planning Exercise and the 2014 P5 recognized the global nature of the field and acknowledged that the best scientific opportunities are often realized through strategic international partnerships. The LHC program is one example of a strategic partnership with a project hosted at CERN. LBNF/DUNE is a U.S.-hosted international project. Any large-scale projects of the future will be international and require the expertise and resources of the international particle physics community.

Core research

FINDING

Decline in support for core research threatens U.S. leadership in particle physics.

The core research program[g] produces scientific results, interprets these results, conceives new experiments, and develops new techniques and capabilities. Core research supports the three experimental frontiers (energy, intensity, cosmic), theory, and the advanced technology programs of accelerators, instrumentation, and computing. The program supports the scientists and students needed to advance the field in these areas and to understand the science in the data generated by the experiments and facilities.

Though overall DOE HEP budgets in support of the U.S. particle physics program have increased significantly over the last ten years, inflation and the increased costs of large long-term projects have diminished the funds available for core research. It is not just that the core research program has not kept up with inflation. Even the unadjusted budget has decreased—from $361M in 2014 to ~$326M in 2023—while inflation additionally reduced spending power by ~30%.[27] Additional funding for targeted initiatives such as those in artificial intelligence and machine learning, quantum information science, and microelectronics have helped to offset the impact of inflation on core research funding over this same period. NSF funding for core research in particle physics has also not increased to compensate for inflation over this period. At the same time, the increase in construction project funding over the last decade will open new scientific opportunities for the next-generation workforce. This next generation will not only be needed to operate, analyze, and interpret the results from the experiments and facilities currently under construction, but also they will be essential to imagine and develop the next-generation experiments and facilities.

Decline in support for core research in particle physics has threatened U.S. leadership in the field by limiting the resources available to cultivate new ideas and to develop the next generation of facilities and therefore new discoveries. The scientific workforce needed to initiate new concepts and to uncover the science from the data are supported through core research programs. These funds are also needed to support the researchers who interpret the findings from operating experiments and facilities. A strong core research program is essential to deliver scientific results. The overall success of the portfolio of projects depends on the experience, creativity, and ingenuity of this workforce. Finally, the core research program is the main source of support for students. A decline in core research directly results in shrinking the pipeline from particle physics to the STEM (Science, Technology, Engineering, and Mathematics) workforce.

RECOMMENDATION

Reinvigorate the U.S. core research program to restore U.S. leadership in the next generation of ideas, experiments, and discoveries.

The role of small experiments in a balanced portfolio

FINDING

U.S. leadership entails leading on small experiments as well as leading on medium and large experiments.

Demonstrator-scale and small projects lay the foundation for future larger experiments. These projects have also produced compelling scientific results. Small projects are also outstanding training grounds for students and postdocs, allowing them to experience the whole life cycle of an experiment. These projects also can lay the groundwork for endeavors at a larger scale.

Over the last decade, the U.S. particle physics community has successfully developed a suite of pathfinder demonstrators and new small experiments to search for dark matter, make measurements of neutrino cross-sections, and explore signs of new physics in the neutrino sector. They also provide a unique opportunity for the training of young scientists.

Many of these experiments take advantage of and further develop key U.S. capabilities. Quantum sensors and advanced instrumentation developed jointly by U.S. consortia of national laboratories and universities have enabled new approaches to study the nature of dark matter, probe neutrino mass, and study cosmic evolution. U.S. scientists have played a leadership role in the development of these technologies and their application to fundamental science.

In the U.S., demonstrator experiments on the scale of $1M or less can be funded via NSF awards including EAGER (Early-concept Grants for Exploratory Research) and MRI (Major Research Instrumentation program) awards, as well as LDRD (Laboratory Directed Research and Development) programs. Following the demonstrator-scale experiment, the next critical step is the small project, roughly $1M–$100M in total cost. The lower end of this range can be funded by NSF with Mid-scale RI-1 (Mid-Scale Research Infrastructure-1) awards and the upper end by the very competitive NSF Mid-scale RI-2 awards.

In the last decade, DOE has had two funding opportunity announcements targeting projects in this range. The Intermediate Neutrino Program made two awards in 2016 for a total of $10M. The more recent DMNI (Dark Matter New Initiatives) funding opportunity announcement awarded project development funds for six concept experiments. Some of these DMNI projects have achieved world-leading dark matter constraints even in their prototype/development stage. One of these initiatives (CCM, Coherent CAPTAIN Mills) has been funded by Los Alamos National Laboratory and is proceeding; the remaining five initiatives are now awaiting project funds.

Despite examples of success, funding small-scale experiments can be challenging in the U.S. Groups from other nations, such as Italy and Korea, have been more nimble in moving from concept to data-taking experiments. This affects U.S. scientists with respect to both their ability to partner with non-U.S. groups and their ability to compete with non-U.S. groups. Timely inclusion of these small new initiatives in the U.S. particle physics portfolio is vital to maintaining the continuity, diversity, and sustainability of the field.

For many small projects hosted overseas, the international community views the U.S. as a partner of choice. The U.S. is seen to bring infrastructure, person power, resources, a long and strong tradition of excellence in experimental and theoretical particle physics, and the ability to lead the agenda—a very powerful combination.

The small project range of $1M–$100M is a scale of experiment that is tractable for many international partners. U.S.-hosted small projects address important physics and attract significant participation from the international community, which makes valuable contributions to the projects. However, siting in the U.S. is not always seen as an attractive option. The international community noted it has become harder to participate in U.S.-hosted projects than was the case in the past, regardless of project scale. This is due to increased difficulties in obtaining visas and the time that it takes to do so, and increased difficulties in obtaining U.S. national laboratory access (see Chapter 5). There is also a perception in both the U.S. and international communities that the cost to build a small project is greater in the U.S. than the cost is to build it elsewhere. Small projects also need the right scale of project management and oversight, commensurate with the size of the project, to ensure timely delivery of the science.

A mechanism is needed that will enable the U.S. community to be nimbler in starting new small-scale projects. A well-defined funding model would enable significant international contributions while simultaneously maintaining U.S. leadership. One example is the DOE HEP DMNI projects. However, these projects are expected to be funded at least 75% by DOE, which discourages DMNI collaborations from seeking equitable international partnerships.

NSF has a strong track record of supporting small projects, while DOE tends to focus on larger-scale endeavors. This limits the extent to which these projects can utilize the expertise of lab personnel and facilities. Dedicated funding lines and greater partnership between DOE and NSF in funding small projects would benefit individual experiments as well as the portfolio as a whole.

RECOMMENDATIONS

Continue to support small projects as a component of a balanced national portfolio of experiments at all scales.

Establish a funding mechanism under which scientifically compelling, well-conceived small projects can be initiated and executed in a timely and competitive fashion.

U.S. in the global community

FINDING

The U.S. particle physics program is part of a global research ecosystem. More scientific advances can be realized through international partnerships.

The U.S. relies on the Snowmass, P5, and National Academy of Sciences Elementary Particle Physics processes to develop long-term strategic plans for particle physics. These processes have been very successful and well aligned. Each process benefits from significant input from international colleagues, but all are inherently U.S. processes.

There is currently no truly global process for decision making or for ensuring global balance for the field. ICFA[h] (International Committee for Future Accelerators) has been the international forum among laboratory directors for discussion of global accelerator-based particle physics projects and programs but is not a decision-making body. CERN has a central role in international cooperation in particle physics, but its planning process, the European Strategy for Particle Physics,[28] is mainly driven by member states. The U.S., as a CERN Observer state, participates in this process but is not a voting member.

Discussions of a global strategy for the field are complicated by the fact that funding agencies in countries and regions define the boundaries of the field differently. Planning for particle astrophysics is organized independently in many countries. The global forum for particle astrophysics is APIF (Astroparticle Physics International Forum)[29] in the OECD (Organization for Economic Co-operation and Development) Global Science Forum. APIF is a discussion forum for funding agencies with an emphasis on strengthening international cooperation for large programs and facilities.

The 2014 P5 adopted the principle that the regions work together to address the full breadth of the field's most urgent scientific questions by each hosting unique world-class facilities at home and partnering in high-priority facilities hosted elsewhere. Both hosting and partnering are essential components of an achievable global vision for the field, and both are essential for U.S. leadership of particle physics. Moreover, both contribute economic, technological, and workforce development benefits to the nation, and to building a strategic alliance of nations.

The international scientific community currently defines goals and priorities through regional and global strategy processes, such as P5 or the European Strategy for Particle Physics. For smaller projects, competition among the regions enhances balance across the field and provides more opportunity and complementarity, and a steadier stream of scientific results. Imagining the large facilities of the future, global coordination and collaboration become increasingly necessary to ensure the project has adequate access to resources and expertise.

The development of large international collaborations becomes a necessity as part of this globally shared science program. The international nature of the projects should not be viewed as a "risk" to successfully achieving the science goals but as an opportunity to pursue a global science program at the frontier of particle physics in a resource-limited environment, sharing technical and scientific expertise between the collaborating partners.

Despite the lack of a formal global planning process, the communication channels are open among scientists and their funding agencies across the globe, even in the face of growing world tensions. Interest in addressing the big questions remains. Particle physicists around the world, at CERN, in the U.S., and in Japan and China have expressed their interest in developing a next-generation high energy collider while maintaining balanced, comprehensive, and open global programs. Any next-generation collider facility will be a large-scale international project.

All countries that contribute to large international projects benefit. The ecosystem works best when each country or region contributes in a fair and equitable way. There is an expectation that each major region hosts a facility that welcomes scientists from the other regions. In the past, these facilities would compete, but as facilities have grown in size and complexity, international (even global) partnerships are required to find the necessary resources and expertise. Consolidation of resources helps increase scientific opportunities and diversity globally.

RECOMMENDATION

The U.S. strategic planning processes should take into consideration the global particle physics ecosystem in setting priorities. International partnerships that create a compelling scientific program with a healthy global balance among the lifecycle stages—construction, operations, and core research activities—should be sought.

3.3

Importance of collaboration

Collaborating across the globe

KEY FINDING

Frontier research in particle physics necessitates international collaboration and cooperation. The combined expertise and resources from nations around the world enable discoveries and technological advances impossible to achieve by any single nation. It is the global particle physics program that collectively addresses the burning scientific questions across the breadth of the field.

KEY RECOMMENDATION

Continue support for and actively seek engagement with international collaborations and partnerships of all sizes.

Common characteristics of successful collaborations emerged in the subpanel's interviews and case studies. An overarching characteristic is shared scientific objective. International partnerships are observed to be strongest among partners who are engaged from the earliest stages of a project. Partnerships, particularly for large projects, require agreed-upon governance structures. Shared governance and shared responsibility are principles observed in successful partnerships and large collaborations. Mutual trust and respect are also fundamentals of success. Governance structure should be agreed upon among partners early during the formation of the partnership. The most effective international collaborations demand the partnership of scientific communities and the partnership of their funding agencies. International partnership on construction of major particle physics accelerator facilities has been growing.

International experiments hosted outside the U.S. seek U.S. participation, and U.S. participation in these experiments is a means of enabling U.S. scientists to engage in important science opportunities that are not available in the U.S. Participation of U.S. scientists and institutions in the development and execution of experiments hosted outside the U.S. should be enabled and facilitated. Some special measures to facilitate time spent abroad and to facilitate collaboration at remote facilities are needed for U.S. scientists.

The remainder of this subsection expands upon subjects important to successful collaboration (*i.e.*, the roots of strong collaboration), upon the impact of early engagement and collaboration governance, and upon some topics related to international partnership on accelerator facilities and on experiments hosted outside the U.S.

The roots of strong collaborations

FINDING

Strong collaborations exhibit common characteristics. Shared scientific objectives and a shared sense of responsibility are overarching common characteristics.

Common characteristics of successful collaborations emerged in the subpanel's interviews and case studies. These characteristics, listed below, are the roots of strong collaborations and thus of successful science in the field of particle physics. Such characteristics are generally manifest in successful large experimental collaborations; nonetheless, these traits are also present in successful collaborations of all sizes. Moreover, such traits are also expected of successful collaborations that are constructing facilities, *e.g.*, accelerator facilities.

- shared scientific objective(s)
- shared decision making
- shared governance
- shared sense of ownership
- shared sense of responsibility
- shared problem solving
- shared credit
- shared authorship
- shared sense of success
- shared values
- shared culture
- shared respect

Shared scientific objectives, or technical objectives in the case of facility projects, are the glue that binds the collaboration. Independent ideas for technical solutions or analysis techniques often compete within a collaboration. Conflicts are resolved through a shared decision-making process, ideally informed by scientific criteria and moderated by the collaboration's shared governance structure. The latter is collectively defined by the collaboration. While there is no ideal organizational and governance structure, the process of discussion and determination reinforces an overall shared sense of ownership, giving rise to a shared sense of responsibility. A shared sense of responsibility, in turn, promotes shared problem solving.

The principle of shared credit is central to many collaborations in particle physics. This principle is evident in the particle physics tradition of listing all scientific collaborators as coauthors on all the scientific publications resulting from the collaboration.[i] This tradition recognizes that all collaborators' contributions—from development of the apparatus, to experimental operations and data acquisition, to processing and analysis of the experiment's data—played a role in generating scientific results. Sharing credit reinforces both a shared sense of responsibility and a shared sense of success.

The policies and practices adopted by the collaboration embody the collaboration's shared values and define the shared culture of the collaboration. Shared values and shared culture are thus fundamental to the collaboration and its success. The principle of shared respect should be inherent to all collaborations' shared culture. Respect is essential not only to strong collaborations but also is fundamental to the development of a strong and diverse cadre of young scientists.

RECOMMENDATION

Collaborations should strive to establish an organizational structure and governance model that enables and cultivates the shared characteristics of current and past successful strong collaborations.

Engage with partners in the earliest stage

FINDING

International partnerships are strongest when partners are engaged starting from the early conceptual development of projects.

As an example, all major international partners (Canada, France, Italy, Germany, and the United Kingdom, U.K.) were engaged in the conception of the U.S.-hosted *BaBar*[j] experiment at the PEP-II (Positron Electron Project-II) *B*-factory at SLAC (SLAC National Accelerator Laboratory), resulting in a strong international partnership with a strong sense of shared ownership among all partners. *BaBar* collaborators, both U.S. and non-U.S., attribute the strength of the partnership to the early involvement of all partners in the conceptual design of the experiment and in the establishment of the collaboration's organization and governance.

As another example, U.S. groups have participated in the development of the major detector upgrades of the large international experiments

ATLAS and CMS for CERN's HL-LHC since the earliest conceptual phases of the upgrades. Consequently, the impact of the U.S. on the upgrades is on equal footing with the impact of major international partners. By contrast, most U.S. groups joined the original construction projects for ATLAS and CMS after the conceptual designs of the experiments were complete and their Letters of Intent were submitted. The major impact that U.S. scientists had on both experiments, which benefited from years of R&D for the SSC (Superconducting Super Collider), could have been even more significant if U.S. scientists had had the opportunity to participate in the conceptual designs and early technology selections for the original experiments.

Finally, as discussed in greater detail in Section 3.4, the conceptual design of the large U.S.-hosted DUNE experiment, which derived largely from the concept of the predecessor, LBNE (Long-Baseline Neutrino Experiment), was developed without the involvement of many international partners who later joined DUNE. The DUNE collaborators interviewed, both U.S. and international, felt that partner engagement could have been augmented if there had been greater partner engagement in the conceptual design of DUNE.

Several benefits accrue from the early engagement of partners. Foremost, early engagement maximizes participant impact. Partners engaged from project inception are more likely to influence the overall trajectory of the project (from design to technical implementation, culturally, *etc.*). The project can only benefit fully from the capabilities and expertise of partners to the extent that all partners participate through all phases of the experiment, and the collaborators' shared sense of ownership is more pronounced if partners engage at project inception. In addition, building a shared culture is significantly more likely if participants work together from the beginning and through all subsequent project phases. For these reasons, early engagement is beneficial for both the partner and the collaboration. Finally, early engagement also fosters fairness. That is, if new partners join a project late, when the project is essentially complete, then the original partners will have borne an unfair share of the construction costs, even if all partners share in the operating costs. Nevertheless, collaborations should remain open to collaborators who do not join at project inception, with appropriate expectations for participation.

Looking forward to future international experiments, support should be provided for U.S. groups to engage in early conceptual development and R&D activities to maximize the potential for U.S. impact. For instance, given the high science priority placed on Higgs factories (see Chapter 2), support should be provided for the conceptual design of experiments for these facilities. Although U.S. support was provided for the conceptual design of the experiments for the ILC (International Linear Collider) during the ILC GDE (Global Design Effort), the conceptual design of experiments for the FCC-ee (Future Circular Collider for electron-positron collisions) has started without substantial U.S. engagement.

Analogously, the impact of international scientists on U.S.-hosted international experiments can be largest, and thus most beneficial to U.S.-hosted experiments, if the engagement of international scientists is established as early as possible in the conceptual development.

Early engagement should start with scientists at the grass roots level. However, engagement should be facilitated by potential host laboratories and by funding agencies. Moreover, engagement by agencies in discussion during this phase is important to the development of a sound basis for international partnership, as further discussed in the next section on collaboration governance.

RECOMMENDATIONS

DOE and NSF should support involvement of U.S. scientists and institutions starting from the early conceptual development and R&D phase for future international experiments and accelerator projects.

Future U.S.-hosted experiments and accelerator projects should seek to engage scientists and institutions of potential international partners in the projects' early conceptual design and R&D phase while remaining open to additional partners who may want to join later.

Collaboration governance

FINDING

Shared governance and shared responsibility are principles observed in successful partnerships and large collaborations.

All scientific collaborations require a governance structure. For international collaborations, the governance structure needs to reflect the international nature of the collaboration and to be agreed upon by all the international partners and their funding agencies. There is no unique or single best governance structure; several international governance models have been successfully implemented for experiments in particle physics, particle astrophysics, and cosmology. Although this subsection discusses collaboration governance for international experiments, the same principles would apply for accelerator facilities. The discussion here is generally independent of whether international projects are hosted in the U.S. or abroad. However, Section 3.4 details collaboration governance topics that are more specific to U.S.-hosted projects.

A given international collaboration first defines its scientific priorities and develops the design of the experiment. Next, the international collaboration moves into a construction phase, followed by an operations phase, and is ultimately responsible for the scientific results. During the construction phase, the international collaboration must closely coordinate with any and all national construction projects that contribute to the construction.

The independence of the international collaboration, particularly in terms of the scientific goals and priorities, is essential for the success of any ambitious science program. The international collaboration governs itself, guided by the framework of the governance structure, with oversight provided by the host institution and the funding agencies.

The governance structure of truly international scientific projects should reflect the shared responsibility for the scientific success of the project and the commitment of all partners to provide the necessary resources to achieve the scientific goals. It requires a culture of collaboration and cooperation, based on open communication, transparency, and trust in the ability of the partners to deliver. The goal of such a structure is to achieve a shared sense of ownership and a shared responsibility for the success of the project. The exact form chosen for the governance structure should reflect the science goals, infrastructure and facility requirements, and the resource model. The international partners must be actively involved in defining the governance structure.

A process for decision making must be defined as part of the governance structure definition. Collaboration decisions must be made in a transparent way. To yield proper optimization of the experiment design, decisions should be based on scientific and technical considerations as opposed to political factors, such as which group has more funding or which nation is hosting the experiment. Clear decision-making processes based on scientific considerations will improve acceptance of decisions and help overcome tensions among groups or individuals. Such processes also strengthen collaboration and a sense of joint ownership.

Construction of the experiment requires agreement of partners to provide specific deliverables (such as specific components of the experimental apparatus or specific software required by the experiment) on a specific schedule. Agreement among partners on the integrated project schedule is as important as the agreement among partners on their deliverables. The international collaboration is responsible for agreement among all partners on the sharing of responsibilities, *i.e.*, on each partner's deliverables, in coordination with partner funding agencies.

Likewise, the successful construction and future operation of the experiment require commitments from all partners to contribute to the joint experimental infrastructure and to the experiment's operations phase. These commitments need to be achieved by a timely agreement forged by the international collaboration in coordination with partner funding agencies.

Governance structures are complicated by the typically unequal distribution of contributions from various partners, where the host nation usually provides the largest contribution, with a very large variance of contributions from other partners. A two-tier system based on a core group of larger partners and a broader representation of smaller partners may facilitate an effective governance and management structure.

Each partner's agreed-upon deliverables to the construction of the experiment (and eventually to the operations) are typically delivered by national projects reflecting the source of funding. These national projects usually manage the progress of their work independently and are coordinated by an overall integrated project management structure which is normally provided by the host laboratory. The integrated project management system must accommodate the differing requirements of the host and all other partners and have the buy-in of all partners. Meeting these requirements can be challenging. Decisions that impact national projects need to proceed through this integrated project management system and should not be unilaterally imposed by any one partner. In the same spirit, the structure of reviews needs to be clearly aligned with the international governance structure, with a well-defined scope of each review and avoiding duplication and contradicting recommendations. Duplication of reviews was a concern frequently cited in interviews.

A common characteristic of successful international partnerships is the existence of an oversight body that endorses the sharing of responsibilities for construction and that can help define shared solutions to the unexpected problems that inevitably arise. It also oversees the fair sharing of operating costs. For instance, for the CERN experiments, the bodies that play this role are the RRB (Resource Review Board) of each CERN experiment. The RRBs, which embody shared responsibility, are composed of representatives from each partner funding agency and are chaired by the CERN Director for Research. During the construction of the LHC experiments, the RRBs quite effectively fostered shared problem solving, being very valuable partners in implementing solutions proposed by the collaboration scientists. The International Finance Committee of *BaBar* played a similar instrumental role (see Section 3.4).

To successfully implement project organization, all partners need to agree upon the fundamental characteristics of the governance structure early in the development of the project; agreements should occur no later than the completion of the experiment's overall conceptual design and the initiation of discussion of sharing of responsibilities among collaborators. Engagement of funding agencies during collaboration formation is best. Agreements should involve all relevant government departments, funding agencies, national laboratories, and collaborating institutions. All levels of DOE, as the principal U.S. funding agency for particle physics, should have an internally consistent view of the international nature of the governance structure and be jointly committed to implementing this structure.

RECOMMENDATION

Formally agree among partners on an international governance structure early during the formation of the international project.

International partnership on accelerator facilities

FINDING

International partnership on construction of major particle physics accelerator facilities is growing. International partnerships yield more powerful capabilities for scientific discovery.

Although becoming increasingly common, international partnerships to construct accelerator facilities for particle physics are not yet as prevalent as international partnerships on experiments, nor is the degree of partnership as advanced, as measured by either the fraction of the total investment that is provided by partners other than the host or by the number of individual partners. The strong leadership of the U.S. in a number of key accelerator science and technology areas (see Section 4.1) makes the U.S. national laboratories very desirable partners for future accelerator construction projects. International partnerships also facilitate the development of an expert workforce for accelerator science and technology.

The new accelerator facilities at DOE national laboratories are increasingly constructed by partnerships among national laboratories that bring together accelerator expertise. For example, the EIC (Electron-Ion Collider) being constructed at BNL in partnership with TJNAF (Thomas Jefferson National Accelerator Facility) is a current example of a national lab partnership. BNL and TJNAF established an integrated management team and are engaging other labs, U.S. and non-U.S., as additional partners. In Europe, in addition to facilities at CERN, several accelerator facilities are the product of international partnerships. The electron-proton collider HERA (Hadron-Electron Ring Accelerator), built at DESY (Deutsches Elektronen-Synchrotron) in Germany in the late 1980's for particle physics research, is regarded as the first truly internationally financed project of its magnitude, with about 25% of its cost of construction delivered in-kind by international partners.[30] The governance model adopted for HERA was adapted from models used by international experiments. Four other accelerator facilities[k] have been or are being constructed as international partnerships with predominately European partners, however, these accelerators are not particle physics facilities.

The LHC at CERN was the first international accelerator project the U.S. joined as a partner. That collaboration gave impetus to the initiation of LARP (LHC Accelerator Research Program) in the U.S., which led to U.S. partnership on the LHC upgrade to the HL-LHC. The U.S. is now leading an international partnership to construct the PIP-II accelerator at Fermilab. The U.S. has also partnered for years on the R&D and design for the ILC. Brief summaries of the international character of major accelerator projects with U.S. engagement follow.

Large Hadron Collider (LHC) at CERN

The earliest example of substantial U.S. partnering on an international accelerator project was the LHC at CERN, starting in 1997. Japan and Russia also partnered with the U.S. and CERN on the LHC.[l]

U.S. national laboratories—BNL, Fermilab, and Lawrence Berkeley National Laboratory—designed and constructed 50% of the superconducting magnets used to focus the LHC beams into collision at its four interaction points. Japan provided the other 50% of the superconducting magnets. The U.S. contribution was made possible by the strong U.S. expertise and capabilities in superconducting magnet technology developed for the never-completed U.S. SSC project, which was terminated in 1993. The U.S.-CERN partnership provided CERN with invaluable expertise and experience from the SSC community and provided the U.S. community with the opportunity to apply the expertise developed for the SSC and to stay at the forefront of superconducting magnet R&D. CERN also leveraged the U.S.'s progress on superconducting magnets for the design of the superconducting dipole magnets that bend the LHC beams.

LHC Accelerator Research Program (LARP)

As LHC construction was advancing, circa 2003, LARP was established. LARP was a U.S. collaboration[m] of laboratories and universities working to 1) partner on LHC commissioning and performance enhancement and 2) develop in-kind deliverables that the U.S. could provide to future upgrades of the LHC. Naturally, LARP collaborated closely with CERN in choosing and coordinating activities. Given its targeted objectives, LARP was established as a directed R&D program, supplementing the scope of the GARD (General Accelerator R&D) program in DOE HEP (see Section 4.1). LARP was notably successful with respect to both of its objectives: 1) contributing to the remarkable performance ramp-up of the LHC and 2) establishing a firm foundation for the accelerator components that the U.S. is now delivering to the CERN HL-LHC project. LARP's superconducting magnet R&D, which included dipoles for bending the beams as well as quadrupoles for focusing the beams into collision, also became foundational to CERN's final development of high-field superconducting dipole magnets for location in the new HL-LHC beam interaction points. In addition, the U.S. superconducting magnet R&D resulting from these programs included development of new superconductor (Nb_3Sn, niobium-tin) and superconducting Nb_3Sn cable, which also benefitted CERN in building Nb_3Sn capabilities.

High-Luminosity LHC (HL-LHC) at CERN

Based on technical advances made by LARP, as well as advances made under the auspices of the GARD program, a U.S.-CERN partnership on the HL-LHC project was established. The US-AUP (U.S. Accelerator Upgrade Project) is the U.S. construction project formed to deliver to HL-LHC, as in-kind contributions, superconducting magnetic quadrupoles and SRF (superconducting radio frequency) cavities designed and fabricated in the U.S. The HL-LHC superconducting magnets, which are similar in function to the superconducting magnets delivered by the U.S. and Japan to the LHC, are based on the higher magnetic fields possible using Nb_3Sn conductor rather than the NbTi (niobium-titanium) conductor customarily used in accelerator magnets. The SRF cavities are so-called crab cavities that align the bunches of particles in the beam as they come into collision to maximize the interaction of the two beams. These crab cavities will be the first to be applied to beams of protons. Collectively, these deliverables to the HL-LHC represent major U.S. investments in R&D and in fabrication.

Proton Improvement Plan-II (PIP-II) at Fermilab

PIP-II at Fermilab is the first U.S. accelerator project being constructed with significant international partnership. Institutions in France, India, Italy, Poland, the U.K, and the U.S. bring together their expertise and resources to the design and fabrication of components of this state-of-the-art accelerator. The capabilities of PIP-II are essential to the 2014 P5 recommendation to develop, in collaboration with international partners, a coherent short- and long-baseline neutrino program hosted at Fermilab. PIP-II also replaces the outdated first stage of the Fermilab accelerator complex and will provide ample proton beams for new scientific opportunities; for instance, a research program based on muon beams. Construction of PIP-II by an international partnership is aligned with P5's vision of hosting world-class facilities.

The U.S.-hosted PIP-II project benefits from technical collaboration on the design as well as the provision of accelerator components by partners. The international partners are incentivized by access to state-of-the-art accelerator technology and scientific and technical opportunities. PIP-II advances the degree of international partnering on accelerator facilities for particle physics and the degree of U.S. engagement of international partners on accelerators.

The PIP-II Project is finding its international governance structure effective. It has recognized the important principles of governance for international collaboration, which are generally similar for construction of accelerator facilities as for construction of large international experiments. The PIP-II Project is structured along the lines of DOE construction projects, with a project office directing and managing a hierarchical organization structured by technical systems and subsystems. Technical subsystems are frequently managed by members of international partner institutions. PIP-II project oversight is provided at the highest level by the INC (International Neutrino Council), which consists of representatives of the major partner funding agencies and is chaired by the DOE Associate Director for High Energy Physics. The INC also has oversight of the LBNF/DUNE project. Oversight at the next level is provided by the PIP-II Lab Directors Council, which consists of the directors of partner laboratories and is chaired by the Fermilab Laboratory Director. Finally, oversight at a third level is provided by the PIP-II Project Executive Board, which consists of the technical coordinators of all partner nations and is chaired by the PIP-II Project Director. The creation of these bodies recognizes the importance of the engagement of stakeholders at all levels in the project; in these instances, the international funding agencies, the heads of the partnering institutions, and the technical leaders of the national projects. The existence of these international bodies also facilitates reliable and transparent communication among partners.

International Linear Collider (ILC)

Although not yet in construction, the ILC is another example of international partnership on future accelerator facilities. After years of independent R&D in Germany, the U.S., and Japan, ICFA in 2005 initiated the design of the ILC as a "global" project in which nations from all the three regions (Europe, North America, and Asia) would jointly govern the project and share equally in the construction of the accelerator. Thus, the global partnership sought for ILC construction is much like the partnerships used to construct the LHC experiments at CERN. Nevertheless, this concept of the ILC as a global project is a different paradigm from any accelerator facility constructed or in construction today, pursuing as it does a project without a lead partner. ILC is noteworthy for its accomplishments, including developing as a global partnership a complete technical design for the accelerator and developing SRF accelerating technology to the point that it is now widely used for accelerators for science in other fields, including the LCLS-II (Linear Coherent Light Source-II) at SLAC in the U.S. and the European XFEL (X-ray free-electron laser). The ILC is also interesting for its challenges, particularly in its inability to date to secure a host. Recent questions have been raised regarding whether such a global project can be realized without a potential host laboratory or nation assuming the lead in advancing the project further.

Looking to the future of international partnership on accelerator facilities

Future particle physics accelerators will require higher energies and/or higher intensities as well as brightness than accelerators currently in use or in construction. These future accelerators will be more complex, requiring more expertise, and are likely to be physically larger and more expensive, requiring a suitable site and more financial resources. Extrapolating from the growing degree of international partnership on accelerator facilities outlined above, the construction of future accelerators will be increasingly accomplished by international partnerships. This trend is in line with the global nature of particle physics articulated the 2014 P5 report[7] which stated, "Hosting world-class facilities and joining partnerships in facilities hosted elsewhere are both essential components of a global vision." Numerous candidate future particle physics accelerators were discussed at the recent Snowmass Community Planning Exercise,[8] as the U.S. community is interested in hosting future accelerators in the U.S. and partnering on future accelerators abroad. The 2014 P5 report also stated, “As work proceeds worldwide on long-term future-generation accelerator concepts, the U.S. should be counted among the potential host nations.”

RECOMMENDATION

The U.S. particle physics program should 1) strive to engage as partners in the construction and operation of major future particle physics accelerator facilities constructed outside the U.S. and 2) actively seek international partners to engage in the construction and operation of major future particle accelerator facilities constructed in the U.S.

High energy colliders are expected to be an integral part of the future global particle physics program. Given LARP’s success and the trend of increasing partnership on accelerator projects, establishing a collaborative U.S. national accelerator R&D program on future colliders[31] would be advantageous. Such a program would 1) advance the development of future colliders and 2) coordinate U.S. R&D activities with those of future partners. Importantly, this program would facilitate early engagement among U.S. scientists and engineers and international partners on projects that might be constructed on U.S. soil and abroad. These activities would position the U.S. for major roles in future colliders built anywhere in the world. They would also ensure the continuity of required expertise for future U.S.-based facilities.

RECOMMENDATION

Establish a collaborative U.S. national accelerator R&D program on future colliders to coordinate the participation of U.S. accelerator scientists and engineers in global energy frontier collider design studies as well as maturation of technology.

International experiments and accelerator projects hosted outside the U.S.

FINDING

International experiments and accelerator projects hosted outside the U.S. seek U.S. participation. U.S. participation in programs hosted outside the U.S. enables U.S. scientists to participate in the best science wherever it is done.

Consistent with its vision of particle physics as a global field of discovery, the 2014 P5 report’s[7] first recommendation was, “Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.” U.S. participation in international experiments and accelerator projects hosted abroad enables engagement of U.S. scientists in the important science opportunities that are not available in the U.S.

U.S. participation is in demand for both experiments and accelerator projects hosted outside the U.S. and is often essential to enable and achieve scientific goals. International experiments and accelerator projects seek the participation of U.S. national laboratories and universities to benefit from U.S. experience, expertise, technology, and technical capabilities, including experience in operating large-scale facilities. These attributes make the U.S. a partner of choice for international experiments.

The technical expertise and resources available through the national laboratories are a strong attraction to international projects, as well as a national asset. For example, international collaboration leaders of both large LHC experiments (ATLAS and CMS) recognized the invaluable U.S. contributions made on the development of some of the large structural components of the experiments. However, the national laboratories’ expertise reaches far beyond physically large components; for instance, designing the most advanced circuitry to instrument the smallest precise particle tracking systems.

RECOMMENDATION

Continue to enable and facilitate the participation of U.S. scientists and institutions in experiments and accelerator projects hosted outside the U.S.

Recent events have spurred progress in technology to support remote participation and collaboration. However, whether an experiment is sited in the U.S. or abroad, collaborating scientists generally require a degree of physical presence at the experimental site, with extended presence required by some. This need is not as strong for accelerator scientists, especially beyond a project's commissioning phase.[n]

FINDING

Mechanisms to support both the physical and remote participation of U.S. scientists collaborating on experiments hosted outside the U.S. are essential.

The need for effective communication among globally dispersed particle physics collaborations led to the creation of the World Wide Web at CERN (1990). Now ubiquitously known as *The Web*, this invention is used worldwide for sharing of information. Members of the particle physics community were also early adopters of collaborative tools such as video conferencing and conference meeting agenda management systems. Modern means of communication, personal interaction, and remote experiment control have obviated the need for all collaborators of an experiment to be physically on site.

Nonetheless, many experimental tasks depend upon the onsite presence of scientists, especially during the installation and commissioning phases. Moreover, research experience at experiments located abroad, particularly at a major laboratory such as CERN, is engaging for young scientists.

Travel and/or presence at the experimental site is required to have maximum impact on the science of experiments hosted abroad and to fully benefit from such engagement opportunities. This requirement holds for students and postdocs as part of their scientific training as well for more senior scientists and faculty members. For the latter, travel/presence on site enables leadership roles in their collaborations. Indeed, leadership positions frequently depend on presence at the experiment and/or 100% effort. For non-U.S.-based experiments, such requirements put U.S. scientists at a competitive disadvantage relative to scientists based at institutions closer to the experiments for whom frequent short trips to the experiment are a possibility.

In general, these considerations mean that a long-term presence of some scientists at the experimental site is necessary, and for some period of time for scientists more generally. For university faculty members who have teaching responsibilities, long-term presence at the experimental site requires a teaching buyout or support during a sabbatical, as do leadership roles requiring 100% effort. In general, a source of support for cases where physical presence or 100% effort is required should be identified.

The location of an experiment outside the U.S. is an impediment to the effective participation of U.S. scientists, and it can discourage the participation of individual scientists. Likewise, for scientists from outside the U.S., the location of an experiment in the U.S. is an impediment to participation. Consequently, experiments in the U.S. should organize so as to facilitate effective remote participation and increase capabilities for remote physics analysis and leadership. Improvements in this aspect would also aid small U.S. university groups. Meanwhile, agencies should support travel to and from the experimental site to the extent that is needed.

RECOMMENDATION

To maintain an active presence and intellectual leadership in experiments outside the U.S., support for faculty teaching buyouts or during a sabbatical should be expanded, and laboratory and university groups should support members to be based at experimental sites.

3.4

How to be a partner of choice

The U.S. is considered a strong partner in international particle physics experiments. Innovation in instrumentation, the technical competency of U.S. scientists, the strength of the national laboratory and university systems, and the breadth and capacity of the U.S. program are common positive themes expressed by the international particle physics community. These traits also position the U.S. for hosting international projects.

Being a partner of choice

KEY FINDING

Success in hosting and participating in international collaborations requires tailored approaches to collaboration governance and project management, host lab environments that are conducive to international research teams, and the ability to make reliable agreements with international partners.

The value and principles of international collaboration in general were discussed in the preceding section (3.3, Importance of collaboration). The principles discussed largely apply to both U.S.-hosted international collaborations and international collaborations hosted abroad. This section focuses on topics associated most frequently with U.S.-hosted collaborations. Nonetheless, most topics discussed here are also relevant more generally. The first subsection here discusses the subject of collaboration governance again; this time content is presented in the context of examples of successful international collaborations hosted in the U.S. in order to discuss some governance issues of particular interest to the U.S. as host. This discussion includes conclusions drawn from the recent initiation of the international LBNF/DUNE project. The next subsection discusses international collaboration on cosmic surveys, an area that differs somewhat from international collaboration on accelerator-based experiments and an area in which the U.S. is the leading host for international collaborations. The following subsection discusses a small number of characteristics of the U.S. particle physics program that are seen as impediments by many international collaborators. The final subsection discusses the responsibility of the host laboratory to provide an environment conducive to international collaboration. For international collaborators to partner on projects hosted in the U.S., the U.S. must offer compelling research opportunities that are not available elsewhere in the world.

KEY RECOMMENDATION

Implement structures for hosting strong international collaborations, act with timeliness, consistently meet obligations, and facilitate open communication with partners.

Governance of U.S.-hosted projects

Governance of U.S.-hosted international projects can be guided by the experience of past and present successful international partnerships both in the U.S. and abroad. This experience includes the values and principles of strong collaboration and governance described in Section 3.3. This subsection, which discusses governance topics and experience pertaining to U.S.-hosted projects, begins by introducing two models of governance to facilitate this discussion. It then draws upon the experience of the *BaBar*, DESI, PIP-II, and LBNF/DUNE projects to highlight some of the successes and challenges of hosting major international projects.

Host-led vs. CERN models of governance

FINDING

The governance of international partnerships on particle physics projects can be broadly characterized as following either the host-led model or the CERN model. The principal distinction between the two models is that the host usually carries the largest responsibility in the host-led model, whereas sharing of responsibility is more distributed in the CERN model. Both models have been successful, and the CERN model is found to work well when the project's degree of financial sharing is high.

Host-led model

Prior to the inception of LBNF/DUNE, the U.S. funding model largely focused on national projects, with non-U.S. international partners providing well-defined contributions but not carrying responsibility for the overall project. CDF (Collider Detector at Fermilab), the first large experiment at Fermilab's Tevatron collider, was such a national project. CDF was very successful and benefitted from substantial contributions from international partners, especially Italy and Japan. In this model, which this document refers to as the *host-led model*,[o] the project is led by a host laboratory or facility and has international partners. Another example of a successful project using the host-led model was the HERA accelerator at the DESY laboratory in Germany. DESY led construction of HERA,[p] with components delivered by international partner laboratories from ten nations in Asia, North America, and Europe and with human resources as in-kind contributions from two additional nations. HERA was one of the first truly internationally financed projects of this magnitude. About 25% of its cost of construction was delivered in-kind. In leading HERA construction, DESY implemented international committees[q] for oversight and guidance that are similar to those used for other international experiments and facilities today.

In host-led projects, the host typically has a majority stake in the experiment or facility, carries the greatest share of responsibility for the project, and plays the lead role in decision making. Host-led projects with international partners tend to be based upon bilateral agreements between the host and individual partner funding agencies.

CERN model

In the model exemplified by the experiments at CERN's LHC accelerator facility, the experiments have evolved collaboration governance structures based upon multilateral agreements regarding 1) each partner's responsibilities to the multinational collaboration and 2) all partners' rights within the collaboration. In this model, which this report refers to as the *CERN model*, a collaboration is not led by one institution or nation *per se*. Collaboration leadership is selected according to procedures defined by a governance agreement (see Section 3.3), and responsibilities, financial commitments, and decision-making authority are shared more broadly than in the host-led model. For example, in the CERN model, CERN as an institution is just one of the partners in each collaboration, although CERN as the host laboratory provides access to the accelerator facility and provides a larger share of needed infrastructure. The major LHC experiments—ALICE (A Large Ion Collider Experiment), ATLAS, CMS, and LHCb (Large Hadron Collider beauty)—are very large international collaborations that follow the CERN model. ATLAS and CMS, for instance, each involve approximately 3,000 collaborating scientists, 200 collaborating institutions, 40 partner nations, and both CERN Member States and non-member nations. The LHC international scientific collaborations and their experiments at CERN are widely recognized for their success.

In practice, the CERN model, as implemented in detail by CERN for the LHC experiments, places some requirements on the governance of the collaborations to ensure proper coordination of the collaborations with the host laboratory. CERN remains the legal home of the collaborations. The collaborations' Technical Coordinators, whose responsibilities include safety, and their Resource Coordinators, who are responsible for financial contracts, must be members of the CERN staff during their term in office and can be appointed or elected by the collaborations only after CERN has officially approved their nominations. Thus, the Technical and Resource Coordinators have dual reporting lines: to their collaborations and to CERN. The collaborations' elected Spokespersons must be nominated in consultation with CERN. They do not formally report to CERN, although they do work closely with CERN in practice.

The CERN model is rather natural for experiments sited at CERN given that CERN itself is an international organization governed by a multilateral treaty. Nevertheless, construction of accelerator facilities at CERN has historically been organized solely as CERN projects or, more recently for the LHC accelerator, as a host-led project with international partners.[r]

In both the host-led model and the CERN model, partners are responsible for providing certain deliverables to the collaboration, for instance, an agreed-upon piece of experimental apparatus. However, the two models typically differ in the degree to which partners share responsibility. In the host-led model, the host usually carries the largest responsibility, typically the majority of the project cost, and often serves as a backstop in case of financial difficulties. In the CERN model, the sharing of responsibility is usually more distributed, frequently with no partner carrying a majority share. Often in the CERN model, the sharing of responsibility for experiments' operation and upgrade is roughly in proportion to the number of participating scientists, which is referred to as the *fair-share model*. When there is a high degree of sharing of responsibility among partners, the CERN model of collaboration governance is capable of implementing the roots of strong collaborations (see Section 3.3) and the best practices of collaboration governance.

The *BaBar* experiment

FINDING

BaBar was a highly successful U.S.-hosted international partnership.

The *BaBar* experiment, which operated at SLAC's PEP-II *B*-factory until 2008, was initially host-led. However, it had a high degree of integration of its major international partners (Canada, France, Germany, Italy, and the U.K.). *BaBar*'s founders sought to establish an international collaboration according to the CERN model. They sought and embraced international collaborators and their funding agencies very early in *BaBar*'s inception. The full international collaboration was involved from the beginning in developing the conceptual design of the experiment and in establishing its governance structure. The governance structure of *BaBar* reflected its strong international partnership. The collaboration had a governance structure in which all partners were equal and collaboration leadership that was elected by the collaboration members. *BaBar* Project Management consisted of the Spokesperson, Deputy Spokesperson, Technical Coordinator, and Project Engineer. The Spokesperson, Deputy Spokesperson, and Technical Coordinator were elected by the Collaboration Council, consisting of representatives of collaborating institutions, and the Project Engineer was appointed. *BaBar*'s governance structure incorporated an IFC (International Finance Committee) composed of partner funding agencies which provided not only project oversight but also served as a forum for finding shared solutions to challenges arising during experiment construction, operations, and upgrades. *BaBar*'s IFC functioned similarly to the RRBs of the LHC experiments at CERN. The *BaBar* IFC was notable for its degree of engagement. The partners in *BaBar* also established and contributed to a *common fund*[s] which paid for some infrastructure-like items. All partners found *BaBar*'s shared governance and shared responsibility to be very successful, and the scientific success of *BaBar* is widely recognized.

Dark Energy Spectroscopic Instrument (DESI)

FINDING

DESI is a current example of a successful U.S.-hosted international partnership.

DESI is conducting a cosmic survey to measure the effect of dark energy on the expansion of the universe. It is a *Stage IV* (*i.e.*, 4th generation) dark energy experiment complementary to the upcoming LSST at the Rubin Observatory. DESI will collect optical spectra from tens of millions of galaxies spanning the universe—from nearby galaxies back in time to distant galaxies. It is being conducted at Kitt Peak National Observatory.

DESI, a mid-scale project, was constructed by a U.S.-hosted international partnership in response to a recommendation by the 2014 P5 report. U.S. collaborators coalesced from two prior surveys, DES (Dark Energy Survey) and BOSS (Baryon Oscillation Spectroscopic Survey), and from a space mission SNAP/JDEM (SuperNova Acceleration Probe/Joint Dark Energy Mission). International partners in construction engaged early, being recruited before the construction project was baselined. International deliverables to DESI construction were significant. Canada, France, Mexico, Spain, Switzerland, and the U.K. were among the partner nations that contributed most substantially to DESI construction. The split between DOE (the U.S. sponsoring agency) and non-federal funding sources was approximately 75%:25%. During construction, lead institutions in some nations produced impactful national efforts. International partners reliably delivered on their commitments which were documented in Cooperative Research and Development Agreements. Competition between technical options during construction was seen to improve solutions, and the decision-making process was designed to be transparent and based on sound input. A flexible non-federal pool of funding, (*i.e.*, a *common fund*) was important to the collaboration's ability to overcome some unexpected construction challenges. Together, the U.S. and international partners made DESI a notably successful construction project that was completed early and under budget. The time from P5's recommendation to DESI commissioning was a remarkably short five years, including the formation of the international collaboration.

Now in the operations phase, the DESI collaboration has grown to ~80 member institutions from the U.S. and 15 other nations[t] with a composition that is approximately 50% U.S. and 50% non-U.S. The collaboration is notably young and diverse, with ~250 graduate students. The instrument commissioning phase was found to be a very valuable period for the integration of new collaborators that were not involved in DESI construction. All collaborators are expected to contribute or to have contributed to DESI construction, commissioning, or operations. Instrument operations are funded by DOE while DESI science is supported by both DOE and NSF Astronomy, and international partner agencies. With regards to authorship of publications, DESI has adopted a model that can be seen as a bit of a hybrid between the traditional particle physics model and the model in astronomy. Collaboration members who meet a minimum level of activity are eligible to *opt-in* as coauthors on publications presenting major DESI results and are listed alphabetically. Papers with supporting results and technical papers have lead authors and author lists composed only of direct contributors. All phases of DESI have benefitted from governance principles and policies established early in the collaboration.

Proton Improvement Plan-II (PIP-II)

FINDING

The PIP-II accelerator project has established an effective governance structure for international partnership for accelerator facility construction.

The construction of the large international PIP-II accelerator project at Fermilab (see Section 3.3) is proceeding effectively. PIP-II is essential to the U.S.-hosted international neutrino program. The PIP-II Project is a host-led partnership. The U.S. is the majority partner, providing approximately 75% of the required financial resources, with five other nations[u] playing substantial roles. Its governance structure is held to be an important part of PIP-II's ongoing success. Noteworthy characteristics of its governance include the engagement of international stakeholders at all levels, specifically the engagement of heads of funding agencies, of laboratories, and of national projects as well as the integration of international scientists into the technical organization. Emphasis has also been placed on open and frequent communication in order to foster good coordination and technical integration among international partners. Shared technical objective, shared sense of responsibility, shared sense of success, and shared respect are also characteristics that have been highlighted.

Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment (LBNF/DUNE)

FINDING

LBNF/DUNE, the first U.S.-hosted international particle physics mega-project, has been launched successfully as a project with broad international participation. Nevertheless, its inception encountered new organizational challenges which offer instructive experience.

In response to the U.S. strategic plan defined in the 2014 P5 report, Fermilab and DOE initiated LBNF/DUNE. International partners were sought both for LBNF, a facility, and for DUNE, an experiment. The P5 report[7] called for the U.S. long-baseline neutrino program to be strongly international, specifically that it be:

reformulated under the auspices of a new international collaboration, as an internationally coordinated and internationally funded program, with Fermilab as host. There should be international participation in defining the program's scope and capabilities. The experiment should be designed, constructed, and operated by the international collaboration. The goal should be to achieve, and even exceed if physics eventually demands, the target requirements through the broadest possible international participation.

The LBNF/DUNE program was reformulated from its conceptual predecessor, the LBNE experiment. The reformulation has led to a more ambitious and international project and experiment, as laid out in the P5 report. However, the timescale for launching the new LBNF/DUNE program restricted the time to take advantage of the best practices that lead to successful joint ownership and shared partnership in international collaborations. Nonetheless, while LBNF/DUNE began with a somewhat rushed version of international partnership, it has evolved to follow the best practices of a U.S.-hosted multi-national endeavor. Overall, the $4B U.S.-hosted facility and experiment share in the total cost with about 80% U.S. support and 20% non-U.S. support, from many partner nations (among them: the U.K., France, Switzerland, Italy, Brazil, and CERN). The cost sharing of the DUNE experiment is roughly 50% U.S. and 50% non-U.S. CERN's participation represents the first time that it has contributed to facilities outside of Europe. It designed and is providing to LBNF the enormous novel cryostats that will house the liquid argon-filled time projection chambers in which neutrinos will interact and be measured. In addition, CERN constructed at CERN a major facility called the Neutrino Platform that has played an essential role in prototyping and testing DUNE detectors.

CERN's partnership on LBNF/DUNE, alongside U.S. partnership on CERN's LHC and HL-LHC, demonstrates a new level of international cooperation and collaboration between the U.S. and CERN particle physics programs.

The ~1,400-member DUNE collaboration comprises 47% U.S. and 53% non-U.S. collaborators with 39 partner nations, including CERN. The governance structure follows similar structures in place on the LHC experiments, including technical and scope oversight boards (the LBNC, Long-Baseline Neutrino Committee and the NSG, Neutrino Scope Group) and a RRB with member nations' funding agencies meeting regularly to oversee the experiment. Fermilab, as host lab, chairs these committees while the DOE chairs a similar committee overseeing the broader international neutrino program and facilities for partner nations (the INC). Fermilab has a DUNE Coordination Office to oversee and foster mission support activities vital for Fermilab's role as an international host. Overall, while there are lessons learned on international partnership from the formation of the LBNF/DUNE experiment, it is a successful and established model of international collaboration on a large scale.

As an international project hosted in the U.S., LBNF/DUNE is a big step beyond *BaBar*, DESI, and PIP-II, both in physical and financial scale and in degree of international participation. For instance, LBNF/DUNE is the largest construction project undertaken to date by DOE SC, and it engages 36 partner nations and CERN.

LBNF/DUNE's large scale and high degree of international participation and partnering have posed organizational challenges not previously encountered by U.S.-hosted experiments or construction projects. Based upon interviews of past and present LBNF/DUNE leaders, both U.S. and non-U.S., four major organizational challenges stand out: 1) the drive to start the scientific program as soon as possible, 2) the coupling of the facility LBNF and the experiment DUNE, 3) the integration of substantial non-U.S. deliverables within the DOE system of oversight, and 4) the integration of construction project management and collaboration governance. LBNF/DUNE's organizational challenges are seen to have influenced the degree of international partnership on DUNE.

Challenge 1: Drive to start the DUNE scientific program as soon as possible

The drive to start the DUNE scientific program as soon as possible led to the DUNE collaboration being assembled from the international community in a relatively short period of time. Despite the nearly decade-long U.S. investment in LBNE, the conceptual predecessor of DUNE, the pressure to launch provided limited time for collaboration building.

Time is required to engage international partners to maximally benefit from their expertise and resources and to jointly establish a collaboration governance structure (see Section 3.3). As noted earlier in this report, partners engaged early in the conceptual design phase are more easily integrated and develop a stronger sense of shared ownership. DUNE's international partners did not have adequate involvement in the collaboration formation or preparatory phase. Some non-U.S. collaborators commented that the manner in which the collaboration was assembled diminished their ability to contribute, and some U.S. leaders commented on the time for collaboration building being too short.

Challenge 2: Coupling of the facility LBNF and the experiment DUNE

LBNF/DUNE was established as a single DOE construction project. Project management of LBNF and DUNE as a single project is challenging because of the disparate scales and different degrees of international partnership on each. Moreover, treatment of LBNF/DUNE as a single DOE construction project made realizing DUNE as a full international partnership challenging.

Although LBNF and DUNE are physically coupled, their natures are substantially different. LBNF is a facility project with the U.S. as the dominant partner and with a relatively small number of international partners. DUNE is an experiment with a large number of international partners and a relatively equal balance of U.S. and non-U.S. participation. The U.S. share of LBNF's cost is much larger than the U.S. share of DUNE's cost. Much of the scope of the LBNF project is civil construction, whereas DUNE demands the construction of a complex of state-of-the-art particle detectors requiring the expertise of the international neutrino physics community. The host-led governance model appropriately fits LBNF. DUNE was conceived as an international partnership inspired by the CERN model.

While effective and efficient coordination between the LBNF facility and the DUNE experiment remains crucial for the success of the overall program, the hybridization of governance structures and the asymmetry in resource requirements and in international sharing between facility and experiment lead to significant tensions. Ideally, the governance and management of the facility and experiment need to be clearly separated, with a coordinating structure that ensures priorities are aligned with overarching science goals.[v]

Challenge 3: Integration of substantial non-U.S. deliverables within the DOE system of oversight

DOE project management protocols do not readily accommodate substantial deliverables from outside the U.S. project. Nevertheless, the international nature of LBNF and DUNE should not be viewed as a "risk" with respect to successful execution of the project.

The international nature of projects should be viewed as an opportunity to pursue a global science program at the frontiers of particle physics in a resource-limited environment, sharing technical and scientific expertise among collaborating partners.

Challenge 4: The integration of construction project management and collaboration governance

The organizational structures of construction project management and of international collaboration and governance need to be appropriately integrated and coordinated for coherence. For instance, appropriate integration and coordination are necessary to ensure that project decisions are made with proper consideration of 1) the scientific objectives of the international collaboration and 2) the impacts on international partners.

Appropriate integration in the case of LBNF/DUNE, and especially for DUNE, is sometimes seen as lacking, particularly by collaboration leaders and by international partners. Indeed, integration of construction project management and collaboration governance is sometimes seen as a challenge already for U.S.-only projects and for U.S.-led international projects. The problem is greater in striving to implement the CERN model in the DOE system.

Lack of appropriate integration and coordination of construction project management and collaboration governance in the case of LBNF/DUNE may arise in part because of application of existing DOE project management policies, which are best suited to the host-model of governance, to the construction of DUNE, which was conceived in the CERN model of governance. Moreover, in any international collaboration, integrating the project management and oversight practices of all partners is generally a challenge. Nevertheless, there is no fundamental reason why appropriate integration and coordination cannot be established. For instance, interviewees generally perceived that appropriate integration and coordination has been achieved in the CERN model as implemented for the major LHC experiments.

The challenge of appropriate integration of construction project management and international collaboration governance is of major importance, particularly regarding future U.S.-hosted experiments and facilities. For U.S.-hosted international partnerships, at least part of the challenge seems to arise from current DOE policy and practice.

Considering the growing importance of international partnership to the U.S. particle physics program and other U.S. science programs, an effort should be made to reconcile U.S. project management and oversight practices with mandatory U.S. policies, principles of international partnership, and policies of international partners. A well-informed study performed by experts from all relevant perspectives (*e.g.*, U.S. and international scientific community, laboratory management, U.S. and non-U.S. funding agencies, DOE and U.S. project oversight bodies) should be established in order to recommend project management and oversight procedures suitable for international and interagency partnerships. The possibility to streamline administrative processes concerning international agreements and export control could also be investigated.

RECOMMENDATION

DOE and NSF should convene a task force to study and recommend project management and oversight procedures that facilitate and cultivate international and interagency partnerships on large scientific research infrastructures for particle physics.

Cosmic surveys

FINDING

Partnerships between DOE High Energy Physics and NSF Astronomy have produced pathfinding advances and capabilities in the study of dark matter, dark energy, and inflation.

As telescopes have become capable of probing deeper into the universe, and therefore further back in time, the horizons of particle physics have expanded in directions of fundamental physics that overlap with those of astronomy and astrophysics. In its 2008 strategic plan for particle physics, P5 embraced the study of dark energy as a scientific priority of the field. In the subsequent 2014 strategic plan, P5 embraced the study of the cosmic microwave background and included this together with dark energy in the science driver "Understand cosmic acceleration: dark energy and inflation."

Common scientific interests have led to new partnerships between particle physics and astronomy, with support primarily from DOE HEP and NSF Division of Astronomical Sciences.[w] DOE is mission driven in its partnership in cosmic surveys with NSF, *i.e.*, DOE focuses on science related to dark energy, dark matter, and the cosmic microwave background. Nevertheless, a well-designed survey will lead to a broader and often unexpected set of discoveries. Notable examples of very successful past interagency partnerships are SDSS (Sloan Digital Sky Survey), BOSS, and DES. Current partnerships are the Vera C. Rubin Observatory, which is now in the commissioning phase, and the CMB-S4 project, which is now in a pre-approval concept phase. DESI is a very successful DOE project operating now. For these facilities, the particle physics community has brought its expertise in instrumentation, enabling fabrication of the sensitive telescope cameras needed for these cosmic surveys.[x] NSF Astronomy has brought its leading capabilities in telescope construction and operation. The result is telescopes that serve both particle physics and astronomy. The telescopes used for cosmic surveys are typically located in Chile or at the South Pole. With these projects, the U.S. hosts the world-leading ground-based program in cosmic surveys.[y] At present, U.S. particle physics does not partner on any cosmic surveys hosted abroad while it develops leading facilities in the U.S. and hosts international collaborators on these facilities.

The fields of particle physics and astronomy practice their science in different ways. In experimental particle physics, collaborating scientists generally build and operate the experiment and analyze the data, whereas in astronomy, many scientists who did not contribute to building the instrument, *e.g.*, the Hubble telescope or the Rubin Observatory, analyze data and publish scientific results. Consequently, the models of collaboration on the cosmic surveys on which particle physics and astrophysics partner generally differ from the models in other areas of experimental particle physics and traditional astronomy. Publication and authorship policies also generally differ. Scientists engaged in cosmic surveys agree that the most recent surveys are more structured than earlier surveys—with active Working Groups, Science Leads, and Spokespeople—and are taking on some of the characteristics of particle physics experiments.

Next-generation cosmic surveys: Rubin and CMB-S4

Rubin

The Vera C. Rubin Observatory, formerly known as the LSST (Large Synoptic Survey Telescope), is a facility jointly funded by DOE HEP and NSF Astronomy. The facility was constructed with NSF as the majority partner with funding from an MREFC award. DOE provided the LSST camera that instruments the Simonyi Survey Telescope, the heart of the Rubin Observatory. Rubin operations are funded 50-50 by DOE and NSF, although there are also substantial in-kind contributions from international partners. DOE's significant investment in the Rubin Observatory is motivated by the exploration of dark energy.

Eight science collaborations have formed around the Rubin Observatory. Each science collaboration is an independent worldwide community of scientists, self-organized into collaborations based on their research interests. Each adopts its own governance structure and publication policy.

DESC formed to study dark energy (and dark matter). It is one of the eight Rubin science collaborations. DESC is presently the only Rubin science collaboration supported by DOE HEP, whereas NSF Astronomy supports scientists who work in DESC as well as scientists working in the other science collaborations. DESC operations are 100% funded by DOE.

DESC has an organizational structure akin to the particle physics model. It is also quite an international collaboration, with >1,000 members from >20 nations. In order to earn Rubin *data rights*, *i.e.*, the right to access and analyze data from the Rubin Observatory, DESC collaborators must share in the operational activities of DESC and/or Rubin, although collaborators from the U.S., which built the telescope, and from Chile, where the telescope is situated, all have data rights *ab initio*. This policy contrasts with that of typical particle physics collaborations, which generally require ongoing sharing of operational activities for continued access to the data, even for collaborators from the nation(s) that constructed the facility. The authorship policy of DESC can be seen as a hybrid of the traditional particle physics policy, in which all scientists active in the experiment share authorship, and of the astronomy authorship model, in which only the scientists involved in a given data analysis share authorship of the associated paper. In DESC, the author list of a science publication consists of the collaborators who performed the data analysis plus other collaborators who opt in by identifying their specific contributions. All DESC collaborators must continue sharing DESC (and/or Rubin) operational activities to maintain membership in DESC.

As mentioned, DESC is very international in nature. However, LSST (now the Rubin Observatory) was principally a U.S. interagency construction project. Although international partners, such as French institutions funded by IN2P3 (French National Institute for Nuclear Physics and Particle Physics),[z] made some key contributions to the construction of the LSST camera, the international fraction of the overall investment in construction was about 10% of the camera and a much smaller fraction of the overall LSST construction cost. Some international partners on construction believe they could have contributed more value to LSST if engaged more fully in the project, and some felt they were not as involved in project decisions as they would have liked. International partners have also observed that support from their funding agencies would have been enhanced if they had been able to assume impactful project responsibilities and leadership roles. LSST benefitted from substantial private donations which enabled early prototyping and development of novel aspects of the telescope that reduced overall project risks.

Cosmic Microwave Background-Stage 4 (CMB-S4)

Construction of an ambitious fourth-generation cosmic microwave background experiment (CMB-S4) was recommended in the 2014 P5 strategic plan and the National Academies' 2020 decadal survey on astronomy and astrophysics.[20] This project has been developing as an NSF-DOE partnership. CMB-S4 is a large, complex project that will employ almost 500,000 state-of-the-art superconducting photon detectors. The project has the logistical challenges of 12 telescopes at two remote sites, the South Pole and the Chilean Atacama Desert. CMB-S4 will be a single, unique project because of its scale, whereas multiple U.S. Stage 2 and Stage 3 experiments existed. Establishing a Stage 4 collaboration among interested U.S. scientists was an early organizational challenge.

CMB-S4 consists of a CMB-S4 Project for constructing the experiment and a CMB-S4 Collaboration for performing the science. This arrangement has become usual in large DOE construction projects, although the degree of separation between project and collaboration varies. CMB-S4 governance provides for good coordination and communication between project and collaboration. Moreover, membership of the CMB-S4 Project and of the Collaboration are not entirely separate. Many collaboration members have important roles within the project and within its leadership. The CMB-S4 Collaboration is currently about one-third international scientists from 54 collaborating international institutions in 20 nations.

CMB-S4 is still in the relatively early stages of recruiting international partners on the project. It is presently engaged in discussions with groups from eight nations with significant membership in the science collaboration. Discussions and arriving at potential commitments are complicated by potential partners being tentative about committing to a project that has not yet received full approval in the U.S. This understandable situation creates a conundrum, because CMB-S4 has need of international financial and intellectual resources in order to achieve its full scientific capabilities. Engaging international partners was further complicated by differences in national and even regional funding models for cosmic microwave background projects. Another possible impediment, the initial complete conceptual design for CMB-S4, was made by a task force set up by NSF and DOE without any international participation. As stated in Section 3.3, engagement in a U.S.-hosted project is easiest early in the conceptual development of the project when partners can have the greatest impact. Agency engagement early in the collaboration building phase is also generally beneficial.

International partnership on future cosmic surveys

NSF-DOE partnerships on cosmic surveys have been a success. They have combined DOE leadership in instrumentation capabilities with NSF leadership in telescope construction and operation to build bold, powerful facilities that place the U.S. in the leadership role in ground-based cosmic surveys. However, these NSF-DOE surveys have been largely U.S. projects.

International partnership on the construction of DESI was significant, with about 25% of the cost being provided in non-federal funds. However, international partnership on construction of larger NSF-DOE cosmic surveys is relatively undeveloped in comparison to DESI or to large accelerator-based experiments. The fraction of human and financial investment in construction of Rubin from non-U.S. partners on the whole was not substantial and, as yet, CMB-S4 has not secured large international commitments for its construction. Yet, the motivations for international partnerships for construction of cosmic surveys mirror the motivations for other large projects of particle physics. For instance, increased international partnership would provide cosmic survey projects with access to increased intellectual and financial resources. International partnerships would additionally contribute to the vision of a global particle physics program that offers a full scope of the best scientific opportunities to the global scientific community. For these reasons, a greater degree of international partnership on future cosmic survey projects is desirable, whether a survey is hosted in the U.S. or abroad. Universal support was heard from those interviewed for increased international partnership as the scale of cosmic surveys grows. Potential international partners have also expressed their desire to be part of the early planning and design phase of the project as well as part of later stages. Although there are some impediments to international partnership at the intersection of particle physics and astrophysics, these impediments are not fundamental. The Large Area Telescope of the Fermi Gamma-ray Space Telescope was a successful partnership of NASA (National Aeronautics and Space Administration), DOE, and international partners from France, Germany, Italy, Japan, and Sweden launched in 2008. International partnership on future cosmic surveys, with substantial sharing of project responsibilities and leadership among qualified institutions and individuals, will lead to 1) more capable facilities and experiments and 2) a stronger global particle physics program. Future U.S.-hosted cosmic surveys should seek a greater degree of international partnership on facility design and construction, and the U.S. should seek to partner on international opportunities when forefront cosmic surveys are mounted abroad.

RECOMMENDATION

Future cosmic survey projects should engage with U.S. agencies to develop a plan for strong strategic international partnerships across all stages of the project lifecycle, including conceptual design and construction, in order to realize next-generation capabilities and scientific opportunities. Plans should include sharing of responsibilities and leadership opportunities with international partners.

Impediments to being the partner of choice

Some U.S. policies and procedures related to funding and oversight are identified by some international and/or U.S. leaders as being deterrents to potential international collaborators joining U.S.-led projects. Examples are the uncertainty of the U.S. appropriations process and the burden of rigorous U.S. project management and oversight processes. For instance, the efficiency and effectiveness of project execution in the U.S. is questioned by some potential international partners; there are perceptions that U.S. full cost accounting, risk aversion, conservative scheduling, and project management costs and practices make the U.S. less likely to execute large projects on a competitive schedule and at a competitive cost in comparison with other potential hosts (*e.g.*, China or Japan). To offset these perceptions, the U.S. could emphasize the high priority that it assigns to prompt project completion within the financial constraints of the overall program. In addition to perceptions regarding efficiency and effectiveness, two other issues identified are discussed below under the headings of *Being a reliable partner* and *Funding mechanism*.

Being a reliable partner

FINDING

Being a reliable partner is essential to international collaboration and especially to hosting international partnerships.

Unfortunately, the U.S. has not always been viewed as a reliable partner, and such perceptions can be an impediment to consideration of the U.S. as a partner of choice.

Some difficult decisions regarding the termination of DOE construction projects or facility operations, primarily decisions driven by funding constraints, have made some potential international collaborators wary. The termination of the construction of the SSC in 1993 is the most often cited example. More recent examples of the termination of DOE construction projects include the silicon tracker upgrade projects for the Tevatron experiments (2003) and the BTeV project, also called B Physics at the Tevatron (2005). Examples of termination of facility operations include the end of the SLAC *B*-factory program and the *BaBar* experiment (2008) and the end of Tevatron program and the CDF and D0 experiments (2011).

This subpanel finds that perceptions questioning the reliability of the U.S. as a partner generally arise from unilateral decisions taken by the U.S. that have been inadequately communicated between U.S. decision makers and international partners.

Once a project is funded and begins, mid-project cancellations without due cause should be avoided. It is important to have a proper mechanism to terminate projects if they turn out to be not viable or competitive. The decision process should be well communicated to all partners in the project.

RECOMMENDATION

Discuss and communicate with international partners before making decisions that affect partners. Seek ways to mitigate the impact of necessary U.S. decisions on international partners.

The U.S. record as a reliable partner on internationally hosted projects is generally excellent. Reliable funding is a prerequisite for maintaining this record (see Subsection below on *Funding mechanism*). The U.S.—both U.S. scientists and U.S. agencies—should maintain and strengthen roles as a reliable partner both for contributions to internationally hosted projects and in hosting U.S.-based international projects.

Funding mechanism

FINDING

The uncertainty of the annual U.S. appropriations process is an impediment to good international partnership, whether the partnership's project is hosted in the U.S. or abroad. Continuity of funding is especially important for U.S.-hosted experiments in both the construction and operations phases because of its importance to international partners.

U.S. funding for particle physics is subject to annual appropriations which has on some past occasions been very disruptive to the U.S. particle physics program. Abrupt decreases in funding level can negatively impact construction projects, facility operations, and research programs. For instance, cancellation of the construction of the SSC in 1993 was exceptionally jarring to the U.S. program and also negatively affected international partners. This event led to a questioning of the U.S. as a reliable partner. As another example, an abrupt change in DOE HEP funding in 2008 led to the abrupt termination of operation of the *B*-factory program at SLAC, disrupting a successful international partnership.

The uncertainties of annual funding are a challenge for program planning at DOE and NSF, because funding profiles are unpredictable for multi-year projects and experimental programs. Multi-year timescales, or even multi-decade, are the norm in particle physics. By contrast CERN has stable year-to-year funding which facilitates the establishment and planning of multi-year programs. It also enables CERN to arrange loans to finance (*i.e.*, forward fund) large construction projects. Although the funding mechanism differs from nation to nation, other nations provide construction projects with stable multi-year funding profiles.

DOE HEP and NSF place a valuable emphasis on maintaining annual funding allocations according to planned budget profiles for construction projects, however, the agencies' ability to sustain budget profiles can be limited by annual appropriations. Line-item construction projects are individually subjected to annual appropriation, and Congress frequently provides guidance on the annual funding of other construction projects. Delays in funding with respect to profile would likely lead to project delays and hence to higher cost to complete and sometimes to loss of competitiveness. Delays are also disruptive to partner nations delivering components as changes in the U.S. schedule have cascading effects; changes affect the overall project schedule and hence the schedules of partners' national construction projects. The difficulty of planning in the atmosphere of unpredictable budgets, even in the absence of abrupt reductions, tends to lead to inefficiencies in project execution which sometimes lead to loss of competitiveness. Therefore, it is good that the U.S. agencies emphasize maintaining annual funding allocations according to planned budget profiles in the annual President's Budget Request and in the detailed allocation of funding. Unfortunately, with this emphasis on maintaining construction projects on planned profiles, unexpected decreases in overall annual funding lead to decreases in facility operations and/or funds for scientific R&D.

Stable, predictable funding of U.S.-hosted projects is especially important to international partners—both scientists and their funding agencies—because partners are dependent upon the U.S. as the project host. Moreover, continuity of funding is important in order that potential partners see the U.S. as a reliable partner, are willing to partner on U.S.-hosted projects, and can plan their own contributions to these projects.

RECOMMENDATION

Stakeholders in the U.S. executive branch and in Congress should understand the negative consequences—both immediate and long term—of abrupt reductions in funding, including the negative impact on international partners.

The decline in funding over the last decades at universities for support of technical experts, such as engineers, compromises U.S. competitiveness and leadership by limiting the intellectual impact that university scientists can achieve on experiment design and construction. The lack of technical support, along with a lack of funding for R&D, also limits the ability of university scientists to provide training opportunities for the next generation of scientists.

Host laboratory environment

FINDING

A welcoming environment is critical for hosting an international experiment or facility.

Only by providing an environment that encourages and supports international collaboration will U.S.-hosted projects be attractive to international partners. The host laboratory has a special responsibility to provide a welcoming environment. All international (and U.S.) collaborators, faculty, research and technical staff, and students should be welcome to visit the host laboratory to work on their projects and to meet with collaborators.

A welcoming environment starts with providing assistance in planning visits to the host laboratory or to an off-site facility for both short- and long-term visits. Support for acquiring necessary visas is essential. The U.S. visa acquisition process is difficult and time-consuming, particularly for scientists of certain national origins. Visa acquisition is currently an impediment to international collaboration. Consequently, host lab support for this process is especially important.

An open and welcoming environment with a streamlined site access process is key to successful international collaboration. A welcoming environment needs unhindered access to the laboratory or facility, without exclusion of scientists from full participation in experiments based on place of birth. Based on interviews, there is concern that the changing overall security posture across the labs and the recent challenges in site access at Fermilab are having a negative impact on the field. Laboratories should work to lower barriers to collaboration by streamlining site access without compromising research security.

A welcoming environment also includes facilities for visiting collaborators, *e.g.*, offices, as well as onsite accommodation for short-term visits and spaces for visitors and lab staff to meet and discuss informally. Assistance with finding housing for long-term visits by international collaborators is highly desirable as is orientation on community resources. Access to computing resources is required. Resources like the LHC Physics Center, as well as active seminar programs and other events, contribute to a welcoming environment. Fellowship and associateship programs, accessible to collaborators independent of background and nationality, are desirable.

The principles of equity, diversity, and inclusion should govern the policies of both the host laboratory and the international collaboration. Respect for individuals from different cultural backgrounds is of particular importance to providing a welcoming environment. Finally, safety on the host laboratory or facility site is of highest priority.

RECOMMENDATION

U.S. laboratories hosting international experiments should provide an environment that encourages and supports international collaboration.

“The field of particle physics is a vibrant research ecosystem, built by an international network of partnering nations, facilities, experiments, and people.”


UP
STRANGE
ELECTRON
TAU

4

Technologies and Expertise

Science enabled by new tools, techniques, and national initiatives

What is the world made of? What holds the world together? How did the world begin? For millennia, humans have asked these questions. Invented tools include a wide range of particle detectors which are broadly referred to as instrumentation in this chapter. Associated experiments are carried out at advanced scientific facilities, such as particle accelerators, both at home and abroad.

Particle physics is inextricably linked to the advancement of the physical sciences as a whole. Particle physics theory and experimentation have long benefitted from the ideas and technical developments of other scientific disciplines. In turn, particle physics innovations have impacted other fields, often dramatically, with several notable examples in accelerators, detectors, and computing.

In accelerator science, there is a long history of particle physics-driven innovation which is a rich resource for the nation. Some specific innovations include conductors for superconducting magnets, the klystron,[aa] and light sources.[bb]

In detector development, particle physicists have developed custom devices for specific particle signals; techniques and associated technology have permeated and revolutionized other fields. For example, PET (Positron Emission Tomography) scans enable doctors to evaluate patient organs and tissues using radiotracers.

In large-scale advanced computing, groundbreaking progress is rapidly accelerating. The imperative of effective communication among globally dispersed particle physics collaborators provided the impetus for the creation of the World Wide Web at CERN (European Laboratory for Particle Physics Research) in 1990.

The national initiatives in AI/ML (artificial intelligence and machine learning), QIS (quantum information science), and microelectronics have driven new research avenues in particle physics. It is a symbiotic relationship with particle physics making contributions to these initiatives in return. For example, particle physics data and theory provide a testbed for AI/ML algorithms, a new quantum platform has been made possible by advanced accelerator science, and expertise in cryogenic electronics provides solutions to connectivity in quantum technologies including quantum computing.

This chapter examines the status of the U.S. particle physics community through the lens of these tools and capabilities and benchmarks findings relative to those of other nations. Key areas where the U.S. currently has—or could aspire to have—leadership roles in particle physics via its unique, and in some cases, world-leading capabilities are identified. In some areas, U.S. leadership has lapsed, and in all areas, there is intense international competition. To preserve and foster U.S. leadership roles, particular technical areas and capabilities that should be emphasized and strengthened are identified. Other technical resources and capabilities that could be leveraged through collaborations beyond the particle physics community, both with other disciplines and other funding agencies, are also identified.

4.1

Foundational pillars and unique capabilities: theory, instrumentation, accelerator development, and scientific computing

Strengthening critical capabilities

KEY FINDING

It is our state-of-the-art expertise in the tools, technology, and techniques of particle physics that makes the U.S. a sought-after partner and gives us the ability to impact future experiments at home and abroad.

KEY RECOMMENDATION

Continuously develop critical technologies to maintain and grow U.S. leadership in particle physics at home and abroad.

Theory, a foundational pillar of particle physics

The Snowmass 2021 report[8] emphasized the role and importance of theoretical particle physics with text quoted below, while the Theory Frontier Report[32] reviewed the status of U.S. theoretical particle physics in detail.

Theoretical particle physics seeks to provide a predictive mathematical description of matter, energy, space, and time that synthesizes our knowledge of the universe, analyzes and interprets existing experimental results, and motivates future experimental investigation. Theory connects particle physics to other areas of physics and extends the boundaries of our understanding. Together, fundamental, phenomenological, and computational theory form a vibrant interconnected ecosystem whose health is essential to all aspects of the U.S. high energy physics program.

The U.S. particle theory community has benefited tremendously over many decades from sustained government investment. This has resulted in a long history of seminal accomplishments and Nobel Prize-winning discoveries by particle theorists at U.S. institutions. Today, the U.S. particle physics theory community remains at the forefront of the full breadth of the field, from formal foundational questions to phenomenological and computational theory efforts in direct support of experiments.

FINDING

Theory is a foundational pillar of particle physics, and declining investment threatens U.S. leadership.

Theory-driven experimental efforts

U.S.-based theoretical particle physics research is noteworthy for its creativity and has taken a leading role in the expansion of particle theory, particularly through developing connections to other areas, including astrophysics, cosmology, QIS, AMO (atomic, molecular, and optical) physics, condensed matter physics, nuclear physics, and computer science. The theory community has remained responsive to experimental developments, adjusting directions to reflect experimental outcomes. One of its special strengths is innovation that often initiates new experimental programs. New experiments proposed, initiated, and/or driven by U.S. theorists in recent years include a range of small international projects hosted in the U.S. and overseas that search for new physical phenomena. These projects include FASER (ForwArd Search ExpeRiment), MAGIS-100 (Matter-wave Atomic Gradiometer Interferometric Sensor-100), CASPEr (Cosmic Axion Spin Precession Experiment), LDMX (Light Dark Matter Experiment), CODEX-b (COmpact Detector for EXotics at LHCb), GQuEST (Gravity from Quantum Entanglement of Space Time),[cc] and other small innovative experiments to search for light dark matter and dark sectors. Theory leads not only to new experiments but also new ways of looking at the data within existing experimental collaborations like ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid).

Formal, phenomenological, and computational theory

The U.S. theory community has played a leading role in driving recent advances in formal, phenomenological, and computational theory. Formal theory includes the discovery of new symmetries of nature, new connections between gravity and gauge theory, and new approaches to quantum gravity leveraging the tools of QIS. U.S.-led research in phenomenology has developed new paradigms for the electroweak hierarchy problem, broadened the search for dark matter over decades of energy, opened new windows into early universe cosmology, and profoundly expanded the LHC's (Large Hadron Collider's) sensitivity to subtle new physics with proposed synergistic detectors. In computational theory, the U.S. community has played a leading role in bringing lattice QCD (quantum chromodynamics) to bear as a tool for precision physics (including prominent contributions to the theoretical prediction of the muon particle's magnetic strength), spearheaded progress in the quantum simulation of quantum field theories, and unleashed the transformative potential of machine learning for neutrino physics, cosmology, collider phenomenology, lattice field theory, and other computations in particle physics.

Theory networks

Theory networks are an important way to strengthen the theory community by connecting researchers from different institutions. Networks can be national or international. For example, the existing U.S. Neutrino Theory Network supported by DOE (Department of Energy) aims to strengthen the U.S. neutrino theory community and its impact on the U.S. and international experimental neutrino programs. In Europe, international theory networks are successful in connecting researchers from different institutions and different countries by providing funding for workshops or conferences. Importantly, such networks also fund junior positions across borders (*i.e.*, young scientists from one country are hired into junior positions in another country), helping to grow international ties among researchers.

The creation of further topical U.S. theory networks would revitalize theory visitor programs that are an important component of healthy scientific discourse and allow the targeting of specific research areas relevant for the U.S. particle physics program. Networks also contribute to broadening the pipeline to attract and train a more diverse workforce. These U.S. theory networks should collaborate and coordinate activities with corresponding international theory networks. In addition, the European Union has funding opportunities to support networks. Researchers from outside the European Union can take part in this program if their country offers a corresponding program that would qualify for the required matching funds. Creating a common program between the European Union funding agencies and the DOE and NSF (National Science Foundation) could be a unique opportunity to join forces allowing the creation of funded international theory networks including the U.S. community as a major partner.

Declining funding in theory

Theoretical particle physics research in the U.S. has three principal sources of support: 1) from programs at two federal agencies, DOE HEP (DOE Office of High Energy Physics) and NSF Elementary Particle Physics, 2) from universities in the form of academic year salaries for faculty positions, non-governmental graduate student assistantships, and endowed fellowships as well as support from programs at university-based research centers, and 3) from small but growing private funding for targeted initiatives. Additionally, some in-kind funding comes through computational facilities and occasionally from NASA (National Aeronautics and Space Administration) for astrophysics and cosmology. NSF supports approximately one third of the university program but does not support the DOE national laboratories.

Federal agency funding for U.S. institutions, especially from DOE but also from NSF, has not kept pace with inflation in the past decade. DOE HEP has seen an 18% reduction in research funding from 2012 to 2022 in addition to the loss of purchasing power due to inflation estimated to be 26%.[33] This is true both at the national laboratories and at the universities but is felt even more strongly at universities. The flat funding in the NSF Elementary Particle Physics program equates to a 26% reduction accounting for inflation.

The field of particle physics is becoming increasingly competitive, and while funding for particle theory has declined in the U.S., the number of theoretical particle physicists in China has doubled in the past decade.[34] This relative disinvestment in DOE HEP theory in recent decades has weakened U.S. leadership in established programs and is eroding the country's competitive and innovative edge.

The 2014 P5 (Particle Physics Project Prioritization Panel) report[7] expanded the portfolio of experimental projects (and the breadth of the field), providing exciting opportunities for discovery. There is a need to invest in the research program —both the theory and the experimental programs that exploit projects—to take full advantage of these opportunities. For example, the U.S. DOE experimental HEP and NSF programs are currently making significant investments in the LHC and large U.S.-hosted projects, like LBNF/DUNE (Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment). Increased support and improved recognition for theoretical research in precision calculations related to the phenomenology of colliders and other experiments and the development of essential Monte Carlo simulation packages are required. Although much effort in the U.S. theory community has been recently devoted to neutrino physics including in neutrino nuclear interactions and neutrino generators (for projects like LBNF/DUNE), theoretical understanding must be increased to the level where it does not limit the precision of experimental measurements so that the precision of the measurements can improve the interpretation of the experimental results. Increased theory support will also be required for the interpretation and synthesis of our understanding from multiple new, large cosmological datasets, including those from the Vera Rubin DESI (Dark Energy Spectroscopic Instrument) and cosmic microwave background observatories.

Increased investment of U.S. federal funding is crucial for the present and future impact of U.S. theoretical particle physics research to staunch the decline in the size of the community, attract the best talent, and compete worldwide. Since theory research funds mainly support personnel, funding cuts reduce the ability to support people—most critically students and postdoctoral fellows. There are now fewer U.S.-trained particle theorists supported by theory base funding than in previous decades. A shrinking base overall has the effect of limiting the ability of U.S. physicists to lead in new areas of research.

Balancing U.S. federal investment in theoretical particle physics research to support a strong base program as well as new initiatives creates a robust portfolio poised for growth. New non-base, targeted initiatives invigorate the program but lack stability and continuity, putting the proper development of the field at risk.

Non-base private funding is limited and less broad in scope. At present, private funding is more prevalent in formal theory compared to phenomenology. Due to the decline in federal funding, an increasing fraction of postdoctoral scholars are funded by private foundations.[dd]

U.S. leadership in theory

Increase investment in theory, as it is critical for U.S. leadership in particle physics, as part of an increase in investment in the overall research program. A healthy ecosystem of experimental and theoretical particle physics is critical to advance the field.

RECOMMENDATION

Invest in a strong and innovative theory program.

Accelerator science and technology for particle physics

Originally developed for subatomic physics, accelerators now provide many other fields, such as materials science, chemistry, biology, and medicine, with indispensable tools for discovery. Accelerators are also deeply embedded in commercial operations and services used daily by society (*e.g.*, medical technology, airport security, wastewater treatment, curing manufactured products). AS&T (accelerator science and technology) is sufficiently rich, and its applications are sufficiently wide, that AS&T should be considered a field of its own. AS&T R&D (research and design) programs not only benefit U.S. fields of accelerator-based science by maintaining a competitive stance with respect to their international peers but also train, attract, and retain the best and brightest future AS&T workforce.

Both the DOE and the NSF support U.S. AS&T R&D. DOE HEP continues to steward AS&T R&D for the DOE SC (DOE Office of Science). DOE HEP supports medium- and long-term AS&T research that is aimed at enabling discovery science in particle physics, although its long-term R&D often benefits other applications as well.

DOE HEP support is principally through the GARD (General Accelerator R&D) program. GARD has five scientific thrusts: 1) Advanced Accelerator Concepts, 2) Accelerator and Beam Physics, 3) Particle Sources and Targets, 4) Radio Frequency Acceleration Technology (both normal conducting and superconducting radio frequency), and 5) Superconducting Magnets and Materials. The GARD program also supports AS&T workforce development through programs including USPAS (U.S. Particle Accelerator School), university-led traineeships, and other network activities. Both DOE NP (DOE Office of Nuclear Physics) and DOE BES (DOE Office of Basic Energy Sciences) support facility-oriented accelerator R&D. DOE HEP and DOE NP support university accelerator R&D through their Comparative Funding Review programs. Cornell University's Center for Bright Beams has been funded as an NSF Science & Technology Center. NSF is also funding high intensity proton source development at MIT (Massachusetts Institute of Technology) and the development of a CXFEL (Compact X-ray Free-Electron Laser) source for biological studies at Arizona State University.

The U.S. AS&T program is strong and is world leading in select areas, making the U.S. a natural partner of choice. However, overall accelerator R&D funding has shrunk, and the limited funding remaining is aimed primarily at research and facilities at DOE labs. At the same time, both Europe and China have been heavily investing in key AS&T areas. The supply chain for core accelerator technologies is also dominated by offshore sources. It is evident that U.S. large-scale projects have significantly benefited the establishment of certain key accelerator technology capabilities outside the U.S. However, support for U.S. R&D in AS&T and development of a robust supply chain at home is vital for the U.S. to be a partner of choice and for the future of U.S. competitiveness.

AS&T R&D areas making the U.S. a partner of choice

FINDING

Areas of AS&T (accelerator science and technology) in which the U.S. is identified as a leader and is sought as a partner in accelerator projects outside the U.S. include superconducting magnets, superconducting and normal radio frequency high brightness particle sources, and advanced beam physics, including modeling and techniques of high intensity and brightness beam physics.

Superconducting magnets, conductors, and materials

Significant advances in high-field superconducting magnets and conductor technologies are essential to future energy frontier accelerator concepts, such as the FCC-hh (Future Circular Collider of proton beams) and the International Muon Collider. These proposed accelerator concepts aim for the next level of high energy particle collisions that are sought by the scientific community beyond the capabilities of the LHC. The U.S. is a world-leading partner in the development of superconducting magnets and conductors for ongoing large-scale accelerator projects and programs, such as the HL-LHC (High-Luminosity LHC). Although the current international magnet R&D ecosystem has operated well, there are concerns about how to address emerging challenges and seize opportunities. In addition to technical challenges, existing tensions and geopolitical conflicts hamper international collaboration in some regions and impact the supply chain for superconducting materials. On the other hand, the magnetic technology requirements for a future muon collider present compelling technological synergies with both the fusion community and the NSF-supported National High Magnetic Field Laboratory. For example, advances in solenoid technology (coiled wire that produces a magnetic field when conducting an electric current) have applications in fusion and MRI

(Magnetic Resonance Imaging) diagnostics. Exploiting these synergies augments DOE HEP's magnet R&D program and amplifies the influence of discoveries and applications beyond the realm of particle physics.

Ongoing effort worldwide seeks to advance high-field magnet technology using novel materials with higher transition temperatures and a larger critical field, such as niobium-tin (Nb_3Sn) and HTS (high-temperature superconductor) materials. The U.S. has been a leader in both Nb_3Sn and HTS materials, but both China and Europe have been investing and plan to invest at comparable and/or higher levels of funding than the U.S. R&D portfolio in this field.

Radio frequency acceleration technology

The U.S. is a leader in both SRF (superconducting radio frequency) acceleration and normal conducting RF (radio frequency) acceleration.

SRF is a cornerstone technology for accelerators. To date, SRF R&D has benefitted from a high degree of global collaboration, with research conducted through collaborations like the TESLA Technology Collaboration, the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics, the International Linear Collider Global Design Effort (ILC GDE), and other collaborations through CERN and at labs and universities worldwide. U.S. national laboratories and universities are leading SRF R&D partners worldwide and have made significant contributions in advancing superconducting cavity surface treatments. For instance, the U.S. led the development of nitrogen doping processes for niobium SRF cavities; this major breakthrough in surface treatment has significantly improved the performance of CW XFEL (Continuous Wave X-ray Free-Electron Laser) facilities such as the LCLS-II/HE (Linac Coherent Light Source-II/High Energy) in the U.S. as well as SHINE (Shanghai High Repetition-Rate X-FEL and Extreme Light Facility) in China. This surface treatment is also used in the acceleration technology of the PIP-II (Proton Improvement Plan-II) accelerator under construction at Fermilab. SRF will also play a critical role in future electron-positron colliders, such as the FCC-ee (Future Circular Collider for electron-positron collisions) at CERN, CEPC (Circular Electron Positron Collider) in China, and ILC.

The global SRF community also develops ancillary systems that augment high-gradient, high-efficiency performance and confer greater cost effectiveness. The recent European Strategy for Particle Physics Update identified several R&D focal areas for cavities and laid out a five-year nominal investment strategy to position European research institutions and industry as the leaders in these SRF areas. If the proposed European spending plan is realized, it is critical for the U.S. to maintain and increase its current funding level to keep its lead in basic SRF R&D.

The GARD RF technology R&D program has also made impressive progress in normal conducting RF acceleration. A recent successful demonstration pushed a normal conducting RF structure at cryogenic liquid nitrogen temperature beyond a 150-MV/m (megavolts per meter) acceleration field strength (acceleration gradient). This technological advance opens a new frontier in the development of very high brightness electron sources. Such sources would substantially benefit the DOE mission in XFELs and future collider technologies. These significant results have led to the SLAC-initiated proposal of C3 (Cool Copper Collider), a compact linear collider. Future steps are needed to demonstrate, advance, and industrialize this technology. Once mature, this technology offers a pathway to cost-effective compact linear accelerators not only to fulfill DOE HEP's mission but also to support medical and industrial applications.

In Europe, acceleration gradients at the level of or more than 100 MV/m have been achieved in CLIC-type (Compact Linear Collider-type) X-band accelerating sections. The current European Strategy proposed multi-year investment in R&D efforts to overcome the challenges needed to translate these impressive results into practical applications.

Accelerator and beam physics

The GARD ABP (Accelerator and Beam Physics) program is one of the primary sources of support for U.S. accelerator researchers at DOE national laboratories and universities. ABP research addresses the fundamental properties of beam dynamics, particle generation and beam diagnostics, manipulation, and control. Program results have illuminated understanding of high brightness beam dynamics and high intensity beam dynamics as well as advanced beam-based modeling and manipulation and AI/ML-assisted beam diagnostics and optimization. Recently, the Fermilab IOTA (Integrable Optics Test Accelerator) Facility successfully demonstrated optical stochastic cooling. Beyond addressing DOE HEP mission needs, ABP achievements are leveraged by other fields such as XFEL science and ongoing and future projects like the EIC (Electron-Ion Collider) at Brookhaven National Laboratory.

RECOMMENDATION

In the AS&T areas in which the U.S. is identified as a leader and a partner of choice, R&D investment should keep pace with the increasing performance demands, technological challenges, and investments in other regions.

AS&T R&D areas in which U.S. leadership is challenged or overshadowed

FINDING

Funding for AS&T R&D in Europe is growing. Key areas of AS&T in which the U.S. was formerly a leader and in which the U.S. is now falling behind or in which U.S. leadership is now being seriously challenged include 1) collider beam physics, technology, and operation, 2) plasma wakefield acceleration R&D, and 3) fabrication of accelerator components and systems.

The U.S. has the potential to be a major partner in future accelerator facilities for particle physics. Robust support is needed to engage U.S. universities and national laboratories in the early stages of concept exploration and design studies. The following subsections describe the areas that the U.S. founded and/or has the potential to lead and in which U.S. leadership is challenged or at risk of being overshadowed.

Collider beam physics, technology, and operation

Both the 2020 European Strategy update and the 2021 U.S. Snowmass process identified a Higgs factory, based on a next-generation electron-positron collider, as a top priority for the research at the energy frontier. AS&T R&D to develop the enabling technologies needed for future multi-TeV colliders (hadron and muon) operating at unprecedented energies and luminosities were also high priorities of both studies.

Despite shared priorities, the AS&T R&D locus for the energy frontier, including for a muon collider, has shifted from the U.S. to Europe over the past decade. In the absence of an operational particle physics collider on U.S. soil and definite plans to host a future collider, members of the U.S. AS&T community have shifted their attention from collider physics, technology, and operations to other areas, such as proton drivers, fixed-target facilities, and light sources. Many of these experts are in mid- to senior career stages. Without robust support for R&D for future colliders, capturing and retaining knowledge from these U.S. experts will be a challenge.

The participation of U.S. researchers in AS&T R&D for future collider projects hosted abroad—for instance, the FCC at CERN, the CEPC in China, and feasibility studies of a multi-TeV muon collider—has been on an individual basis. This model for participating in future collider R&D does not enable U.S. national laboratories and universities to partner productively. Furthermore, this model does not provide an effective path for transferring to the next generation of the U.S. AS&T workforce the tremendous U.S. knowledge base for beyond-the-state-of-art accelerator design, system integration, and implementation. Establishment of a collaborative and coordinated

U.S. national accelerator R&D program on future colliders would pave the way to R&D partnerships while also creating valuable training opportunities for the future AS&T workforce. Such a program would enable early U.S. engagement in development of next-generation colliders in other regions as well as knowledge transfer to the next-generation workforce. Laying this groundwork will also help position the U.S. to host a future international energy frontier collider project.

RECOMMENDATION

Establish a collaborative U.S. national accelerator R&D program on future colliders to coordinate the participation of U.S. accelerator scientists and engineers in global energy frontier collider design studies as well as maturation of technology.

Laser-driven and beam-driven plasma wakefield acceleration

U.S. scientists pioneered the field of plasma wakefield acceleration, both LPA (laser-driven plasma wakefield acceleration) and beam-driven PWFA (Plasma WakeField Acceleration). Two major U.S. facilities, BELLA (Berkeley Lab Laser Accelerator) at LBNL (Lawrence Berkely National Laboratory) for LPA and FACET (Facility for Advanced Accelerator Experimental Tests) and FACET-II at SLAC National Accelerator Laboratory for PWFA, have been world leading. After successfully demonstrating a proof-of-principle multi-GeV/m (gigaelectronvolts per meter) acceleration gradient in 2006 for LPA and 2014 for PWFA, the U.S. LPA and PWFA program has focused on increasing acceleration gradients and improving beam quality. BELLA was first to demonstrate staging or injecting a beam from one stage of acceleration into a second stage for further acceleration. FACET-II was commissioned in 2022 and has commenced operation as a user facility. One of only four beam-driven PWFA facilities in the world, FACET-II generates an ultra-high peak electron drive beam current of 10+ GeV, a unique capability for demonstrating high-quality positron acceleration.

Institutes in Europe and Asia, however, have made substantial investments in LPA and PWFA over the past decade or so, resulting in impressive progress. Recent accomplishments include a proof-of-principle application of LPA-driven and PWFA-driven FEL (free-electron laser) and demonstrated plasma stability. Europe has been developing a plan to establish a dedicated accelerator research infrastructure based on plasma acceleration concepts, both LPA and PWFA, and laser technology. This ambitious project, known as EuPRAXIA (European Plasma Research Accelerator with Excellence in Applications), is included in the 2021 European Strategy Forum on Research Infrastructures Roadmap.[35] Compared to the envisioned capabilities that EuPRAXIA will offer, the laser technology and infrastructure at the U.S. BELLA and FACET-II facilities will require substantial upgrades and modernization to remain at the forefront of LPA and PWFA.

RECOMMENDATION

Develop a strategic plan to maintain leadership in plasma wakefield acceleration as needs for R&D facilities evolve and research programs abroad grow.

Domestic accelerator components and systems manufacturing supply chain

FINDING

The manufacturing supply chain for key accelerator components and systems is dominated by foreign companies.

DOE SC now purchases slightly more than half of all key accelerator components from foreign sources.[36] Among these expenditures, purchases in select technological areas are predominately from foreign vendors. For example, 100% of optics components, 70% of SRF cavity manufacturing, 67% of advanced ultrafast laser systems, 66% of high-vacuum/ultra-high vacuum components, and 51% of high-power RF systems are purchased from vendors abroad. In addition, 50% of superconducting cable and wire for superconducting magnets is obtained from foreign vendors. Given the importance of accelerators to applications such as commerce and medicine, as well as discovery science, the U.S. needs a more robust supply chain for accelerator components.

DOE SC established a new program office, ARDAP (Accelerator R&D And Production) in 2020, to strengthen the U.S.'s domestic manufacturing supply chain for accelerator components and systems. Even with progress from ARDAP, the U.S.'s industrial-scale manufacturing capabilities for SRF LINAC (linear accelerator) cavities and cryomodules has been overtaken by Europe and Asia. Fermilab and Thomas Jefferson National Accelerator Facility successfully produced the required cryomodules for the SLAC LCLS-II. However, future U.S. partnerships for the implementation of SRF-based facilities including the ILC, or even the U.S.'s suitability to host the ILC or other international facilities, may be challenged by lack of domestic supply. The loss of future large-scale projects from the U.S. would result in the further migration of expertise to hosting countries. Finally, the U.S.'s continuing dependence on non-U.S. suppliers for accelerator components and systems also puts U.S. accelerator-related companies at a disadvantage in bringing their R&D to the required maturity for being competitive.

RECOMMENDATION

Increase the investments in supply chain development for accelerator components and systems in the challenge areas identified by the DOE Office of Accelerator R&D and Production.

In summary, renewed investment is needed to revitalize DOE HEP AS&T R&D in order to 1) sustain U.S. leadership in key R&D areas, 2) develop new accelerator technologies, 3) construct domestic R&D facilities, 4) be a leading contributor to international particle physics accelerator facilities and to U.S. accelerator facilities for basic science, 5) be prepared to lead design and construction of future U.S.-hosted particle physics accelerator facilities, and 5) train the next-generation AS&T workforce.

RECOMMENDATION

Renew investments to revitalize DOE HEP AS&T R&D.

Invest in instrumentation development to enable the discovery science of the future

The mysteries of our world, from the fundamental building blocks of matter to the largest structures in the universe, are understood through measurement. From the first measurements undertaken in particle physics, instrumentation has been essential to discovery. Investment in instrumentation, from new ideas and through development to deployment, pays dividends for the field's discovery science and drives applications beyond the field. For example, instrumentation R&D in particle physics has led to beneficial innovations like the World Wide Web, PET scanners, and the superconducting magnets used in MRI machines. Future work in instrumentation will lead to the creation of new technologies that continue the tradition of improving the human condition and will capture the imagination of citizens and act as a magnet to attract the next generation of scientists and engineers.

The experiments outlined in the 2014 P5 plan have been enabled by innovative instrumentation with discoveries pushing the frontiers of science into new territory. To explore this new territory, U.S. particle physics will embark on planning the next generation of experiments under the guidance of the new 2023 P5. Realizing these next-generation experiments, which span all the frontiers of particle physics, will require giant leaps in capabilities beyond the instrumentation of today and across a broad range of technologies. Accordingly, the release of the 2023 P5 report will be a pivotal moment to invest in the accelerated development of cost-effective instrumentation with greatly improved sensitivity and performance. Making measurable the previously unmeasurable will empower a tool-driven revolution to open the door to future discoveries in all the frontiers of particle physics. Historic scientific opportunities await the field through the execution of an instrumentation research program to advance the 2023 P5 plan.

FINDING

U.S. scientists and institutions will be partners of choice and will have the greatest impact in future international experiments hosted at home and abroad if they maintain state-of-the-art expertise in instrumentation.

Developing new instrumentation for particle physics frequently takes decades, even when building on previous generations of instrumentation. Experimental requirements push the state of the art as well as the reliability and longevity of instrumentation as detectors often operate in hostile and inaccessible environments once data-taking commences.

Operating at the vanguard of instrumentation research strategically poises U.S. scientists to be in-demand international partners who can help shape the trajectory of collaborative science. For example, when the ATLAS and CMS detectors were being constructed at CERN's LHC beginning in 1993, the U.S. was sought as a partner because of the leading expertise of U.S. scientists and the capabilities of U.S. institutions. The U.S. assumed responsibility for the delivery of major portions of the detectors. The U.S. was positioned to strongly impact the design and construction of the ATLAS and CMS detectors and to define their key science program, because U.S. scientists had gained nearly a decade of instrumentation R&D and design experience from work on the SSC (Superconducting Super Collider) program. SSC detector R&D provided a fertile ground for developing new experimental techniques and building invaluable knowledge. Many developments for the SSC were incorporated into the LHC detectors.

Instrumentation research comes in several varieties: 1) Project-driven research (also known as directed research) occurs after a project has been formed and funded. This research is primarily intended to address the instrumentation needs of the project and is usually sufficient to deliver the project. The funding and the personnel supported for project-driven research are linked to the duration of the project. 2) Proof-of-principle research normally receives short-term funding to demonstrate the viability of a concept. Modest funding originates from some national programs. 3) Blue sky research is entirely exploratory. Funding for this type of research is very limited in the U.S. and abroad. 4) Strategic research requires long-term funding to build on proof-of-principle funding to develop a given principle to the point where it could be usefully incorporated in a future experiment.

DOE HEP funds most instrumentation research through the KA-25 funding line which supports detector facilities, beam test and irradiation facilities, and R&D at the national laboratories as well a small fraction at the universities. There are dedicated funds from the DOE for awards in SBIR (Small Business Innovation Research) collaborations with small businesses to develop a specific product that serves a need in the DOE HEP program. In addition, R&D funds to universities are available from the NSF. The DOE also annually selects outstanding young scientists for Early Career Awards (30 awards have been issued between 2010 and 2022), and some of these are awarded specifically for detector R&D efforts. These awards can be quite substantial. Furthermore, national laboratory employees have access to the LDRD (Laboratory Directed Research and Development) program, which funds promising ideas that support the lab's mission, sometimes for extended periods.

Europe funds proof-of-principle and blue sky research through national programs which in some countries, *e.g.*, Italy, are substantial. However, up until now, strategic research has received less recognition and is not specifically funded by the national programs in most countries with the exception of areas of research where an international R&D collaboration exists.

Benchmarking U.S. instrumentation: declining support

The U.S. has a long tradition of innovation in instrumentation and has a strong R&D community, which is coordinated by CPAD, the Coordinating Panel for Advanced Detectors of the American Physical Society's Division of Particles and Fields which was created in 2012. Two major recent reviews of particle physics instrumentation include 1) The *DOE Basic Research Needs for High Energy Physics Detector Research & Development Report* (2020),[9] which identified an instrumentation plan in anticipation of the 2023 P5 vision and 2) *The 2021 ECFA Detector Research and Development Roadmap*,[37] which identified a plan to realize the European Strategy for Particle Physics. ECFA is the European Committee for Future Accelerators.

The Basic Research Needs report found that the U.S. has continued to have a very strong track record in carrying out large-scale detector projects for the world's most important particle physics experiments at colliders as well as for neutrino physics, astroparticle physics, and cosmology. The U.S. community recognizes that the detector facilities, especially but not exclusively at the national laboratories, such as Fermilab's SiDet (Silicon Detector Facility), are a critical resource to the U.S. and international communities.

However, the Basic Research Needs report noted that U.S. funding for instrumentation research has been declining for an extended period at both the national laboratories and universities, especially the latter where today only a small minority of university groups still have the capability to undertake instrumentation research.[ee] Over the last decade the DOE HEP funding line for instrumentation, KA-25, resided at an average level of 80% of its 2014 fiscal year value for eight years before returning to its 2014 level in 2023. When inflation is accounted for, this level is close to a 50% reduction in the value of the funding over the decade. The restoration in funding to the FY2014 level has come about in part from the new national initiative in microelectronics. In contrast, Europe is renewing and expanding an ambitious, collaborative, coordinated program of detector R&D under the auspices of ECFA, as recommended by the ECFA detector roadmap. In China, the number of particle physics instrumentation specialists has doubled in the past ten years.[34]

The decline in U.S. funding significantly reduces the impact of the U.S. community in instrumentation development, which is crucial for the future of the field and for U.S. leadership in small projects and especially large projects such as a Higgs factory, muon collider, and future neutrino and cosmic frontier experiments. It was such expertise that led to leadership roles in ATLAS and CMS. Reduced funds also undermine the workforce talent development pipeline by removing opportunities for students at both undergraduate and graduate levels to participate in instrumentation R&D at their institutions which is often the first step to a career in instrumentation. Finally, and just as importantly, this decline in funding extinguishes the associated innovation that improves the nation's health, wealth, and security and inspires the public and draws young people to science.

Long-term strategic R&D

Long-term R&D is often eliminated in challenging budget environments yet is critical for large international particle physics endeavors that take decades to conceive, build, and run. Examples where strategic R&D is needed include fast-timing and high-precision space point determination for future high energy frontier experiments. This strategic research is, by its nature, longer term. Strategic research has come into particular prominence within the U.S. and international community, where there is both need and opportunity for dramatic instrumentation innovation and refinement during the potentially long period after the HL-LHC upgrade work is complete and before a new energy frontier project or projects have been approved and funded. A widespread concern in the community is to maintain the technical and scientific workforce of detector experts, most of whom are currently involved in the LHC upgrades, after the LHC upgrades are complete.

Instrumentation collaborations

International instrumentation research in certain areas of instrumentation including blue sky and proof-of-principle, but especially strategic research, is coordinated via international collaborations, because collaboration and coordination are needed to realize the transformative technologies required. Collaboration furnishes ideas, expertise, and resources from multiple scientists at multiple universities and national laboratories. Only by aligning efforts is it possible to realize technological challenges. Coordinating efforts allows leveraging of constrained resources. Particle physics exists in a resource-limited funding environment; it is mandatory that R&D efforts are coherent, minimize duplication, and build on progress happening at home and internationally, both in other technologies and in other fields.

Examples of international R&D collaborations include the very successful CERN-based international R&D collaborations for solid state semi-conductor detectors (RD50), gas-based detectors (RD51), microelectronics (RD53), and the CALICE (Calorimeter for Linear Collider Experiment) collaboration. The national communities that compose the RD collaborations seek funding for the components of the overall coordinated RD research program they are responsible for via their national funding agencies. The RD collaborations were initially created to address the formidable R&D strategic research challenges presented by the LHC experiments. U.S. particle physicists are prominent members of these RD collaborations. The agreements governing the CERN-based RDs cease at the end of 2023. The DOE Basic Research Needs report on instrumentation[9] recognized the international RD collaborations as good models for instrumentation research.

To strengthen U.S. instrumentation research for blue sky, proof-of-principle, and strategic research, R&D mechanisms have been explored by the U.S. community over the past year and coordinated by CPAD. In July 2023, CPAD and DOE jointly established 11 U.S.-based RDCs (R&D Collaborations) of multiple institutions around common R&D technology projects or goals guided by the priority research directions laid out in the DOE's Basic Research Needs report for each technology. The RDCs will help harness the distributed expertise that exists at U.S. universities to complement and augment expertise at the U.S. labs, though some RDCs may operate solely through the universities. For many years, this level of coordination and division of labor has taken place for project deliverable development (*i.e.*, directed R&D) but not for other types of instrumentation research. There is a sentiment in the community that this concept would be even better if it could be sustained in the form of a center for development for each RDC's instrumentation technology of focus. For example, SiDet at Fermilab focuses on silicon and other solid state detection technologies. The Microsystems lab at LBNL is another prominent example. Close ties with the nascent ECFA DRD (Detector R&D) collaborations in Europe, as described below, will be developed.

The long-term goal of the DOE/CPAD RDCs[38] is to:

- Provide a collaboration which can link together facilities, expertise, people, and experience to tackle technology challenges across DOE HEP and DOE NP;
- Facilitate new funding mechanisms for R&D related to a specific technology area which will take place as part of the collaborations' activities; and
- Work with the CPAD executive committee, ECFA DRDs, and the broader R&D community to foster a collaborative, supportive, and

coordinated environment for new ideas, blue sky efforts, and non-project specific R&D (*i.e.*, strategic R&D).

The DOE/CPAD RDCs will not:

- Discourage single or small team efforts in R&D. There remains a need for individual principal investigators to work in their labs on their ideas and to leave room for innovation and unexpected solutions;
- Break up existing collaborations and structures. There are communities within DOE HEP and DOE NP which coordinate on specific technological challenges (*e.g.*, HEPIC, see Section 4.2), and their intention is to utilize/leverage these efforts and communities to help make the CPAD RDCs successful; and
- Discourage project-specific R&D, *i.e.*, directed R&D. There is instrumentation R&D which will/has reach(ed) a level of maturity for which it is time to be realized for a specific implementation. RDCs will encourage the transition from generic to project-specific directed R&D.

The ECFA detector roadmap also recognized the RD collaborations as good models for instrumentation research and recommended the concept be generalized to all relevant technologies in particle physics. Thus, select new RDs, termed DRD collaborations, will be created, while those that already exist will be refounded and broadened commencing at the start of 2024 after the existing RDs end. ECFA presented this recommendation to the CERN Scientific Policy Committee and CERN Council who approved the recommendation in September 2022, including a plan for implementation. In response to the ECFA plan, the community primarily within Europe but also beyond, including the U.S., produced proposals for five technology areas (gaseous detectors, liquid detectors, solid state detectors, particle identification and photon detection, and calorimetry) in August 2023. Two additional proposals, one on quantum sensors and emerging technologies and one on the transversal activities on electronics, are expected to be submitted by the end of 2023. All DRDs will be hosted at CERN as CERN Collaborations with CERN-signed memorandums of understanding. However, CERN itself will not be involved in all of the DRDs. The possibility exists for a laboratory or university other than CERN (in Europe or outside Europe, for example, a U.S. national lab or university) to take the leading role and/or provide the leadership of a DRD and host selected DRD activities. This would be welcomed by ECFA.

The Snowmass Instrumentation Frontier[39] made five recommendations, quoted below:

1. *Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.*
2. *Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation at laboratories and universities.*
3. *Double the U.S. Detector R&D budget over the next five years and modify existing funding models to enable R&D consortia along critical key technologies for the planned long-term science projects, sustaining the support for such collaborations for the needed duration and scale.*
4. *Expand and sustain support for blue sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D independently from other research reviews.*
5. *Develop and maintain critical facilities, centers, and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines, and industry.*

These recommendations are important for U.S.

leadership in instrumentation and should be considered by P5.

Regaining U.S. leadership in instrumentation

The U.S. needs to maintain an active, continuous program of instrumentation R&D—avoiding lapses between projects and supporting blue sky, proof-of-principle, and medium-term and long-term strategic R&D—in order that U.S. scientists can strongly impact their future international collaborations, play leadership roles, and attract the best talent to their research activities.

This can be achieved by increased and steady investment, building a diverse instrumentation workforce, and supporting a structure of U.S.-based multi-institutional (university and lab) RDCs around priority research directions (as defined by the DOE Basic Research Needs instrumentation report) for each particle physics technology. DOE and CPAD have recently created this structure which will help harness the distributed expertise that exists at U.S. universities and the national laboratories.

Finally, the U.S. particle physics community has played a prominent role in several of the very successful CERN RDs. The U.S. should build on this by participating in the ECFA DRDs and engage with the broader instrumentation R&D community within and beyond particle physics at home and abroad to foster a global collaborative, supportive, and coordinated environment for new ideas, blue sky research, proof-of-principle and non-project specific R&D (*i.e.*, strategic R&D).

RECOMMENDATION

DOE HEP and NSF Physics should support an active, continuous program of instrumentation R&D and facilitate the development of instrumentation R&D collaborations at home and abroad.

Software and computing, essential capabilities for particle physics

As summarized in the Snowmass 2021 report,[8] "S&C (software and computing) are essential to all particle physics experiments, accelerator and detector design, and many theoretical studies. They are a key enabler of all the other frontiers and all science drivers requiring physics research along with expertise in computer science to address the complex and unique challenges of the field."

The escalating demand for computing resources is a result of the need for more sensitive and more precise experiments, using higher intensity beams and higher luminosity colliders, to collect more astrophysical data over wider and deeper fields with more powerful telescopes and to do more precise theoretical calculations.

The Snowmass report continues, "Experiments may last for many decades. The experimental hardware, driven by the commercial sector, may be upgraded every half-decade or even more frequently. Similarly, the software for the detectors and facilities evolves continuously to respond to operational issues. Larger software changes accompany major detector upgrades and must also adapt on shorter time scales to utilize and exploit the latest computing hardware and S&C infrastructure changes."[8]

In addition, new techniques such as ML, are evolving quickly, and there is a continued demand for algorithm R&D. For example, the need for new ML resources continues to increase at a rate faster than the turnover of the technology.

FINDING

The U.S. is globally recognized as a leader in software and computing for the field of particle physics.

S&C are essential to all modern particle physics experiments and many theoretical studies. The size and complexity of S&C initiatives are now commensurate with that of experimental instruments, playing a critical role in experimental design, data acquisition, and instrumental control, reconstruction, and analysis. S&C often play a leading role in driving the precision of theoretical calculations and simulations, *e.g.*, for lattice QCD. Over the last decade, every experimental result and many theoretical insights were possible, in part due to advances in S&C. Furthermore, the deep learning revolution that started in the last decade is having a wide impact on all aspects of particle physics.

S&C research centers, collaborations, and funding mechanisms

A number of successful cross-cutting S&C research centers and institutes have emerged to enhance the field of particle physics. Such multi-institutional collaborations have the potential to leverage both the multidisciplinary strengths of the universities and the particle physics-specific depth of the expertise at the national laboratories.

Significant progress has been made in adapting software applications for the effective use of hardware accelerators and in preparation for future exascale computing resources. Federal programs in this area include the DOE ECP (Exascale Computing Project), DOE SciDAC (Scientific Discovery through Advanced Computing), DOE CCE (Center for Computational Excellence), Computational HEP more generally, and the NSF IRIS-HEP (Institute for Research and Innovation in Software for HEP).

S&C investment and leadership on the LHC

U.S. investment in S&C has produced high yields. For example, the U.S. has had an outsized impact on S&C for LHC experiments at CERN. S&C were an enabling technology from the earliest days of the data-intensive LHC experiments; S&C continue to be crucial as LHC luminosity has increased and will become even more critical in the High-Luminosity LHC era. The experience gained at the LHC benefits developments of S&C for U.S.-hosted neutrino and cosmic frontier experiments, and this experience has benefitted other sciences as fields become increasingly data intensive.

The U.S. was the strongest original contributor to LHC S&C. In the early 2000s, the U.S. invested in approximately 10 software professionals for both ATLAS and CMS. These individuals were instrumental in facilitating the transition to a modern programming language and establishing the first distributed computing infrastructure and services. The U.S. was a leader in the design and simulation of the MONARC (Models of Networked Analysis at Regional Centers) computing models,[ff] which became the basis for distributed computing by all the LHC experiments. The U.S. grid projects, especially the U.S.-supported Globus project, are the foundation that the current distributed computing systems rely on, and the infrastructure is used by a diverse group of life and physical science projects. The U.S. contributions to the redesign of the CMS software framework in 2005 not only prepared the experiment for the LHC run but also became the basis of the *art* event processing framework[gg] used by many smaller collaborations as well as DUNE for LarSoft (Liquid Argon Software).[hh] The U.S. ATLAS program also developed the PanDA (Production and Distributed Analysis) system that was used globally in ATLAS and was adopted by the AMS (Alpha Magnetic Spectrometer) detector.[ii]

More recently, U.S. S&C support has facilitated the transition to multi-core processing in CMS. The infrastructure built for data federation[jj] began at SLAC with *BaBar* and was expanded for extensive use by CMS and the LHC nuclear physics experiment known as ALICE (A Large Ion Collider Experiment), enabling distributed data access by other science communities. The U.S. continues to lead in a variety of data access and management activities through the IRIS-HEP[kk] program. U.S.-supported developers have been drivers in the exploration of ML solutions and the design of software to run on heterogeneous hardware architectures like GPUs[ll] (graphics processing units) and FPGAs[mm] (field-programmable gate arrays). In 2017, developers at Fermilab successfully performed two cloud demonstrations using CMS reconstruction and simulation applications, which showed the ability to burst to 80K cores on Amazon Web Services and a few months later to 300K cores on Google. This was the largest cloud burst test at the time, doubling the total resources made available to CMS during the burst. In 2019, developers supported by the Open Science Grid and the San Diego Supercomputer Center successfully performed a cloud simulation for the IceCube Neutrino Observatory in Antarctica with 50K GPUs corresponding to 350 petaflops of processing power being used for two hours across multiple cloud providers.

The external computing landscape has changed dramatically since the initial planning for the LHC program in the early 2000s. Two of the largest changes are the availability of resources and credible alternatives to dedicated purpose-bought computing systems and the advent of specialized computing architectures like GPUs and FPGAs. In 2022, the U.S. had an undisputed leadership position in the deployment of HPC (high-performance computing) facilities available to science. The U.S. was the first to deploy an exaflop system and five of the top ten supercomputers are located at U.S. sites. All these HPC facilities derive the bulk of their processing capacity from GPUs. U.S. ATLAS and U.S. CMS have both used these HPC systems already in their computing workflows. On the commercial end of the spectrum, Amazon and Google cloud facilities both dwarf by orders of magnitude the combined resources of the Worldwide LHC Computing Grid.

S&C beyond the LHC

In the future, particle physics will be an exascale science with exabytes of data collected, processed, and analyzed annually by each large collaboration. To process the data, a continuum of dedicated, rented, and contributed computing centers connected to each other and to massive data distribution facilities will be needed. The system will be built on a foundation of high-performance networks. Dedicated analysis facilities are in development to solve the input/output challenges of condensing petabytes of data into manageable analysis samples in close to real time. In the last decade, limited computing resources have gone much farther than expected due to methodological innovation, but it is highly likely that analyzing all the data to be acquired in the next decades will stress the community's financial and human resources.

Maintain and build leadership in S&C

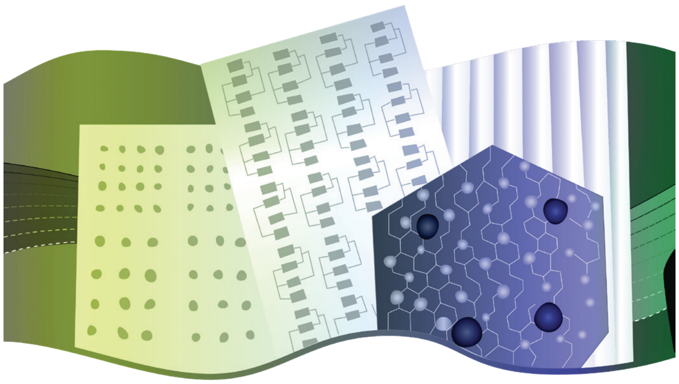
Particle physics in the U.S. should maintain and build leadership in S&C in integrating external and dedicated resources for data-intensive science. This involves continuing to develop expertise in data distribution and access at a massive scale, networking to move tens of petabytes of data per day, the efficient use of heterogeneous architectures, and cyber security, authorization, and cost modeling. Collaborative partnerships will be a fertile base to create a complete ecosystem of high-performance distributed computing for data-intensive science. The U.S. should also aspire to be at the forefront of developing new ways of processing the data, using external and internal resources, developing new services and new approaches to computing using the most up to date and efficient methods of computing developed both inside and outside the field.

RECOMMENDATION

U.S. particle physics should capitalize on its deep experience as leaders in scientific software and computing development as well as the country's emerging high-performance computing and cloud systems of unprecedented scale. The field should also leverage its potential to create national scale collaborations for software and computing spanning experiments, DOE national laboratories, and universities. Collaborations should leverage computer and data science expertise beyond the field of particle physics.

4.2

Particle physics and national initiatives



Advancing national initiatives

KEY FINDING

The national initiatives in artificial intelligence and machine learning, quantum information science, and microelectronics are accelerating new research avenues in particle physics, and particle physics contributions to these initiatives are bringing new ideas and new technologies to a range of disciplines.

The national initiatives in AI/ML, QIS, and microelectronics have driven new research avenues in particle physics and particle physics contributions to these initiatives are driving new ideas and new technologies in related disciplines. Their importance to the nation and to our strategic partnerships is evident from both the continually growing interest and support in these areas and in the research they are generating at national centers, the national laboratory complex, universities, and in industry.

KEY RECOMMENDATION

Enhance and leverage the innovative role that particle physics plays in artificial intelligence and machine learning, quantum information science, and microelectronics to advance both particle physics and these national initiatives.

Artificial intelligence and machine learning—drivers of discovery

FINDING

Artificial intelligence is impacting every element of the cycle of inquiry in particle physics.

AI is the intelligence of machines or software, as opposed to the intelligence of human beings or animals. AI can be characterized as algorithms that perform large-parameter model fitting based primarily on data rather than on physical intuition or analytic models. Key related topics to AI include ML,[nn] deep learning,[oo] and data science.[pp] These topics are nested and overlapping, but all fall under the same umbrella.

AI was founded as an academic discipline in 1956. After 2012, when deep learning surpassed all previous AI techniques, there was a vast increase in funding and interest across many fields. AI recently reached its third age of major development; it has begun to influence almost every sector of modern life, including the physical sciences. Moreover, within physics, AI is impacting every element of the cycle of inquiry—from hypothesis generation and simulations/theories, to instrument control and design, to data analysis. This permeation of AI has critical implications for scientific discovery, workforce development, and interactions between academia and industry.

In the context of scientific discovery, AI demonstrated early on the ability to dramatically improve (in speed and accuracy) the classification of physical systems and objects, from particle interactions to galaxy morphologies. ML techniques have since acquired a prominent role in particle physics, especially over the last two decades. At first, AI use was limited to classification and regression tasks. Already at the time of the LEP (Large Electron Positron collider),[qq] problems such as jet tagging[rr] were handled with shallow NNs (neural networks). In the first decade of the 21st century, BDTs (boosted decision trees)[ss] became the standard, first in neutrino physics (*e.g.*, MiniBooNE, Mini Booster Neutrino Experiment, at Fermilab) and then at collider accelerators (*e.g.*, the *BaBar* experiment at the PEP-II, Positron Electron Project-II, accelerator at SLAC, then the D0 and CDF, Collider Detector at Fermilab, experiments at the Tevatron). The U.S. community has been the driver of these developments, which have been carried out in U.S.-led and U.S.-hosted international collaborations. European institutes (*e.g.*, Italian and French groups involved in LEP experiments) participated in the early developments of NN applications. The French *BaBar* community played a crucial role by providing ROOT[tt]-based tools to train ML algorithms. This tool was the basis on which TMVA (Tool for MultiVariate Analysis), integrated in ROOT before the LHC, was developed. During the first two runs of the LHC, TMVA was the tool on which BDTs were developed for LHC physics and in particular for the discovery of the Higgs boson.

The advent of deep learning has profoundly changed this scenario. Since 2015, the particle physics community has invested substantial resources (in terms of person power and funds) to import the most advanced deep learning tools from computer science. These tools have been applied to experimental particle physics, first mainly neutrino physics and LHC physics and then to theoretical physics. Typical deep learning applications went beyond classification tasks, including anomaly detection for new physics searches, unsupervised clustering for event reconstruction, and generative models for simulation and matrix element[uu] calculations. Due to the specific nature of particle physics data and the unique computing requirements in terms of data throughput and processing latency (especially at the LHC), particle physics research in deep learning became autonomous around 2018 when custom networks (mainly based on the graph NN paradigm) and custom applications (*e.g.*, FPGA inference for the Level 1 trigger via the high level synthesis language for machine learning, hls4ml tool[vv]) were introduced.

Most of this work has been carried out by U.S. institutes, especially at universities with both a strong involvement in the LHC or neutrino experiments and a local community with strong expertise in deep learning (*e.g.*, New York University; University of California, Irvine; University of California, Berkeley; California Institute of Technology, CalTech; MIT; and Stanford University). In Europe, the LHC German community has taken an early lead on this front (thanks to the initiative at the University of Hamburg and the University of Heidelberg), supported by local funding agencies and specific computer science programs. At CERN, work on deep learning has been carried out in collaboration with the U.S. community (*e.g.*, CalTech, Fermilab, MIT, and the University of California, San Diego) and has delivered important results (*e.g.*, the hls4ml library) which have attracted collaborations with private companies from the U.S. and Europe (*e.g.*, AMD-Xilinx, Zenseact, Google, and CEVA). The CERN effort has been mainly funded through private grants and by the European Research Council, a funding body of the European Union. In other countries in both Europe and Asia, early activities carried out by individuals evolved into more structured efforts, thanks to wider programs to promote AI in science, which have also benefitted particle physics. In the U.S., the collaboration with local computer science communities has facilitated these efforts.

Benchmarking U.S. leadership in AI/ML

AI/ML is considered a high-priority area of research and innovation around the world, but funding, culture, and activities vary widely by country. There is a widespread, international perception in the particle physics community that the U.S. particle physics community was the first to strongly embrace AI/ML and is an intellectual leader, although other regions are now catching up. U.S. funding for AI/ML specifically directed to particle physics is tracked; this is not the case for Europe (*e.g.*, CERN). Therefore, it is not possible to compare funding for AI/ML in particle physics between the U.S. and Europe.

U.S. funding agencies solicit proposals for AI/ML in the field of particle physics, and funds compose a fraction of the DOE HEP allocations for group grants. For instance, principal investigators are asked to list AI/ML activities in DOE grant proposals. NSF physics-related AI/ML R&D ranges from foundational, supported through smaller projects and base grants, to the delivery of cyber-infrastructure. Lead agencies NSF and the U.S. Department of Agriculture's National Institute of Food Security, together with other partners, have funded 25 AI Institutes, that are carrying out a broad spectrum of research of critical importance to U.S. competitiveness, food security, public safety, education, and myriad other targets. Several of these institutes are particularly relevant to particle physics including IAIFI (Institute for Artificial Intelligence and Fundamental Interactions) and A3D3 (Accelerated Artificial Intelligence Algorithms for Data-Driven Discovery). The NSF-supported IRIS-HEP institutes create state-of-the-art software cyberinfrastructure for the LHC at CERN. These institutes provide a model for collaboration between universities, fields (*e.g.*, computer science and physics), and stakeholders like individual experiments. Thus far, Europe has not presented a plan to create national institutes for AI like the NSF has, however the U.K. has recently announced a plan to do so.

Transnational, academic-only collaborations in AI/ML for particle physics are rare relative to more traditional particle physics research collaborations. The large funding capacity and logistical flexibility of industry partners tend to make them a nexus for international collaborations, more so than U.S. government-funded institutions.

Impact of deep learning in particle physics

Deep learning research in particle physics has been extremely successful. It has provided sizeable improvements in experimental performance that would have otherwise required expensive detector upgrades. As an example, ATLAS and CMS have improved b-jet tagging (a type of pattern recognition) at large momentum by a factor of approximately three by adopting algorithms based on recurrent and graph NNs. Deep learning is at the heart of development plans for future experiments, such as DUNE and those at the HL-LHC. New research directions are being opened, thanks to novel applications directly exploiting raw data. This development has been possible due to a close collaboration between different regions, in particular the U.S. and Europe.

Future directions for U.S.-Europe collaboration

In the future, this U.S.-Europe collaboration in ML for particle physics could be strengthened, exploiting existing opportunities for common funds. In particular, several European Union grants offer the opportunity to create small research consortia within a specific research domain or across several. Researchers from outside the European Union can take part in this program if their country offers a corresponding program that would qualify for the required matching funds. Creating a common program between the European Union's research funding bodies and the DOE and NSF could be a unique opportunity to join forces to facilitate the exchange of ideas. For Europe, such a partnership would be a key element to facilitate collaboration with U.S. technology companies investing in deep learning research and applications. For the U.S., this initiative would consolidate a well-established program of international collaboration in fundamental research with Europe. Thanks to its strong position in AI research and its strong investment in HPC centers, the U.S. would play a prominent role in this collaboration.

AI beyond physics analysis

While the first applications of AI in particle physics focused on data analysis, AI is also being developed for instrument operations, such as accelerator controls and telescope observation scheduling. Surrogate models[ww] perform best on generative AI[xx] tools like GANs (generative adversarial networks) and autoencoders; these models have opened a new avenue for fast simulations that can in some cases replace more expensive simulators, like n-body. Finally, work in hypothesis generation has been advanced, largely in the form of symbolic regression.

Measuring or predicting values with AI is a high-priority research area. However, tools to make physical and statistically interpretable estimates of uncertainties present the largest barrier. Indeed, uncertainty quantification is an open problem for AI applications across scientific fields. More generally, interpretability of AI models, like deep neural networks, is an open problem as NNs have a large number of parameters and lack physical motivation.

Physics data as verification of AI algorithms

Physics phenomena and data provide a unique avenue for the advancement of AI algorithms, because those data are based on and drawn from fundamental physical principles. This allows for exact numerical studies and experiments in ways that are not available outside the sciences. In particular, particle physics makes an excellent proving ground for ML research; because the field generates large datasets, it has an excellent model (the Standard Model) and a well-tested high-fidelity GEANT4 (Geometry ANd Tracking 4) detector simulation. The success and challenges in the applications and development of AI have been discussed in numerous white papers in the public domain.

Retaining U.S. leadership in AI/ML for particle physics

The U.S. particle physics community benefits from strong DOE SC-wide targeted funding and NSF Institute-class funding for AI/ML. These funding streams have been crucial to the U.S.'s world-leading position in the application of AI/ML to particle physics and subsequent discoveries. The innovations developed have driven the field forward and new techniques are constantly being developed, *e.g.*, the GPT-4 (Generative Pre-trained Transformer) model, which show that the pace is only accelerating, and applying these to science will mean new fields will open up, yielding new discoveries and new and more sensitive probes of the Standard Model. Particle physics is suited to help drive this effort with the huge datasets that come from machines like the LHC and soon from DUNE. This funding level should be enhanced and maintained beyond the targeted funding period in order for the U.S. to retain its leadership in this very competitive field.

RECOMMENDATION

To retain U.S. leadership in the application of artificial intelligence and machine learning to particle physics, enhance funding in this area as it is an important driver of discovery.

Quantum information science opens new vistas for particle physics

FINDING

Quantum information science is driving innovation in particle physics, which in turn creates new capabilities and new ideas for quantum information science.

QIS ideas and methods are starting to find wide application in particle physics. The main areas of application are quantum sensors, quantum computing and simulation, and the use of quantum information ideas to aspects of QFTs (quantum field theories) and gravity theory.

Quantum sensing encompasses the ability to manipulate and control the quantum state of a system and enables technological advances. Quantum sensing presents a host of new opportunities to directly probe fundamental physics and to search for new physics.

Quantum computing and simulation permits exploration of a wide variety of particle physics problems that cannot be addressed using classical computation. Such problems include real-time scattering processes, properties of finite density strongly interacting matter, and some theories that extend beyond the Standard Model of particle physics. Quantum computing is also expected to be important and possibly transformational for event generation and data analysis.

Quantum information has provided an important new perspective on QFT, in which entropy and entanglement play prominent roles. Using information content as the organizing principle allows the structure of entanglement to shed new light on QFT properties.

Particle physics and the second quantum revolution

The second quantum revolution is in progress; it will embed quantum technologies into the fabric of our society and will profoundly influence many areas including communication, finance, healthcare, aerospace, defense, and science at large.

Around the world, countries have created national quantum science and technology programs. The 2018 NQIA (National Quantum Information Act) seeks to prepare the U.S. for leadership in this new world. The NQIA supports the DOE HEP QuantISED (Quantum Information Science Enabled Discovery) program and established multiple national DOE and NSF research centers designed to serve as hubs for innovation and scientific advancement in QIS. The SQMS (Superconducting Quantum Materials and Systems) Center led by Fermilab, DOE's only single-purpose national laboratory with an HEP-focused mission, acknowledges that QIS and particle physics are intertwined and crucial for each other's long-term success. The primary goal of Fermilab's SQMS is to understand and mitigate quantum decoherence[yy] and to deploy superior quantum systems to advance applications in quantum algorithms and sensing. At SQMS, the technology and expertise developed by the particle physics community, primarily based on the needs of particle accelerators, provide exceptional theoretical and experimental resources to advance the physics of decoherence. Fermilab has been able to construct cavity oscillators with the highest Q factor[zz] (quality factor) in the world. This is a crucial contribution that DOE HEP is extremely well-suited to make to the national quantum ecosystem and a prime example of DOE HEP's mission and the national quantum ecosystem mutually benefiting from engaging with each other. The oscillators, when coupled to a quantum bit or qubit (a basic unit of quantum information), create a powerful new quantum information processing platform with the potential to impact particle physics and other fields.

There is also a strong particle physics presence within the other DOE National QIS Research Centers. For instance, the QSC (Quantum Science Center) hosted by Oak Ridge National Laboratory (ORNL) and with Fermilab as a partner, focuses on applications of quantum computing for both high and low energy physics as well as many other scientific domains. ORNL is a large multi-purpose laboratory, and the inclusion of a particle physics research agenda within QSC is strong evidence that QIS benefits from collaborative engagements with multiple disciplines. More broadly, the national QIS ecosystem brings together stakeholders from across scientific domains to address common concerns and shared priorities for QIS research.

Cryogenic and room-temperature microelectronics represent another area where particle physics expertise can contribute strongly to the national quantum ecosystem. Because particle physics has been driven by the stringent experimental requirements of high data rates arising from detectors with a high channel count, the field has developed highly specialized capabilities in areas that have broad importance. This offers opportunities to further grow this expertise for applications within the field by leveraging impact on disciplines outside traditional particle physics.

Support for the fusion of particle physics with quantum information science

The DOE HEP-QIS core research program was developed via a series of community round tables, pilot studies, and reports since 2014 including 1) *Grand Challenges at the Interface of Quantum Information Science and Particle Physics*,[40] 2) *First Workshop on Quantum Sensing for Particle Physics*,[41] and 3) *Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science and Computing*.[42] DOE HEP subsequently issued its first funding iteration of the QuantISED program in the fiscal year of 2018 as part of the DOE SC initiative in QIS. The HEP-QIS QuantISED program is aligned with the "Science First" driver for the national QIS program and requires interdisciplinary partnerships between particle physics and QIS researchers. Topics supported include foundational theory and simulations connecting the cosmos to laboratory qubits, QIS-enabled quantum sensors, and novel experiments to explore new physics, particle physics-developed technology for QIS, and quantum computing approaches for particle physics experiments.

Beyond those dedicated programs in the U.S. (QuantISED, DOE and NSF Quantum Centers, and DOE NP's Quantum Horizons: QIS Research and Innovation for Nuclear Science), NQTP (National Quantum Technologies Program) in the U.K. and NICT (National Institute of Information and Communications Technology) in Japan have dedicated programs; QTFP (Quantum Technologies for Fundamental Physics, 2019) and QUP (Quantum-Field Measurement Systems for Studies of the Universe and Particles, 2021), respectively, are dedicated to applying quantum technologies to address major themes in particle physics and fundamental physics more broadly. These have been followed by Quantum Vision in India, the Quantum Alliance in Germany, France Quantum, and the supranational Quantum Flagship in the European Union.

Other nations are evaluating the importance of creating similar dedicated programs. Thus far, the U.S. has allocated the greatest amount of funding for quantum sensing applied to particle physics of any western nation. China is investing heavily in QIS but does not disclose its funding for quantum sensing applied to particle physics. There is strong international competition in this fast-paced area. To retain U.S. leadership, enhanced funding is necessary.

Quantum sensing for particle physics

Within the broader field of QIS, quantum sensing for particle physics is a demanding set of applications that can be at the limits of the sensitivity of quantum technologies. Particle physics thus stimulates further quantum sensing innovations at universities, national laboratories, and in industry, with discoveries conferring wider benefits.

Quantum sensors have become an essential component of the instrumentation arsenal of particle physicists to answer some of the most pressing open questions in particle physics. Due to their capabilities, quantum sensors are at the heart of a wide range of new non-accelerator particle physics experiments,[9,37] including searches for ultra-light dark matter, new forces, variations in the fundamental constants and the electron dipole moment, the absolute measurement of the electron-neutrino mass, and the detection of gravitational waves. For example, existing searches for dark matter have so far covered only a small fraction of the parameter space in which it could exist. Quantum sensors have extraordinary capabilities to expand the discovery space by 21 orders of magnitude as they probe the previously inaccessible ultra-low mass range. These technologies include qubits, superconducting nanowire detectors, quantum detectors based on the same technique as magnetic resonance imaging, and atomic clocks. Another type of quantum sensor, the atom interferometer MAGIS, a U.S.-led international collaboration at Fermilab, enables searches for the lowest mass dark matter and gravitational waves. MAGIS searches in a region where LIGO (Laser Interferometer Gravitational-Wave Observatory) and other optical interferometers on the ground (and in the future in space with the European Space Agency-led LISA, Laser Interferometer Space Antenna[aaa]) do not have sensitivity.

For accelerator-based particle physics, instrumentation ideas that rely on quantum devices, or are inspired by them, but do not necessarily use them as quantum detectors *per se*, but rather their properties to enhance or permit measurements that are more difficult to achieve otherwise, appear very promising. A program to thoroughly explore such applications with high priority is well motivated.[43]

For example, in high energy particle detectors, measurement of a particle's momentum or energy relies on repeated interactions between the particle to be measured and the sensitive material of a given detector. In these applications, it is often the bulk behavior of systems that can result from engineering at the atomic scale that can provide extended functionality, can improve the sensitivity of existing devices, or can allow heretofore difficult or impossible measurements to be carried out, *e.g.*, on the particle's helicity. Attempts to improve the performance of calorimeters, charged particle trackers, or different techniques that allow particle identification by incorporating quantum dots[44] or two-dimensional molecular monolayers[45] are in their infancy, while devices capable of measurements of high energy photon polarization or particle helicity are only at the conceptual stage.

There have been two recent major reviews of instrumentation in particle physics.[9,37] Both dedicated chapters to quantum sensing. The pace of this field is so fast that had these reports been published three years earlier, quantum sensors would not have had chapters dedicated to them. In addition, for the first time, QIS featured prominently at Snowmass 2021.[46]

Collaboration on quantum sensing

Regarding collaboration, the U.S. and U.K. nationally funded programs in quantum sensing have generated new international partnerships between U.S.- and U.K.-based national laboratories and university consortia. These include MAGIS (U.S.) and AION (Atom Interferometer Observatory Network, U.K.); ADMX (Axion Dark Matter Experiment, U.S.) and QSHS (Quantum Sensors for the Hidden Sector, U.K.); Project8 (a neutrino mass experiment, U.S.) and QTNM (Quantum Technologies for Neutrino Mass, U.K.); and HeRALD (Helium Roton Apparatus for Light Dark Matter, U.S.) and QUEST (Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, U.K.).

Interdisciplinarity in quantum sensing

The field of quantum sensing is very broad, employing a wide range of techniques from other areas of physics including condensed matter physics, AMO physics, and QIS and particle physics as well as from other fields including materials science, electrical and mechanical engineering, and chemistry. Therefore, quantum sensing is intrinsically interdisciplinary. The interaction between particle physicists and those working in other fields is intellectually exciting and very fruitful. Given the interdisciplinary breadth of the quantum sensing community, dedicated programs in quantum sensing open to an interdisciplinary community are well motivated to support this new activity. Indeed, the U.S. QIS funding model is interdisciplinary in character, fostering an interdisciplinary community that is essential to this field and that is a particular U.S. strength and advantage that should be maintained.

The concentration of world-leading quantum sensing expertise in the U.S. suggests that a U.S. university or national laboratory would be a natural home for one or more of the sensor technologies of the ECFA detector roadmap DRDs in quantum sensors.

U.S. leadership in QIS and quantum sensing

There is a strong perception among international quantum sensing practitioners that the U.S. is the global leader in quantum sensing for particle physics. This sentiment is partially attributable to the U.S.'s thriving quantum ecosystem. The remarkable capacity of the U.S. to innovate is reflected in the multi-decades-long tradition of technical preeminence among major international companies with quantum interests including Google, IBM, Microsoft, Intel, and others.

RECOMMENDATION

Establish a funding mechanism for a suite of small-scale experiments that have the potential to advance the scientific goals of the U.S. particle physics program to capitalize on the recent investments made in quantum sensing. These small experiments should be at the technical cutting edge of this rapidly progressing international field and world leading. Funding should be timely, recognize the interdisciplinary character of this field, and be sufficient to ensure the rapid, successful completion of these experiments.

Microelectronics, an essential technology

FINDING

Application Specific Integrated Circuits (ASICs) are ubiquitous in particle physics, in other scientific disciplines, and in society. ASICs are an essential part of almost every detector technology in particle physics.

The transistor, invented in 1947, was commercialized as a discrete component in the 1950s, and this debut was quickly followed by specialized function circuits with multiple transistors on the same substrate. Complex printed circuit boards with broad and sometimes programmable functionality were common by the last decade of the 20th century. Today, much or all of the analog and digital functionality of printed circuit boards resides in an ASIC, an integrated circuit on a silicon chip designed for a specific purpose, *i.e.*, a purpose that is application specific. As ASICs have continued to replace discrete electronics, entire systems are integrated on a chip (*i.e.*, System on a Chip or SoC). An SoC may have ASICs as well as FPGAs, an operating system, utility software, voltage regulators, and power management circuits.

The shrinking of feature size, which has driven these revolutionary changes, is made possible by device physics and technology advances and investments. This reduction has allowed the number of transistors on a chip to double roughly every two years for over five decades—a phenomenon described by Moore's Law—and has enabled the integration of increasingly greater functionality with higher density and performance. Today a mobile phone may have well over 10 billion transistors.

ASICs in particle physics

The majority of detector instrumentation R&D in particle physics requires ASIC development. The challenges include the ability to develop ASICs that can operate in the extreme environments of high radiation, high data rates, low temperatures, and/or outer space.

Current and future custom integration allows higher density, enhanced circuit performance, lower power consumption, lower mass, much greater radiation tolerance, and/or better performance at cryogenic temperatures than is possible with commercial integrated circuits or discrete components.

ASICs are used in many scientific disciplines.

Developing ASICs to operate in the demanding environments found in particle physics can benefit other fields as well. For instance, instrumentation for DOE BES and for NASA uses several ASIC designs developed for particle physics.

ASICs at the energy frontier

U.S. impact on ASICs has waned since the 1990s, when the U.S. had an outsized influence on and made large contributions to front-end electronics, including custom ASICs for the LHC experiments across many detector systems and more broadly. In recent years, declining U.S. leadership in this area has led LHC experiments to more frequently look to CERN or other European groups for integrated circuit designs. The CERN Microelectronics Group has provided access to CAD (computer-aided design) systems, training, and ASIC fabrication processes, and facilitated design reviews as a general community resource in Europe, fostering multi-institutional collaborative design participation.

The recent success of the FEI4 pixel readout chip (containing 100-million transistors at a 65-nanometer feature size) depended on a large international collaboration, primarily between ATLAS and CMS under a CERN RD collaboration (RD53). This kind of collaborative effort, where some U.S. physicists play prominent roles, presents a good model for the development of the highly complex integrated circuits that will be needed for future experiments.

Moving forward, significant R&D effort is needed to explore the radiation sensitivity of smaller feature-size technologies (*e.g.*, 28 nanometers) for detector applications within a time frame of 5–10 years, as the FEI4 readout chip can withstand only one third to one half of the expected HL-LHC radiation dose.

ASICs in neutrino physics

The U.S. community currently spearheads the development of ASICs designed to operate at cryogenic temperatures such as the low-power immersed noble liquid cold electronics at -180° Celsius for the DUNE neutrino experiment. Future experiments will require increased sensitivity, granularity, digitization speed, and an approach to minimize radioactive material background.

ASICs at the cosmic frontier

At the cosmic frontier, today's typical ultra-low temperature -269° Celsius electronics that are used to readout a bolometer (a type of detector), are similar to the electronics boards from the 1990's, with many separate functions on several printed circuit boards reading out hundreds of channels. As cosmic frontier instruments evolve to more than 100,000 channels, it will be necessary to use ASICs on smaller substrates to keep the power low, the channel density high, and the number of input/output cables to a minimum.

In addition, ultra-low temperature ASIC development for particle physics is highly synergistic with QIS R&D objectives seeking to control large numbers of qubits with manageable connections to warm electronics.

Funding in microelectronics

In the U.S., DOE HEP has benefitted from recent DOE SC-wide funding for microelectronics as part of the national microelectronics initiative. Collaboration presents additional funding opportunities. For example, DOE HEP and CPAD recently (2023) created 11 RDCs to cover the main technology areas necessary to advance particle physics. Among them, the RDC in Readout and ASICs is intended to provide a collaboration which can link together facilities, expertise, people, and experience to tackle the ASIC technology challenges across the DOE HEP and DOE NP programs.

Microelectronics research in related fields

Other U.S. agencies have complementary ASIC expertise. For example, stockpile stewardship has stringent requirements on radiation hardness, and this area shares the challenges of foundry access and workforce development. There are opportunities for the particle physics community to collaborate with the stockpile stewardship community, and also with NASA, as radiation exposure is a barrier to deep space exploration. Efforts to better leverage and improve the coordination among groups and collaborations would be beneficial to particle physics and other scientific instrumentation communities. The newly established RDC in Readout and ASICs could help facilitate this.

Foundry access

ASICs are made in foundries. Therefore, foundry access is crucial, but the cost is high, and few foundries will engage with the particle physics community due to 1) the stringent and atypical requirements of ASICs for particle physics, *e.g.*, radiation hardness and 2) the relatively small size of particle physics as a customer compared to that of the commercial sector.

European Union support for microelectronics foundry access in Europe: The advent of Europractice, funded by the European Union, has given particle physics ASIC developers at CERN and across European institutions an advantage in foundry access by providing a brokerage service to lower the costs across industry and academia.

Europractice has provided broad access to and support and training for both CAD development tools and technology node- (feature size-) specific design kits across Europe. Europractice has granted access to many U.S. institutions as well. In addition, CERN's ESE (Electronic Systems for Experiments) group has negotiated multi-institution NDAs (non-disclosure agreements) directly with foundries, first with IBM and then Global Foundries for the LHC. Subsequently, ESE worked in partnership with IMEC (Interuniversity Microelectronics Centre), an international R&D organization active in the fields of nanoelectronics and digital technologies in Leuven, Belgium, to negotiate a multi-institutional NDA agreement with TSMC (Taiwan Semiconductor Manufacturing Company) for the 65-nm (nanometer) and 130-nm technology nodes for the LHC upgrades. This agreement, titled the "Nondisclosure and Master Technology Usage Agreement," was executed between TSMC and IMEC, with IMEC acting as the third-party negotiator, directly sending the agreement to individual particle physics institutions for official signatures. Europractice and CERN ESE have played a crucial role providing both training and technology-specific help including, importantly, design flows for mixed analog and digital designs. It is the widely held view in the community that without CERN's proactive training and support, many of the designs would not have succeeded. There is an absolute necessity for training in the use and application of these state-of-the-art and highly technical design enablers. Without access to a team of experts, university groups can spend months trying to evolve their designs into a submission that complies with foundry requirements. Infrastructure for support, often specific to HEP designs, goes hand-in-hand with predictable design schedules, cost, and informed review.

Foundry access for U.S. institutions: Foundry access, including design tools and third-party intellectual property, is essential for ASIC development but difficult to obtain in the U.S. There are legal hurdles to signing NDAs for foundry access, especially for multi-institution collaborations. Lincoln Laboratories and Sandia National Laboratory, 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 particle physics community and the agencies. In particular, establishing cost-effective access to licenses and tools and high-priority, cost-effective access to foundries in the U.S. would benefit ASIC development across science programs in DOE SC (*e.g.*, DOE HEP, DOE NP, DOE BES) and NSF Division of Physics.

Alternatively, for U.S. institutions, access to advanced process foundries overseas may be provided through multi-project wafer organizations including Europractice if the U.S. institution is working on a project where CERN is also a collaborator (*e.g.*, ATLAS, CMS, and DUNE), otherwise via organizations such as MOSIS (Metal Oxide Semiconductor Implementation Service), Muse (Multi-project wafer University Service), and TAPO (Trusted Access Program Office). These organizations provide access to large industrial foundries, such as TSMC and Global Foundries. The cost of this access can be prohibitively high, especially for small feature size.

Coordination of access to foundries with radiation hardening manufacturing capabilities among the NNSA (National Nuclear Security Administration), NASA, and DOE HEP would help to ensure long-term access to special technologies.

Collaboration and coordination on microelectronics in particle physics

With regards to coordinating international ASIC efforts within particle physics, information is exchanged through CPAD's HEPIC (High Energy Physics Integrated Circuit) design activity. HEPIC is a consortium of integrated circuit design engineers and physicists working in particle physics instrumentation. HEPIC's goal is to exchange information and coordinate activities at a national level. The consortium provides a forum for ASIC designers to interact, synchronize on technical topics, such as foundry processes to standardize on, and advocate for common needs. Workshops, training, and workforce development activities are organized by HEPIC, and a particle physics chip database is being established. HEPIC could be used for shared multi-institution integrated circuit fabrication technology access, a model similar to CERN's successful frame contracts with commercial integrated circuit foundries. The opportunities for collaboration between HEPIC and the newly established RDC in Readout and ASICs will need to be explored.

RECOMMENDATIONS

DOE HEP and NSF Physics should regenerate and maintain at a leadership level expertise in microelectronics for particle physics instrumentation. Efforts should include support of both targeted and generic R&D in microelectronics to advance microelectronics applications as well as to maintain expertise and to attract talent. DOE HEP and NSF Division of Physics should exploit synergies with the needs of other parts of the DOE Office of Science and NSF programs.

The agencies and the community should work together to establish a program providing cost-effective access to design licenses and tools and to foundries for national laboratories and universities. Consider a program that extends across the DOE Office of Science and the NSF Directorate for Mathematical and Physical Sciences.

"To provide answers, the particle physics community develops new theoretical ideas and invents tools to mount ambitious experiments, offering new ways to look at the world and the universe."

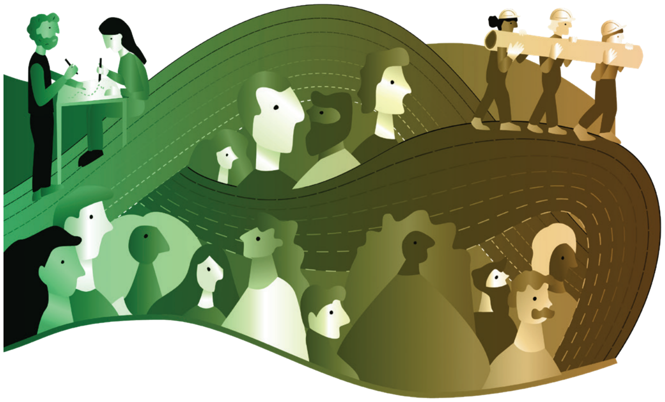
5

Workforce

Attracting and retaining a talented, highly trained, and diverse U.S. workforce

The U.S. is a leader in generating and transforming particle physics ideas into experiments that have the potential for groundbreaking science. The U.S. workforce is the creative wellspring behind the innovations that harness cutting-edge technology to push the bounds of what is possible. Workforce demands in particle physics span the core abilities and national initiatives addressed in Chapter 4 and include theory, accelerator science and technology R&D (research and development), instrumentation, large-scale computing, AI/ML (artificial intelligence and machine learning), QIS (quantum information science), and microelectronics. Although national laboratories and university groups have cultivated a vibrant particle physics community, the U.S. must dramatically increase its workforce numbers of talented, highly trained researchers,[47] engineers, and technicians to develop and maintain world-leading particle physics technologies and capabilities.

To expand the workforce, it is imperative that the particle physics community provide compelling, inclusive, and equitable opportunities for all those who want to explore the secrets of the universe at their most fundamental level. Efforts to open opportunities to all citizens, regardless of gender or ethnicity, must be enacted in parallel with steps to dismantle barriers. Likewise, the invaluable contributions of international collaborators (see Chapter 3) and those internationals who choose to pursue education and careers on U.S. soil must be fostered. Diversity drives the scientific innovations that lead to discoveries. Current and next-generation programs and next-generation research facilities should be structured to attract, train, and retain the best and brightest.



Building a robust workforce

KEY FINDING

Attracting, inspiring, training, and retaining a diverse workforce is vital to the success of all particle physics endeavors and more broadly to U.S. science and technology. A robust particle physics workforce will both leverage and be representative of the diversity of the nation.

KEY RECOMMENDATION

Explore frontier science using cutting-edge technologies to inspire the public and the next generation of scientists while opening new pathways to diversify the workforce and realize the full potential of the field.

5.1

Diversity of the U.S. particle physics workforce

FINDING

The U.S. particle physics program is enriched by international contributions but still suffers from a lack of gender and ethnic diversity, including among students and workers that are U.S. citizens.

Diversity of the U.S. workforce can be defined across many axes: gender identity, race, ethnicity, sexuality, neurodivergence, and disability are a few of the most commonly discussed. Citizenship is an additional axis of diversity, discussed in the following section, while this section focuses on diversity among U.S. citizens. Within this group, gender, race, and ethnicity are often the only axes for which statistics are readily available. These statistics show a troubling picture: over the last decade, the U.S. has made little progress in increasing representation from these groups within the particle physics community.

Gender statistics are the most straightforward to benchmark across different nations, though data sources vary in whether they include non-binary gender identities and whether they allow self-identification of gender. Data from AIP (American Institute of Physics) and NSF (National Science Foundation) both indicate that the fraction of Ph.D.s obtained by women in High Energy Physics remained static from 2014 to 2020, hovering between 14 and 21%, with no significant upward trend (see Appendix K, Figures 1–2). At the U.S. particle physics national laboratories, data on workforce gender for 2019–2021 shows a similar trend (see Appendix K, Figure 3). For comparison, the workforce at DESY (Deutsches Elektronen-Synchrotron), a particle physics laboratory in Germany, had a 23–24% female workforce in the same period (see Appendix K, Figure 4). Data from the IOP (Institute of Physics) Special Interest Group for High Energy Physics in 2022 likewise show only 21% of the group members identify as female (see Appendix K, Figure 5).

Statistics from large experiments provide the most direct comparisons between regions. CMS (Compact Muon Solenoid) and ATLAS (A Toroidal LHC ApparatuS) both provide data on the evolution of the gender distribution among authors and members, broken down by region (see Appendix K, Figures 6–9). While the plots comparing authors consists only of students and professional physicists, the membership plots represent a much more diverse set of careers, each with highly varying fractions of women (see Appendix K, Figures 10–11). Data from both experiments not only show that the U.S. has increased the fraction of its authorship that identifies as female over the last decade, in both cases from about 15 to 20%, but also that the U.S. lags behind many other nations, particularly those in Western Europe, as well as several other regions that vary by experiment.

Race and ethnicity statistics also show little improvement. The NSF reports that from 2014 to 2020, Black or African American students received about 1% of particle physics Ph.D.s, and Native Americans received even less (see Appendix K, Figure 12). Hispanic or Latino students received between 3–8% of particle physics Ph.D.s, but that variation did not represent an increase over time. Collectively, these three groups make up the population referred to as under represented minorities (URMs) in this report, though exact definitions of the term can vary by data source. At the U.S. national laboratories, the URM particle physics workforce each year was between 5–8% URMs (see Appendix K, Figure 13).

Across particle physics, it is imperative to focus on promoting and increasing the representation of women and those from African American, Hispanic, Indigenous, and other underrepresented backgrounds. Particle physics training involves special skills, including theory, applied math, data science, computation, and QIS, and people who pass through the particle physics pipeline end up in a range of STEM (Science, Technology, Engineering, and Mathematics) careers. Though statistics show little progress, there are a number of recent initiatives that are helping the field make changes in this direction. Deeply thoughtful and instructive reports like AIP's TEAM-UP (Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy) report[48] have laid out paths to making physics departments welcoming places for African American students, which are instructive for host facilities and large collaborations as well. Meanwhile, many new funding initiatives have emerged with the goal of increasing URM participation in HEP.

Both DOE (Department of Energy) and NSF have instituted new programs to broaden the participation of underrepresented groups and build infrastructure at institutions that have not traditionally received agency funding, with the ultimate goal of expanding the U.S. workforce pipeline. For example, DOE has launched the FAIR (Funding for Accelerated and Inclusive Research) and RENEW (Reaching a New Energy Sciences Workforce) programs while MPS (Directorate for Mathematical and Physical Sciences) in NSF supports MPS-ASCEND (Ascending Postdoctoral Fellowships). Programs like these are a commendable beginning to the needed greater allocation of funds and all-hands-on-deck effort to make opportunities in particle physics available to all.

Nonetheless, many students not at the major research universities are never exposed to particle physics and its subfields, such as accelerator science and technology. The field of particle physics would benefit tremendously from a funded lectureship program that sends researchers from the national laboratories and universities to MSIs (Minority-Serving Institutions),[49] which include Historically Black Colleges and Universities, Hispanic-Serving Institutions, Tribal Colleges and Universities, Asian American and Pacific Island-Serving Institutions, and numerous four-year liberal arts and two-year community colleges. Visiting expertise will bring the excitement of particle physics to hundreds of thousands of students and faculty.

In addition, enhancing the support for joint/bridge programs that allow universities and national laboratories to co-hire university tenure-track professors could help institutions outside of the traditional particle physics portfolio to attract and retain highly talented people. A new line of funding specifically targeting bridge programs at MSIs would make meaningful and lasting changes to access to particle physics research at participating institutions.

Despite the need to significantly increase those groups that have been traditionally underrepresented in particle physics, some of the data show that undergraduate and graduate student internships/jobs and Ph.D.s in the field have decreased for all groups, probably due to the

COVID-19 pandemic (see Appendix K, Figures 14–17 and Table 1). It is important to reverse this trend as we increase the numbers of those from underrepresented groups.

Looking to the future of U.S. particle physics —especially over the 30–50-year program timescales now under consideration for future colliders —decisions on where to host new scientific facilities have lasting impact on the access that different populations have. It is important to carefully consider how to include geographic regions, inside and outside the U.S., that are developing capacity and could become major contributors to the field in the future.

RECOMMENDATION

The U.S. particle physics program should strive to attract a diverse community in all senses of that word to secure leadership and innovation. In particular, the U.S. should do more to provide compelling, inclusive, and equitable opportunities for U.S. citizens. Some concrete actions include:

1. **Create a program to send national laboratory and university researchers to colleges and universities that do not have particle physics programs to excite students about the field and waiting career opportunities. Include visits to MSIs and small two- and four-year colleges.**
2. **Increase the number of university joint/bridge faculty positions that DOE funds at the 50% level, with the goal of increasing particle physics positions at MSIs.**
3. **Significantly increase the numbers of both undergraduate and graduate internships and other longer-term opportunities in particle physics at the national laboratories and universities. Ensure that participation in one program during one year does not preclude participation in another program during another year.**
4. **Place a high priority on best practices for ensuring the cultural competency of managers at the national laboratories to hire, promote, and retain a diversity of researchers in the particle physics workforce. DOE should continue its commitment to develop and implement best practices in the area of diversity, equity, and inclusion.**
5. **Collect and report statistics on the particle physics workforce, and track its evolution over time across levels: laboratories, collaborations, and nationwide. The DOE SC Office of Scientific Workforce Diversity, Equity, and Inclusion[50] should work with the NSF Office of Equity and Civil Rights,[51] as well the leadership of the national laboratories and large collaborations to align categorizations for consistent comparison across different datasets.**

5.2

Barriers for international employees and collaborators to conduct research in the U.S.

FINDING

There are many impediments faced by the U.S.'s international collaborators who come to the U.S. to conduct their research. These barriers hamper the whole research enterprise.

People from around the globe have long been drawn to the U.S. to be trained and to contribute to U.S.-hosted projects. However, quantifying this flow is a challenge. Most relevant data describe a snapshot of citizenship (at an individual's birth, at the time a degree was received, or at the time of collection), none of which capture this effect precisely. Small children immigrate to the U.S. and later happen to become scientists.

Long-term laboratory staff become U.S. citizens. None of these metrics are perfect, but they still collectively tell the same story: the U.S. is an extremely attractive place to be if you want to contribute to groundbreaking science.

Statistics collected from AIP and NSF show that the U.S. grants 40–50% of its particle physics Ph.D.s to non-U.S. citizens (see Appendix K, Figures 18–19). At the national laboratories, a similar number is seen, with an international workforce making up roughly half of the total workforce on average (see Appendix K, Figure 20). The same is true for the members of DUNE (Deep Underground Neutrino Experiment) (see Appendix K, Figure 21). Note that the definition of international varies from each of these sources and is detailed further in the figures. Regardless of these distinctions, the overall message is clear: that an international workforce is a vital aspect of the U.S. particle physics community.

Recent restrictions placed on scientists and engineers from overseas are concerning, especially those placed on people from sensitive countries. Researchers, especially students and postdocs, must make the difficult choice to not see their families for years or to go home and potentially not be able to return to the U.S. An excellent example concerns those from China who are stuck either in the U.S. for fear of not being able to return to the U.S. or stuck in China with delays in visa processing. Some have been subjected to undue investigations from the leftover impacts of the U.S. Department of Justice's China Initiative. Those caught abroad may endure months without pay, as they cannot be paid overseas. To lessen the barriers to advancing careers of scientific and technical personnel in particle physics, the U.S. could benefit from regularly scheduled surveys and town halls with employees to solicit, share, and act on feedback received about the work environment. Many federal agencies use this approach.

Within some DOE national laboratories, there are also several "mini" barriers faced by international collaborators that have noticeably intensified since the COVID-19 pandemic started, including the following: 1) issues of DOE compliance and a large amount of paperwork required to visit the U.S., 2) changing immigration rules and a long time needed to obtain a short-term visa to the U.S., often ~3 months, and 3) site access challenges and often the necessity of an international collaborator/visitor to obtain a new identification badge for each visit. Because of these mini barriers, site access at DOE national laboratories in the past few years has become more challenging than site access at international counterparts.

RECOMMENDATION

To lessen the burden on international collaborators, DOE and NSF should coordinate with all relevant stakeholders, including the U.S. Department of State, to reduce the impediments caused by agency compliance, visa delays, and on-site security.

5.3 Workforce for enabling technologies

FINDING

Progress in particle physics relies on advances in the state of the art in enabling technologies. Advances in technology rely, in turn, on the ability of particle physics to attract, train, and retain a highly skilled technical workforce.

The enabling technologies of particle physics — both in traditional areas (accelerators, instrumentation, software and computing) and in emergent initiatives (AI/ML, QIS, and microelectronics) —are also enabling technologies not only for other sciences but also for the commercial world. Consequently, attracting highly qualified experts from outside the field is challenging, as is retaining highly qualified experts trained within the field. To address these challenges a number of measures are necessary. Some of these measures are already implemented but must be maintained, and in some cases, expanded or initiated anew.

One of the challenges to attraction and retention is establishing appropriate recognition for the specialized experts that enable progress in the field. This must be done within the particle physics community and within the institutions hosting and sponsoring particle physics, including the universities, national laboratories, and funding agencies. It would be unfortunate if the experimental scientists reaping the harvest of new, powerful accelerators and of innovative particle detection techniques were more highly esteemed than the highly skilled accelerator and instrumentation scientists and engineers who provided the enabling tools to the experimentalists. Unfortunately, this cultural issue exists in portions of the particle physics community.

How can particle physics be made attractive to a workforce with career options in industry, from start-ups to the tech giants? This can be achieved, in part, through recognition, a shared sense of the excitement in particle physics and in scientific discovery, stimulating R&D projects that push the state of the art, advanced training opportunities, an inclusive, diverse culture, and career path and compensation.

How can particle physics look beyond its own cadre of graduate students? Pathways from outside the field should also be developed. A point of entry for students would be from applied physics and engineering departments. However, developing these pathways also requires adequate R&D opportunities in particle physics at universities. Another point of entry could be recruitment from the more general high-tech workforce. The capability of offering a combination of reasonable levels of compensation with the attractive work environment of laboratory and university research, if properly disseminated, could facilitate recruitment from outside the field. Re-entry into the field by those who left the field earlier in their careers for a job in industry should also be facilitated. Traineeships could facilitate these points of entry, although operating training programs on an appropriate scale would be a challenge.

The collaborative nature of the field is also an attractive feature of a career in particle physics for the technological side of the community as well as the more purely scientific side. Collaboration offers opportunities to learn and to expand horizons. Within the enabling technologies, national technological networks and multi-institution centers can promote communication, cross fertilization of ideas, pooling of resources, and creation of research teams to tackle particularly challenging problems. Such networks and centers increase not only the effectiveness of working within the field but also the attractiveness, contributing to the ability of particle physics to retain its workforce.

The goals and methods outlined above can be used to develop a framework to attract, train, and retain a highly skilled technical workforce in the technology areas that propel advances in particle physics research.

RECOMMENDATION

Develop a framework to attract, train, and retain a highly skilled technical workforce.

Workforce development in key technologies

FINDING

The U.S. needs to significantly increase the numbers of U.S. researchers and the country's workforce development capacity in key technologies of particle physics, especially instrumentation, large-scale computing, and particle accelerators.[47]

How can the field provide pathways into the technological workforce of particle physics, both from its cadre of physics graduate students and more broadly? For students within the field, involvement in detector and software development for specific experiments and in advanced technology R&D can provide a point of capture or entry. To enhance this pathway, ample opportunities should exist for graduate students to engage in these activities as part of their university research groups. Such opportunities require suitable support of detector and software development for construction projects and of technology R&D broadly at universities, not just at national laboratories.

Ample support for undergraduate research opportunities in technology development, such as instrumentation development, could also attract undergraduate students into the field. In fact, undergraduate research opportunities can attract a more diverse cadre of undergraduate and graduate students. Traineeships, such as traditional DOE support for graduate students to spend time working at national laboratories, new traineeship grants in instrumentation and in computing and software, and ample opportunity to attend the USPAS (U.S. Particle Accelerator School) can foster pathways for graduate students from within the field. However, these opportunities are not available at an adequate scale to fill the technological workforce needs of the field on their own.

Workforce development in instrumentation

FINDING

More long-term career opportunities are needed for specialists in instrumentation.

Physicists, engineers, and technicians specializing in instrumentation are the bedrock of a successful particle physics program. To lead in instrumentation, the field must create long-term career paths for those specializing in instrumentation.

The case for support for instrumentation schools, lab-university training partnerships, apprenticeship programs, instrumentation awards, and recognition was clearly articulated in the DOE Basic Research Needs Report on instrumentation.[9] It is important to support environments where this new workforce can thrive. For example, small-scale experiments where young scientists are involved in many aspects of an experiment are excellent training grounds; they provide an abundance of opportunities to innovate, take the initiative, take responsibility, and develop a strong sense of ownership and belonging. Small-scale experiments excite scientists to be committed and increase the likelihood they will remain in the field.

Workforce development in software and computing

FINDING

The current standard for software and computing training is project-specific on-the-job training. Career path limitations within the field diminish retention rates.

Specialists in S&C (software and computing) are at the core of nearly every research endeavor in particle physics. The field needs a highly skilled workforce in the development of complex algorithms, machine learning, and in the infrastructure for data-intensive computing—areas that are not only critical to the field but also highly valued outside the field. Many of these specialists learn these skills through on-the-job training, often as part of their particle physics Ph.D. research. The Snowmass report on the Future of High Energy Physics Software and Computing[52] emphasized the need for continual recruitment and training of an S&C workforce. Training programs have been hosted by the HSF (HEP Software Foundation) and several DOE- and NSF-funded initiatives. Training events are also carried out through larger experiments and collaborations and institutes/organizations, and there are growing numbers of university courses. The continuous evolution of the technology means the need for training continues to grow at multiple levels to address the needs of early career and more senior researchers. In addition, S&C is an area where career path limitations within the field influence retention rates. Faculty-level positions for computational researchers or physicists with expertise in S&C for particle physics are scarce. Joint faculty-level appointments in S&C

for particle physics in partnership with national laboratories would create an additional pathway for advancement.

Workforce development in accelerator science and technology

FINDING

Over 50% of the U.S. accelerator science and technology workforce is trained by U.S. universities. Yet, accelerator science and technology training programs are only available at a small fraction of all U.S. universities and have limited overall support.

Currently, over 50% of the U.S.-trained accelerator scientists and engineers working in the U.S. today were trained by fewer than a dozen U.S. universities (see Appendix K, Figure 22). Notably, a large percent received their doctoral degrees from a program at Indiana University which no longer exists. A survey of accelerator scientists at SLAC (SLAC National Accelerator Laboratory), BNL (Brookhaven National Laboratory) and Fermilab (Fermi National Accelerator Laboratory) underscores the importance of international contributions: about 50%–70% of survey participants obtained their Ph.D.s from U.S. academic programs (see Appendix K, Figure 23). Of interest, the majority of the SLAC accelerator workforce is funded by DOE BES (DOE Office of Basic Energy Sciences), while those at BNL are funded by DOE NP (DOE Office of Nuclear Physics) and DOE BES.

Though DOE and NSF make important contributions to training the U.S. workforce—for example, former postdocs and students working on BELLA (Berkeley Lab Laser Accelerator) and FACET-II (Facility for Advanced Accelerator Experimental Tests-II) have joined diverse sectors (see Appendix K, Figure 24)—support overall for accelerator science university programs has been severely restricted. This situation will be exacerbated by the conclusion of the funding for the NSF Center for Bright Beams in 2026. Universities make important contributions to accelerator research and are essential for attracting and training the next generation of accelerator scientists. Because students are drawn to visible research on their campuses, a healthy accelerator R&D ecosystem includes faculty-led, campus-based research. Adequate support will encourage universities to hire young faculty in accelerator science, expanding the reach and visibility of the field.

The cross-cutting nature of accelerator R&D benefits multiple disciplines—ranging from materials science, to medicine, to particle and nuclear physics—but presents challenges for funding agencies, especially the NSF. The NSF now advises submitting accelerator proposals to the program that would benefit from the proposed accelerator advances. While this practice may foster collaborations across disciplines, there are often situations where the proposed research would benefit many programs. As individual programs lack sufficient incentives to assume ownership, research may go unfunded. DOE faces this challenge to a lesser extent.

RECOMMENDATION

Attract, nurture, recognize, and sustain the careers of physicists, engineers, and technicians dedicated to the development of instrumentation, accelerator science and technology, and large-scale computing. Recommended actions include:

1. **Conduct a comprehensive study to identify areas of inadequate expertise in the U.S. particle physics workforce, such as instrumentation, accelerators, and large-scale computing.**
2. **Shore up deficiencies by encouraging more students to pursue those areas of study.**
3. **Establish more university programs offering degrees in accelerator science and technologies.**

5.4

Workforce needs in AI/ML and QIS

FINDING

Too few artificial intelligence/machine learning and quantum information science/quantum sensing students remain in particle physics after receiving their degrees.

Universities are an excellent training ground for AI/ML, QIS/quantum sensing, and quantum technology more generally. Many particle physics graduate students join AI/ML and quantum technology companies after their Ph.D. or after a postdoc in the field. This is a direct and beneficial contribution of particle physics to the economy. However, too few trained in particle physics remain in the field. Even though excellent career opportunities exist at the national laboratories and at universities, the attraction of working in AI/ML and QIS/quantum technology in the commercial world often seems more appealing. To retain a good fraction of the AI/ML and QIS/quantum sensing specialists at universities and national laboratories, a career framework is needed within particle physics that combines long-term funding with an excellent career path that includes good ties to industry; for instance, the chance to take a sabbatical at a company and *vice versa*, and enhanced opportunities to create spin-offs. The proposed framework also would be attractive to those AI/ML and QIS/quantum sensing specialists who have already left the field. Indeed, many of the new startups that have attracted members from the particle physics community will thrive, but many will not survive. Thus, particle physics could greatly benefit from their return. Such a return path would be much easier to pursue if collaborative ties were established and maintained.

RECOMMENDATION

Develop new career frameworks to grow and retain the U.S. AI/ML and QIS/quantum particle physics workforce.

1. **Establish new and attractive career frameworks in AI/ML and QIS/quantum sensing, such as allowing those working in particle physics to take sabbaticals in private companies and *vice versa* and enhancing opportunities for particle physics employees to create spin-offs.**
2. **To compete more effectively with industry in the recruitment and retention of the best talent, national laboratories should provide opportunities for engineers and technicians to work with scientists on blue sky research and provide the possibility for national laboratory researchers to launch private companies via spin-off technologies.**

5.5

Workforce needs in microelectronics

FINDING

Microelectronics, and ASICs (Application Specific Integrated Circuits) in particular, are ubiquitous in particle physics. In the U.S. particle physics community, there is a shortage of both specialist ASIC design engineers and particle physicists sufficiently knowledgeable in ASIC design to work effectively with ASIC designers and to review systems designed with ASICs. These factors limit U.S. leadership in this crucial area of the field.

ASIC R&D is exceptionally specialized and depends on a stable long-term workforce within particle physics. This workforce, and its expertise in particle physics, is challenging to maintain. DOE HEP (DOE Office of High Energy Physics) and NSF Elementary Particle Physics only partially support the workforce upon which particle physics relies; moreover, they support this workforce only on construction projects. Collaborative efforts would alleviate this issue and be mutually beneficial—for instance, collaborations with other areas of DOE Office of Science (*e.g.*, BES and NP) and NSF MPS and collaborations with other sponsors (*e.g.*, NNSA, National Nuclear Security Administration and NASA, National Aeronautics and Space Administration), especially when combined with comprehensive foundry access on a par with that in Europe, as this report recommends in Chapter 4.

Collaboration with other fields would diversify funding sources and increase the possibility of continuity of employment and the hence continuity of expert knowledge. It therefore addresses the challenge in developing and maintaining integrated circuit literacy in future generations of particle physics researchers as integrated circuit designs invariably increase in complexity. The field must draw on a diverse group in developing this pool of researchers to deepen the expertise and talent in the workforce. Both HEPIC (High Energy Physics Integrated Circuit) and the recently created DOE HEP CPAD (Coordinating Panel for Advanced Detectors) Readout and ASICs RDC (R&D Collaboration) may contribute on this front. It is essential for the field to be able to drive integrated circuit design to meet the science needs of particle physics.

U.S. national laboratories and U.S. universities have together long played an important role in the design, development, and implementation of instrumentation for particle physics detectors, including ASICs. Retaining resident knowledge within the university community is important; ASICs expertise is needed to train the next generation of physicists and to enable the innovation and workforce capacity that will be required by future large-scale experiments. Insights, such as determining when and how to use ASICs in favor of or along with other electronics technologies, come with deep topical knowledge and experience. In collaborating with laboratories, universities play an important role in training young physicists to design optimized instrumentation for physics experiments.

Today's students will be the designers and reviewers of tomorrow's detector systems. For the U.S. to play leading roles in the development of next-generation detector systems, the field needs to provide a foundation for the development of particle physics-specific guided (and self-guided) training in system design and detector readout electronics as part of experimental physics training at universities. This training needs to include incorporation of and basic training in FPGA (Field-Programmable Gate Array) and ASIC design along with simulation and verification tools. An understanding of current technologies and design and verification tools will inspire critical evaluation and state-of-the-art designs.

This challenge can be addressed by effective training provided in a partnership between the universities and the national laboratories. Experimental physics Ph.D. and Master's students are trained at universities. Currently, specialized training supported by DOE is conducted at the national laboratories to introduce and support the design of future HEP/NP detector systems. However, university faculty do not perceive great research benefit from this program because it involves taking on a student who will then move to a lab for 3–6 months as soon as their coursework is complete. (An exception is if the university has a healthy electronics instrumentation program and is near a lab.) On the other hand, the university research group would likely perceive a benefit if the instrumentation/ASIC training were better integrated into the Master's or Ph.D. process so that students could bring back design expertise with a higher cadence to their university groups, and, if training centered on topics more relevant to the interests of the research group at the home institution to graduate better informed students.

A successful university program to attract and train Ph.D. students in experiment system design and subsystem design of a detector and its readout and appropriate implementation and design of ASICs for detector readout should be national laboratory-linked but needs to have components of both remote and lab resident training. It would be better to have short (1–3 week) training periods with remote learning or project participation than to require the presence of a student at a national laboratory for 3–6 months. Some of the students being trained will become the next generation of particle physics researchers. This training would broaden their level of understanding so that they obtain positions in the field they are qualified to help guide the progress of the next generation of detector and ASIC developments.

The kind of training proposed could also identify those students with high interest and capability for further in-depth training that could be provided at the national laboratories. Some of these students may ultimately follow a path to becoming ASIC designers.

RECOMMENDATION

DOE should fund and work with universities to create an enhanced integrated program to train university Ph.D. and Master's students in system design of the experiment and subsystem design of the detector and readout and appropriate implementation and design of ASICs for the detector readout.

5.6

Next-generation facility to inspire and train tomorrow's workforce

FINDING

Frontier large-scale research facilities offer the most comprehensive method of answering fundamental questions while exciting and inspiring a whole new STEM workforce.

Ambitious technological and scientific undertakings capture the imagination of the public. The NASA space program fascinates children and adults alike, fostering a sense of wonder and excitement about science. Many of today's physics students cite the turn on of the LHC and the discovery of the Higgs boson as key moments that inspired them to set out on the path towards a STEM career.

These broad-scope, multi-decade projects do not just inspire, they are also crucial training grounds. The LHC program has produced thousands of Ph.D. theses, each representing a new, experienced scientist with a range of practical skills entering the workforce. Their technical requirements also push forward detector, accelerator, and computing technologies, building a skilled workforce and leading to the construction of R&D facilities at national laboratories as well as universities. Large gaps between the operation of these large, multi-purpose projects threaten this pipeline as well as the specific expertise required to build any future facilities.

As the scales of projects increase and timescales for their execution grow, substantial foresight is required to prevent these gaps. Currently in the U.S, there are no approved plans for a flagship particle physics facility beyond LBNF/DUNE, which is already in construction. Concerted R&D and conceptual design work is necessary to explore the options for a next-generation, U.S.-hosted international facility. Such a next-generation facility will not only inspire and attract students into STEM careers, but open new opportunities for scientific discovery. The R&D work for its realization will serve to maintain and fuel the U.S. scientific and technical expert workforce pipeline. Moreover, it will position the U.S. to maintain its role in hosting major international facilities for the worldwide community as a vital part of the global particle physics program.

RECOMMENDATION

A next-generation international flagship particle physics facility based in the U.S. would attract a whole new generation of scientists while boosting opportunities to train students and sustain a leading scientific workforce. The U.S. should not wait until DUNE is commissioned to embark upon its next major particle physics initiative but should move quickly to intensify its R&D program with the aim of accelerating progress in this direction to enable a timely decision.

Conclusions

The U.S. has a long and impressive history of leadership and international collaboration in particle physics. However, maintaining and growing this role in an increasingly global community pursuing science is not guaranteed. To continue to be a premier research destination for particle physics projects hosted at home and an effective partner at leading facilities hosted internationally, the U.S. must continue to deliver groundbreaking science today and develop and maintain world-leading capabilities to realize the discoveries of tomorrow. To be attractive as a host country for international experiments, the U.S. must embrace international collaborators as full partners, both in science and in project management, even on experiments and facilities at the mega-scale. To continue to lead in national initiatives, the U.S. must ensure timely and effective execution of research in these areas. Overall, the field must continue to realize the benefits of particle physics technologies for society at large. Finally, the benefits accrued by a leading U.S. particle physics program are predicated on a strong, diverse workforce. Great care and new ideas are required to attract, train, and empower a workforce of and for the future.

Appendices

Appendix A

References

1 BESAC Subcommittee on International Benchmarking. *Can the U.S. Compete in Basic Energy Sciences? Critical Research Frontiers and Strategies.* United States (2021). https://science.osti.gov/-/media/bes/pdf/reports/2021/International_Benchmarking-Report.pdf

2 BERAC International Benchmarking Committee. *U.S. Scientific Leadership Addressing Energy, Ecosystems, Climate, and Sustainable Prosperity: Report from the BERAC Subcommittee on International Benchmarking.* United States (2022). https://genomicscience.energy.gov/wp-content/uploads/2023/01/BERAC_2022_Intl_Benchmarking_Report_FINAL-1.pdf

3 ASCAC International Benchmarking Subcommittee. *Can the United States Maintain Its Leadership in High-Performance Computing?* United States (2023). https://science.osti.gov/-/media/ascr/ascac/pdf/charges/2023/Report_20230627.pdf

4 FESAC International Benchmarking Subcommittee. *FESAC International Benchmarking Subcommittee Report on International Collaboration Opportunities, Modes, and Workforce Impacts for Advancement of U.S. Fusion*. United States (2023). https://science.osti.gov/-/media/fes/fesac/pdf/2023/IBRept2FESAC_ActualFINAL.pdf

5 National Academies of Sciences, Engineering, and Medicine. "Elementary Particle Physics: Progress and Promise." https://www.nationalacademies.org/our-work/elementary-particle-physics-progress-and-promise. Accessed 18 October 2023.

6 CERN. *CERN Personnel Statistics 2022*. CERN/TREF/506, (2022). https://cds.cern.ch/record/2858688/files/CERN-HR-STAFF-STAT-2022.pdf

7 Particle Physics Project Prioritization Panel. *Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context.* United States (2014). https://www.usparticlephysics.org/2014-p5-report/.

8 Butler, Joel N., Chivukula, R. Sekhar, *et al.*, *Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021).* United States (2023). osti.gov/servlets/purl/1922503/.

9 Fleming, B., Shipsey, I., Demarteau, M., *et al.*, *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.* United States (2019). osti.gov/servlets/purl/1659761/.

10 American Institute of Physics. "Statistical Research Center." (2023). https://www.aip.org/statistics. Accessed 18 October 2023.

11 National Science Foundation. "National Center for Science and Engineering Statistics." (2023). https://ncses.nsf.gov/explore-data. Accessed 18 October 2023.

12 Kolb, R., Weerts, H., Toro, N., *et al.*, *Basic Research Needs for Dark Matter Small Projects New Initiatives: Report of the Department of Energy's High Energy Physics Workshop on Dark Matter.* United States (2018). https://www.osti.gov/servlets/purl/1659757

13 J. Horwitz and Z. El-Kilani. *The Economic Impact of Fermilab's Flagship Long-Baseline Neutrino Initiative.* Fermi Research Alliance, LLC. (2016). https://www.andersoneconomicgroup.com/Portals/0/Fermilab_LBNFImpact_FINAL.pdf

14 Aguillard, D.P., Albahri, T., Allspach, D., *et al.*, Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm. arXiv:2308.06230 (2023). https://arxiv.org/abs/2308.06230.

15 Abratenko, P., An, R., Anthony, J. et al (MicroBooNE Collaboration). Search for Neutrino-Induced Neutral Current Δ Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess under a Single -Photon Hypothesis. Phys. Rev. Lett. 128, 11:111801 (2022).

16 Bartram, C., Braine, T., Burns, E. *et al.*, (ADMX Collaboration). Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range. Phys. Rev. Lett. 127, 26:261803 (2021).

17 J. E. Kim. Weak-Interaction Singlet and Strong CP Invariance. Phys. Rev. Lett. 43, 2:103-107 (1979).

18 Shifman, M.A., Vainshtein, A.I., and V.I. Zakharov. Can confinement ensure natural CP invariance of strong interactions? Nucl. Phys. B, 166, 3:493-506 (1980).

19 Aalbers, J., Akerib, D.S., Akerlof, C.W., *et al.*, (LUX-ZEPLIN Collaboration). First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment. Phys. Rev. Lett. 131, 4:041002 (2023).

20 National Academies of Sciences, Engineering, and Medicine. *Pathways to Discovery in Astronomy and Astrophysics for the 2020s.* National Academies Press (2021). https://www.nap.edu/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s.

21 Narin, F., Hamilton, K., and D. Olivastro. The increasing linkage between U.S. technology and public science. Research Policy, 26, 3:317-330 (1997).

22 P. Lecoq. Spin-off from particle detectors in the field of medicine and biology. Nuclear Instruments and Methods in Physics Research, 581, 1:1 – 11 (2007).

23 P. Delpierre. A history of hybrid pixel detectors, from high energy physics to medical imaging. Journal of Instrumentation, 9:C05059–C05059 (2014).

24 Fermi National Laboratory. "Special-purpose coatings." U.S. Department of Energy. https://iarc.fnal.gov/special-purpose-coatings/. Accessed 18 October 2023.

25 Aartsen, M.G., Abbasi, R., Abdou, Y., *et al.*, (IceCube Collaboration). South Pole glacial climate reconstruction from multi-borehole laser particulate stratigraphy. Journal of Glaciology, 59, 218: 1117–1129 (2013).

26 Snowmass 2021. "Snowmass Community." DPF Community Planning Exercise. https://snowmass21.org. Accessed 18 October 2023

27 R. Rameika. "DOE High Energy Physics Report to HEPAP." Presented to the High Energy Physics Advisory Panel (HEPAP) on 7 August 2023. https://science.osti.gov/-/media/hep/hepap/pdf/202308/HEPAP-RAR_Gina_Rameika_-HEPAP_202308.pdf.

28 CERN. "European Strategy for Particle Physics." CERN Council. https://europeanstrategy.cern. Accessed 18 October 2023.

29 Kavli Institute for Particle Astrophysics and Cosmology. "The Astroparticle Physics International Forum." Stanford University. https://kipac.stanford.edu/astroparticle-physics-international-forum-apif. Accessed 18 October 2023.

30 A. Wagner. International Collaboration with High Energy Accelerators. Proceedings of IPAC, Kyoto, Japan, MOXAMH01 (2010). https://accelconf.web.cern.ch/IPAC10/papers/moxamh01.pdf.

31 Bhat, P.C., Belomenstnykh, S., Bross, A., *et al.*, *U.S. National Accelerator R&D Program on Future Colliders.* arXiv:2207.06213, (2022). https://arxiv.org/abs/2207.06213

32 Craig. N., Csáki, C., El-Khadra, A.X., *et al.*, S*nowmass Theory Frontier Report.* arXiv:2211.05772 (2022). https://arxiv.org/abs/2211.05772.

33 Communication from the U.S. Department of Energy Office of High Energy Physics and National Science Foundation Directorate for Mathematical and Physical Sciences.

34 Communication from Yifang Wang, Director of the Institute for High Energy Physics, Chinese Academy of Sciences.

35 European Strategy Forum on Research Infrastructures. *ESFRI Roadmap 2021 Strategy Report.* Printed on behalf of ESFRI by Dipartimento di Fisica – Università degli Studi di Milano (2021). https://roadmap2021.esfri.eu/media/1295/esfri-roadmap-2021.pdf

36 U.S. Department of Energy. *Summary of the Office of Science FY 2021 Accelerator Science & Technology Supplier Data Call.* DOE national laboratories (2021). https://science.osti.gov/-/media/ardap/pdf/2023/ASnTDataCallOnePage.pdf.

37 European Committee for Future Accelerators. *The 2021 ECFA detector research and development roadmap.* CERN (2021). https://cds.cern.ch/record/2799303.

38 P. Merkel and J. Asaadi. “CPAD R&D Collaborations Community Kick-off Meeting.” Presented at the CPAD R&D Collaborations Community Kick-off Meeting on 5 July 2023. https://indico.fnal.gov/event/60315/.

39 Barbeau, B., Merkel, P., Zhang, J., et al., *Report of the Instrumentation Frontier Working Group for Snowmass 2021*. arXiv:2209.14111 (2022). https://arxiv.org/abs/2209.14111

40 Farhi, E., Jordan, S., Hayden, P., *et al.*, *Grand Challenges at the Interface of Quantum Information Science, Particle Physics and Computing*. United States (2015). https://science.osti.gov/-/media/hep/pdf/files/Banner-PDFs/QIS_Study_Group_Report.pdf

41 Ahmed, Z., Alexeev, Y., Apollinari, G., *et al.*, *Quantum Sensing for High Energy Physics*. arXiv:1803.11306 (2018). https://arxiv.org/abs/1803.11306.

42 Chattopadhyay, S., Falcone, R., and R. Walsworth, *Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science & Computing*. United States (2016). https://www.osti.gov/servlets/purl/1358078.

43 Doser, M., Auffray, E., Brunbauer, F.M., et al., Quantum Systems for Enhanced High Energy Particle Physics Detectors. Front. Phys. 10: 2296-424X (2022).

44 Děcká, K., Pagano, F., Frank, I., *et al.*, Timing performance of lead halide perovskite nanoscintillators embedded in a polystyrene matrix. J. Mater. Chem. C, 10:12836-12843 (2022).

[45] Orlandini, G., "Integration of CVD graphene in Gaseous Electron Multipliers for high energy physics experiments." Presented at The 7th International Conference on Micro Pattern Gas Detectors MPGD2022, 15 December 2022. https://indico.cern.ch/event/1219224/contributions/5130761/ .

[46] Cecil, T., Irwin, K., Maruyama, R., et al., Snowmass 2021 IF01: *Quantum Sensors Topical Group Report.* arXiv:2208.13310v1 (2022). https://arxiv.org/abs/2208.13310v1.

[47] HEPAP Workforce Development Subcommittee. *HEP Workforce Development Needs.* U.S. Department of Energy Office of High Energy Physics (2014). https://science.osti.gov/-/media/hep/hepap/pdf/Reports/OHEP_Workforce_Letter_Report.pdf.

[48] AIP National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP). *The Time Is Now: Systemic Changes to Increase African Americans with Bachelor's Degrees in Physics and Astronomy.* American Institute of Physics (2020). https://www.aip.org/sites/default/files/aipcorp/files/teamup-full-report.pdf

[49] Office of Diversity, Inclusion, and Civil Rights. "Minority Serving Institutions Program." U.S. Department of Commerce (2023). https://www.doi.gov/pmb/eeo/doi-minority-serving-institutions-program. Accessed 4 October 2023.

[50] U.S. Department of Energy Office of Science, "Office of Scientific Workforce Diversity, Equity, and Inclusion." https://science.osti.gov/SW-DEI. Accessed 13 November 2023.

[51] National Science Foundation. "Office of Equity and Civil Rights." https://www.nsf.gov/od/oecr/. Accessed 13 November 2023.

[52] Elvira, V.D., Gottlieb, S., Gutsche, O., and B. Nachman. *The Future of High Energy Physics Software and Computing* (V2.1). United States (2022). https://www.osti.gov/biblio/1898754

[53] Chou, A.S., Soares-Santos, M., Tait, T., et al., *The Future of U.S. Particle Physics: Report of the 2021 Snowmass Community Study – Chapter 5: Cosmic Frontier.* arXiv: 2211.09978m (2022) https://arxiv.org/pdf/2211.09978.pdf

[54] Gourlay, S., Raubenheimer, T., Shiltsev, V., *et al.*, *Snowmass'21 Accelerator Frontier Report*. arXiv:2209:14136 (2022). https://arxiv.org/abs/2209.14136

[55] Communication from Patrick Mulvey, Research Manager, AIP on 20 July 2022. Data obtained from the American Institute of Physics. "Statistical Research Center." https://www.aip.org/statistics.

[56] Communication from Patrick Mulvey, Research Manager, AIP on 20 July 2022. Data obtained from the National Center for Science and Engineering Statistics. "Doctorate recipients from U.S. universities." National Science Foundation. https://www.nsf.gov/statistics/doctorates/.

[57] Communication from Dmitri Denisov, Deputy Associate Laboratory Director for DOE HEP, BNL on 01 August 2022.

[58] Communication from Lia Merminga, Laboratory Director, FNAL on 11 August 2022 and communication from FNAL Human Resources on 08 November 2023.

[59] Communication from Natalie Roe, Associate Laboratory Director for the Physical Sciences, Lawrence Berkeley National Laboratory on 12 August 2022.

[60] Communication from Christine Soldahl, Business Operations Manager, SLAC on 12 February 2023.

[61] Figures obtained from: ATLAS Collaboration. *Studies related to gender and geographic diversity in the ATLAS Collaboration*. ATLAS Experiment (2022). Accessed 25 October 2023. https://cds.cern.ch/record/2202392

[62] Figures obtained from: CMS Collaboration. “Approved Plots for Diversity and Inclusion Statistics (August 2023).” CERN (2023). Accessed 25 October 2023. https://twiki.cern.ch/twiki/bin/view/CMSPublic/Public_plots_Aug2023.

[63] Communication from Regina Rameika, Head of DUNE, FNAL on 09 August 2022.

[64] Communication from Laura Childs, Senior Policy Advisor, Institute of Physics on 22 July 2022.

[65] Communication from Manfred Fleischer, Deputy Director for High Energy Physics, DESY on 08 August 2022.

[66] Communication from Ritchie Patterson, Professor, Cornell University. Data collected via Google spreadsheet with survey open from 15 January 2023 – 1 March 2023.

[67] Communication from Cameron Geddes, Director of the Accelerator Technology & Applied Physics Division, BELLA on 9 December 2022.

[68] Communication from John Power, Director of AWA on 01 February 2023.

[69] Communication from Christine Clarke, FACET User Program manager on 31 January 2023.

[70] Communication from Wolfram Fisher, Head of Collider Accelerator Department, BNL on 16 January 2023 and communication from Timur, Shaftan, Head of NSLS-II Accelerator, BNL on 19 January 2023.

[71] Communication from Alexander A. Valishev, Associate Laboratory Director for Accelerators, FNAL on 25 January 2023.

[72] Communication from Mei Bai, Deputy Director for Science, Accelerator Directorate, SLAC in February 2023.

[73] Communication from Todd Satogata, Director of the Center for Advanced Studies of Accelerators, TJANF on 2 March 2023.

Appendix B

Endnotes

a. The terms "Particle Physics" and "High Energy Physics" (HEP) are both used when referring to the scientific discipline. HEP is often 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 (*i.e.*, DOE HEP) (see Executive Summary).

b. In addition to Fermilab, Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, and SLAC National Accelerator Laboratory, other DOE national laboratories participate in the DOE particle physics program: Thomas Jefferson National Accelerator Facility, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory (see Section 1.1).

c. Examples of U.S. colliders and high-profile discoveries include SPEAR (Stanford Positron Electron Accelerating Ring) at SLAC National Accelerator Laboratory (charm quark and tau lepton), the Tevatron at Fermi National Accelerator Laboratory (top quark), and PEP-II (Positron Electron Project-II) at SLAC (CP violation in bottom quark systems). Examples of advances in accelerator technology at U.S. colliders include the pioneering use of superconducting radio frequency acceleration at CESR (Cornell Electron Storage Ring), superconducting accelerator magnets at the Tevatron, and linear electron-positron collisions and electron collider beam polarization at the SLC (SLAC Linear Collider) (see Section 2.1).

d. APS (American Physical Society) divisions represented in the Snowmass Steering Group are as follows: DPF (Division of Particles and Fields), DNP (Division of Nuclear Physics), DAP (Division of Astrophysics), DPB (Division of Physics of Beams), and DGRAV (Division of Gravitational Physics) (see Section 3.1).

e. The U.S. LHC (Large Hadron Collider) program and HL-LHC (High-Luminosity LHC) detector upgrade projects benefit from the joint support and oversight by DOE and NSF. An NSF MREFC (Major Research Equipment and Facilities Construction) award is critical to the upgrades. NSF also funds U.S. participation in the LHCb (Large Hadron Collider beauty) experiment (see Section 3.1).

f. SBN (Short-Baseline Neutrino program) consists of a chain of three particle detectors —placed in a straight line about a third of a mile long—that probe a beam of muon neutrinos created by Fermilab's particle accelerators. The three detectors, each filled with hundreds of tons of liquid argon to record the interactions of neutrinos, are 1) SBND (Short-Baseline Near Detector) which is expected to commence data taking in 2023, 2) MicroBooNE (Micro Booster Neutrino Experiment) which took data until 2021 and is still analyzing its data, and 3) ICARUS (Imaging Cosmic And Rare Underground Signals) which took data at LNGS (Laboratori Nazionali del Gran Sasso) in Italy from 2010–2014, then moved to CERN for an upgrade before being shipped to Fermilab in 2018. Commissioning was completed in 2022, and the experiment is now taking data (see Section 3.1).

g. Note that in Congressional budgets, the budget line titled "Research" includes significantly more activities than does the term "core research program" used in this report. In particular, the Congressional budget line for Research includes the entirety of the DOE HEP budget with the exception of line-item construction projects (see Section 3.2).

h. ICFA (International Committee for Future Accelerators) was created in 1976 by IUPAP (International Union of Pure and Applied Physics) (see Section 3.2).

i. The tradition of listing all scientific collaborators as coauthors of all scientific publications is not practiced by all particle physics cosmic surveys, which are generally performed in partnership with astronomy (see Section 3.3).

j. *BaBar* is a play on words derived from B mesons and anti-B mesons (see Section 3.3).

k. Two other successfully completed European accelerator facilities constructed by international partnerships are ESRF (European Synchrotron Radiation Facility) in France with 13 member countries and the European XFEL (X-ray free-electron laser) facility in Germany with 12 partner countries. Two additional European accelerator facilities are under construction now: FAIR (Facility for Antiproton and Ion Research) in Germany with nine partner nations including India and the ESS (European Spallation Source) in Sweden and Denmark with 13 partner nations (see Section 3.3).

l. Japan, Russia, and the U.S. were given Observer status in the CERN Council on the basis of their contributions to the construction of the LHC (see Section 3.3).

m. Brookhaven National Laboratory, Fermi National Accelerator Laboratory, SLAC National Accelerator Laboratory, and Lawrence Berkeley National Laboratory plus Argonne National Laboratory, Thomas Jefferson National Accelerator Facility, the National High Magnetic Field Laboratory (at Florida State University), Old Dominion University, and Texas A&M University (see Section 3.3).

n. U.S. accelerator scientists have collaborated with host laboratories in the commissioning of accelerators outside the U.S.; for instance, in the commissioning of the LHC (Large Hadron Collider) through the LARP (LHC Accelerator Research Program) program and recently in the commissioning of the Japanese accelerator, SuperKEKB (an upgraded KEKB electron-positron collider) (see Section 3.3).

o. The terms "host-led model" and "CERN model" are introduced in this document to simplify discussion of governance of collaborations and partnerships. They are not terms with widespread meaning or acceptance beyond this document. Moreover, both the host-led and CERN models can be implemented in many variations (see Section 3.4).

p. HERA (Hadron-Electron Ring Accelerator) was constructed between 1986 and 1991 and operated between 1992 and 2007. Although the HERA accelerator was a partnership in the host-led model, the HERA experiments Zeus and Argus were partnerships in the CERN model (see Section 3.4).

q. The increasingly international nature of research and projects led DESY (Deutsches Elektronen-Synchrotron) to introduce an "Extended Scientific Council" with international membership from contributing countries in the 1970's to advise the DESY directorate on all scientific issues. For HERA, DESY also established the Finance Committee, which discussed and decided issues like shortfalls in funding and remedies (see Section 3.4).

r. For the LHC (Large Hadron Collider) accelerator, Canada, India, Japan, Russia, and the U.S. were international partners, with Japan, Russia, and the U.S. being given CERN Observer State status for their major roles (see Section 3.4).

s. A common fund is a shared pool of funds to be used by the collaboration to cover the cost of expenses of the collaboration's choice. During construction, common funds typically cover infrastructure-like items, *e.g.*, mechanical structures that support the experimental apparatus and unexpected expenses (see Section 3.4).

t. Australia, Brazil, Canada, China, Colombia, France, Germany, Israel, Italy, Korea, Mexico, Spain, Switzerland, Taiwan, and the U.K. (see Section 3.4).

u. France, India, Italy, Poland, and the U.K. (see Section 3.4).

v. LBNF/DUNE (Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment) has been broken into several subprojects to facilitate project management since the establishment of this international benchmarking subpanel of HEPAP. LBNF and DUNE are not separated from one another by the subprojects (see Section 3.4).

w. DOE, NSF, and NASA (National Aeronautics and Space Administration) are jointly advised by the AAAC (Astronomy and Astrophysics Advisory Committee) on selected issues in astronomy and astrophysics that are of mutual interest (see Section 3.4).

x. The term "cosmic survey" is used in this report in the sense defined by the 2014 P5 report Building for Discovery. Cosmic surveys are ambitious astronomical campaigns using powerful telescope instruments to survey large portions of the cosmos to study large-scale astronomical phenomena, such as dark energy, the cosmic microwave background, and the impact of dark matter on large-scale structure formation (see Section 3.4).

y. When this report refers to a cosmic survey as U.S.-hosted, it is not referring to the physical location of the facility. Rather it is indicating that the location of the leadership of the survey is in the U.S. (see Section 3.4).

z. IN2P3, the French National Institute for Nuclear Physics and Particle Physics, is one of two funding agencies in France that support particle physics (see Section 3.4).

aa. Klystrons are a power source for terrestrial microwave relay communications links. High-power klystrons are used in television transmitters, radar transmitters, satellite communications, and to generate the drive power for particle accelerators (see Section 4.0).

bb. Light sources are particle accelerators that produce intense X-rays to study the world at the atomic and molecular level, allowing for research and advances in energy production, environmental remediation, nanotechnology, new materials, and medicine (see Section 4.0).

cc. The following small experiments search for physics beyond the Standard Model including light dark matter and other dark sectors, or seek a fundamental understanding of the nature of gravity. FASER (ForwArd Search ExpeRiment) is an experiment at the LHC (Large Hadron Collider) at CERN. MAGIS-100 (Matter-wave Atomic Gradiometer Interferometric Sensor-100) is an experiment at Fermilab. CASPEr (Cosmic Axion Spin Precession Experiment) is an experiment conducted at the University of Mainz, Germany. LDMX (Light Dark Matter Experiment) is a proposed experiment at SLAC (Light Dark Matter Experiment). CODEX-b (COmpact Detector for EXotics at LHCb) is a proposed experiment at the LHC (Large Hadron Collider) at CERN. GQuEST (Gravity from Quantum Entanglement of Space Time) is an experiment at Fermilab (see Section 4.1).

dd. Thorough documentation does not yet exist, but the Simons Collaborations, funded by the Simons Foundation, offers clear evidence. To date, the Simons Collaborations have almost exclusively funded formal theory in particle theory collaborations including Celestial Holography, Global Categorical Symmetries, It from Qubit, The Non-perturbative Bootstrap and Confinement and QCD Strings. (More information at: https://www.simonsfoundation.org/collaborations/) (see Section 4.1).

ee. DOE KA-25 funding (see Section 4.1).

ff. Already in the late 1990s, it was clear that the expected amount of LHC (Large Hadron Collider) data would far exceed the computing capacity at CERN alone. Distributed computing was the sensible choice. The first model proposed was MONARC (Models of Networked Analysis at Regional Centers) on which the LHC experiments originally based their computing models (see Section 4.1).

gg. *art* is an event-processing framework. In the context of the experiments using art, an event is all the relevant data describing what happened during a particular time period of interest. In the case of a collider experiment, this is one beam crossing which may represent multiple particle collisions (see Section 4.1).

hh. LArSoft (Liquid Argon Software) is a toolkit of experiment-agnostic Lar Time Projection Chamber reconstruction algorithms. The goal of the LArSoft collaboration is to provide common software tools that all LAr Time Project Chamber experiments such as DUNE (Deep Underground Neutrino Experiment) can use (see Section 4.1).

ii. AMS (Alpha Magnetic Spectrometer) is a state-of-the-art particle physics detector operating on the International Space Station (see Section 4.1).

jj. A data federation is a software process that allows multiple databases to function as one (see Section 4.1).

kk. IRIS-HEP (Institute for Research and Innovation in Software for HEP) is a software institute funded by NSF. It aims to develop the state-of-the-art software cyberinfrastructure required for the challenges of data-intensive scientific research at the HL-LHC (High-Luminosity-LHC) and other planned particle physics experiments of the 2020's (see Section 4.1).

ll. A GPU (graphics processing unit) is a specialized electronic circuit initially designed to accelerate computer graphics and image processing. Subsequently, GPUs were found to be useful for non-graphic calculations involving embarrassingly parallel problems due to their parallel structure. Other non-graphical uses include the training of neural networks (see Section 4.1).

mm. An FPGA (field-programmable gate array) is an integrated circuit designed to be configured after manufacturing. The FPGA configuration is generally specified using a hardware description language similar to that used for an application-specific integrated circuit (see Section 4.1).

nn. ML (machine learning) is an umbrella term for solving problems for which the development of algorithms by human programmers would be cost-prohibitive. Instead, such problems are solved through methods that help machines 'discover' their 'own' algorithms, without needing to be explicitly told what to do by any human-developed algorithms. There are several kinds of ML. Unsupervised learning analyzes a stream of data and finds patterns and makes predictions without any other guidance. Supervised learning requires a human to label the input data first and comes in two main varieties: classification (where the program must learn to predict what category the input belongs in) and regression (where the program must deduce a numeric function based on numeric input) (see Section 4.2).

oo. Deep learning uses ANNs (artificial neural networks). ANNs, also shortened to neural networks or neural nets are a branch of ML (machine learning) models that are built based on a collection of connected units or nodes called artificial neurons, which loosely model the neurons in a biological brain (see Section 4.2).

pp. Data science is an interdisciplinary academic field that uses statistics, scientific computing, scientific methods, algorithms, and systems to extract or extrapolate knowledge and insights from noisy, structured, and unstructured data (see Section 4.2).

qq. LEP (Large Electron Positron collider), a particle accelerator at CERN operating from 1990–2003, is located in the tunnel now housing the LHC (see Section 4.2).

rr. A jet is a collimated set of particles. Jet tagging is a process of identifying a jet. It is a form of pattern recognition (see Section 4.2).

ss. Decision trees build up a set of decision rules in the form of a tree structure which helps to predict an outcome from the input data. Decision trees belong to a class of supervised ML algorithms which are used in both classification (discrete outcomes) and regression (continuous numeric outcomes) predictive modeling. Boosting is an ML (machine learning) method to reduce errors in predictive data analysis. Data scientists train ML software, called ML models, on labeled data to make guesses about unlabeled data. A single ML model might make prediction errors depending on the accuracy of the training dataset. For example, if a cat-identifying model has been trained only on images of white cats, it may occasionally misidentify a black cat. Boosting tries to overcome this issue by training multiple models sequentially to improve the accuracy of the overall system (see Section 4.2).

tt. ROOT is an object-oriented computer program and library developed by CERN. It was originally designed for particle physics data analysis and contains several features specific to the field; it is also used in other applications such as astronomy and data mining (see Section 4.2).

uu. A matrix element gives information about whether a transition from an initial to a final state is possible, and if so, the strength of that transition (see Section 4.2).

vv. The European Union-funded hls4ml project developed an open software library that automatically adapts deep neural networks to electronic circuits by utilizing high-level synthesis tools and reducing resource utilization (see Section 4.2).

ww. Surrogate models, for example physics simulations of particle accelerators, are essential tools for predicting optimal settings for different configurations. These simulations can also be computationally expensive, which can be prohibitive during the design stage as well as for online use in accelerator operations. ML (machine learning) models of accelerator systems, known as surrogate models, are a viable solution. Although data generation and model training might require significant computational resources, once trained, these models have a faster execution speed over classical simulation methods by orders of magnitude. Thus, surrogate models can be used for virtual diagnostics, offline experiment planning, design of new setups, control, and tuning (see Section 4.2).

xx. Generative AI algorithms (*e.g.*, ChatGPT) are a subset of all AI (artificial intelligence) algorithms that take a prompt as an input and generate (hence the name) an output in the form of text, images, and other forms of media. Generative AI tools include GANs (generative adversarial networks) that generate data and autoencoders, a type of neural network that can compress and decompress training data, making them useful for data compression and feature extraction. The ultimate goal of a generative network is to generate new data that has the same distribution as its training set. Generative networks are typically considered part of unsupervised learning, because they do not require labelled data (see Section 4.2).

[yy.] Quantum decoherence is the loss of quantum coherence, the process in which the behavior of a system changes from that which can be explained by quantum mechanics to that which can be explained by classical mechanics. For a quantum computer, the decoherence time dictates the length of time the qubits can be entangled without loss of any information. Any computation must be finished before the qubits lose information (see Section 4.2).

[zz.] For a bell, a quality factor, Q, is a measure of how efficient the bell is. A higher Q means the bell is losing less energy, so when struck, it rings for longer. For a cavity oscillator, a higher Q means a cavity is losing less energy (see Section 4.2).

[aaa.] The LISA (Laser Interferometer Space Antenna) mission is a collaboration among the European Space Agency, NASA, and an international consortium of scientists (see Section 4.2).

Appendix C

Acronyms and Abbreviations

A3D3
Accelerated Artificial Intelligence Algorithms for Data-Driven Discovery

AAAC
Astronomy and Astrophysics Advisory Committee

ADMX
Axion Dark Matter Experiment

ADMX-G2
Axion Dark Matter Experiment-G2

AI/ML
artificial intelligence and machine learning

AION
Atom Interferometer Observatory Network

AIP
American Institute of Physics

ALICE
A Large Ion Collider Experiment

AMO
atomic, molecular, and optical physics

AMS
Alpha Magnetic Spectrometer

ANL
Argonne National Laboratory

ANN
artificial neural network

APIF
Astroparticle Physics International Forum

APS
American Physical Society

ARDAP
Office of Accelerator R&D And Production (in DOE Office of Science)

ASCEND
Ascending Postdoctoral Fellowships program (supported by NSF MPS)

AS&T
accelerator science & technology

ASIC
Application Specific Integrated Circuit

ASPIRE
Accelerator Science Program to Increase Representation in Engineering

ATLAS
A Toroidal LHC ApparatuS

AWA
Argonne Wakefield Accelerator

BaBar
a play on words derived from B mesons and anti-B mesons

BDT
boosted decision tree

BELLA
Berkeley Lab Laser Accelerator

Belle
experiment at KEKB electron-positron collider

Belle II
experiment at SuperKEKB electron-positron collider

BES
Office of Basic Energy Sciences (in DOE Office of Science)

BNL
Brookhaven National Laboratory

BOSS
Baryon Oscillation Spectroscopic Survey

BTeV
B Physics at the Tevatron

C3
Cool Copper Collider

CAD
computer-aided design

CALICE
Calorimeter for Linear Collider Experiment

Caltech
California Institute of Technology

CASPEr
Cosmic Axion Spin Precession Experiment

CCE
Center for Computational Excellence

CCI
Community College Internship

CCM
Coherent CAPTAIN Mills

CDF
Collider Detector at Fermilab

CEPC
Circular Electron Positron Collider

CERN
European Laboratory for Particle Physics Research (formerly called the European Council for Nuclear Research)

CESR
Cornell Electron Storage Ring

CH
Switzerland

CLIC
Compact Linear Collider

CMB-S2
Cosmic Microwave Background-Stage 2

CMB-S3
Cosmic Microwave Background-Stage 3

CMB-S4
Cosmic Microwave Background-Stage 4

CMS
Compact Muon Solenoid

CODEX-b
COmpact Detector for EXotics at LHCb

COHERENT
A collaboration at ORNL SNS, Spallation Neutron Source, aiming to make a first direct measurement of CEvNS, coherent elastic neutrino-nucleus scattering

COMET
Coherent Muon to Electron Transition

CPAD
Coordinating Panel for Advanced Detectors

CW XFEL
Continuous Wave X-ray Free-Electron Laser

CSGF
Computational Science Graduate Fellowship

CXFEL
Compact X-ray Free-Electron Laser

D0/DZero
an international collaboration that conducted experiments at Fermilab's Tevatron

DAP
Division of Astrophysics (of the American Physical Society)

DE
Germany

DES
Dark Energy Survey

DESC
Dark Energy Science Collaboration

DESI
Dark Energy Spectroscopic Instrument

DESY
Deutsches Elektronen-Synchrotron (laboratory in Germany)

DGRAV
Division of GRaVitational Physics (of the American Physical Society)

DM Radio
Dark Matter Radio

DMNI
Dark Matter New Initiatives

DNP
Division of Nuclear Physics (of the American Physical Society)

DOE
U.S. Department of Energy

DONUT
Direct Observation of the Nu Tau

DPB
Division of Physics of Beams (of the American Physical Society)

DPF
Division of Particles and Fields (of the American Physical Society)

DRD
Detector R&D

DUNE
Deep Underground Neutrino Experiment

EAGER
Early-concept Grants for Exploratory Research (supported by NSF)

ECFA
European Committee for Future Accelerators

ECP
Exascale Computing Project

EIC
Electron-Ion Collider

EPFL
École Polytechnique Fédérale de Lausanne

ESE
Electronic Systems for Experiments

ESRF
European Synchrotron Radiation Facility

ESS
European Spallation Source

EuPRAXIA
European Plasma Research Accelerator with Excellence in Applications

FACET
Facility for Advanced Accelerator Experimental Tests

FACET-II
Facility for Advanced Accelerator Experimental Tests-II

FAIR
Facility for Antiproton and Ion Research

FAIR
Funding for Accelerated and Inclusive Research (supported by DOE)

FASER
ForwArd Search ExpeRiment

FCC
Future Circular Collider

FCC-ee
Future Circular Collider for electron-positron collisions

FCC-hh
Future Circular Collider of proton beams

FSCF Internship
FSCF (Far Site Conventional Facilities) Internship at for LBNF/DUNE in South Dakota

FCSI
Fermilab Computational Science Internship

FEMI
Fermilab Environmental Management Internship

Fermilab/FNAL
Fermi National Accelerator Laboratory

FOA
Funding Opportunity Announcement

FPGA
field-programmable gate array

FR
France

FRIB
Facility for Rare Isotope Beams

GADZOOKS!
Gadolinium Antineutrino Detector Zealously Outperform Old Kamiokande Super!

GANs
generative adversarial networks

GARD
General Accelerator R&D

GDE
Global Design Effort

GEANT4
Geometry ANd Tracking 4

GEM
Graduate Fellowships for Minorities in Engineering and Science

GeV
gigaelectronvolts

GPT-4
Generative Pre-trained Transformer

GPU
graphics processing unit

GQuEST
Gravity from Quantum Entanglement of Space Time

HEP
Office of High Energy Physics (in DOE Office of Science)

HEPAP
High Energy Physics Advisory Panel

HEPIC
High Energy Physics Integrated Circuit

HERA
Hadron-Electron Ring Accelerator

HeRALD
Helium Roton Apparatus for Light Dark Matter

HL-LHC
High-Luminosity LHC

HPC
high-performance computing

HSF
HEP Software Foundation

HTS
high-temperature superconductor

Hyper-Kamiokande
Hyper-Kamiokande Neutrino Detection Experiment

IAIFI
Institute for Artificial Intelligence and Fundamental Interactions

ICARUS
Imaging Cosmic And Rare Underground Signals

ICFA
International Committee for Future Accelerators

IFC
International Finance Committee

IHEP
Institute of High Energy Physics

ILC
International Linear Collider

IMB
Irvine, Michigan, Brookhaven experiment

IMEC
Interuniversity Microelectronics Centre

IN2P3
French National Institute for Nuclear Physics and Particle Physics

INC
International Neutrino Council

INFN
Instituto Nazionale di Fisica Nucleare (the National Institute for Nuclear Physics in Italy)

IOP
Institute of Physics

IOTA
Integrable Optics Test Accelerator Facility at Fermilab

IRIS-HEP
Institute for Research and Innovation in Software for HEP

IsoDAR
Isotope Decay-At-Rest

IT
Italy

IUPAP
International Union of Pure and Applied Physics

JP
Japan

J-PARC
Japan Proton Accelerator Research Complex

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Kavli-IPMU
Kavli Institute for the Physics and Mathematics of the Universe

K0TO
an experiment at J-PARC in Japan to measure a rare decay of the neutral long-lived kaon subatomic particle to a neutral pion (a neutrino and an anti-neutrino) to search for new physics beyond the standard model

KEK
High Energy Accelerator Research Organization (in Japan)

LANL
Los Alamos National Laboratory

LARP
LHC Accelerator Research Program

LArSoft
Liquid Argon Software

LBNC
Long-Baseline Neutrino Committee

LBNE
Long-Baseline Neutrino Experiment

LBNF
Long-Baseline Neutrino Facility

LBNL
Lawrence Berkeley National Laboratory

LCLS-II
Linear Coherent Light Source-II

LCLS-II/HE
Linac Coherent Light Source-II/High Energy

LDMX
Light Dark Matter Experiment

LDRD
Laboratory Directed Research and Development

LEP
Large Electron Positron collider

LHC
Large Hadron Collider

LHCb
Large Hadron Collider beauty

LIGO
Laser Interferometer Gravitational-Wave Observatory

LINAC
linear accelerator

LISA
Laser Interferometer Space Antenna

LLNL
Lawrence Livermore National Laboratory

LNGS
Laboratori Nazionali del Gran Sasso

LPA
Laser-driven Plasma wakefield Acceleration

LSST
Large Synoptic Survey Telescope (now the Simonyi Survey Telescope)

LSST
Legacy Survey of Space and Time

LZ
LUX-ZEPLIN experiment

MAGIS-100
Matter-wave Atomic Gradiometer Interferometric Sensor-100

MicroBooNE
Micro Booster Neutrino Experiment

MINERvA
Main Injector Neutrino ExpeRiment to study v-A interactions

MiniBooNE
Mini Booster Neutrino Experiment

Mid-scale RI
Mid-Scale Research Infrastructure program (supported by NSF)

MINOS
Main Injector Neutrino Oscillation Search

MIT
Massachusetts Institute of Technology

MONARC
Models of Networked Analysis at Regional Centers

MOSIS
Metal Oxide Semiconductor Implementation Service

MPS
Directorate for Mathematical and Physical Sciences (in NSF)

MREFC
Major Research Equipment and Facilities Construction (supported by NSF)

MRI
Major Research Instrumentation program (supported by NSF)

MRI
Magnetic Resonance Imaging

MSI
Minority-Serving Institution

Mu2e
Muon-to-electron experiment

Muon g-2
experiment to measure the anomalous magnetic moment of the muon

Muse
Multi-project wafer University Service

MV/m
megavolts per meter

NASA
National Aeronautics and Space Administration

Nb_3Sn
Niobium-tin

NbTi
Niobium-titanium

NDA
non-disclosure agreement

nEXO
next Enriched Xenon Observatory

NICT
National Institute of Information and Communications Technology

NN
neural network

NNSA
National Nuclear Security Administration

NOvA
NuMI Off-axis ν_e Appearance

NP
Office of Nuclear Physics in the DOE Office of Science

NQIA
National Quantum Information Act

NQTP
National Quantum Technologies Program

NSF
National Science Foundation

NSG
Neutrino Scope Group

OECD
Organization for Economic Co-operation and Development

OQI
Open Quantum Initiative

ORNL
Oak Ridge National Laboratory

OSCURA
Observatory of Skipper CCDs, Charged Coupled Devices, Unveiling Recoiling Atoms

P5
Particle Physics Project Prioritization Panel

PanDA
Production and Distributed Analysis

PEP-II
Positron Electron Project-II

PET
Positron Emission Tomography

PIP-II
Proton Improvement Plan-II

PNNL
Pacific Northwest National Laboratory

Project-8
a neutrino mass experiment

PWFA
plasma wakefield acceleration

Q
quality factor

QCD
quantum chromodynamics

QCIPU
Quantum Computing Internship for Physics Undergraduate program

QFT
Quantum Field Theory

QIS
Quantum Information Science

QSC
Quantum Science Center

QSHS
Quantum Sensors for the Hidden Sector

QTNM
Quantum Technologies for Neutrino Mass

QuantISED
Quantum Information Science Enabled Discovery

qubit
quantum bit, a basic unit of quantum information

QUEST
Quantum Enhanced Superfluid Technologies

QUP
Quantum-Field Measurement Systems for Studies of the Universe and Particles

R&D
research and development

RD
an R&D collaboration

RD50
an R&D collaboration for solid state semi-conductor detectors

RD51
an R&D collaboration for gas-based detectors

RD53
an R&D collaboration for microelectronics

RDCs
R&D Collaborations (coordinated by CPAD)

RENEW
Reaching a New Energy Sciences Workforce (supported by DOE)

RF
radio frequency

RHIC
Relativistic Heavy Ion Collider

ROOT
an object-oriented computer program and library developed by CERN

RRB
Resource Review Board

Rubin
Vera C. Rubin Observatory

S&C
software & computing

SBIR
Small Business Innovation Research

SBN
Short-Baseline Neutrino Program

SBND
Short-Baseline Near Detector

SC
Office of Science (in DOE)

SCGSR
DOE Office of Science Graduate Student Research

SciDAC
Scientific Discovery through Advanced Computing

SDSS
Sloan Digital Sky Survey

SHINE
Shanghai High Repetition-Rate X-FEL and Extreme Light Facility

SiDet
Silicon Detector Facility

SIST
Summer Internships in Science and Technology

SLAC
SLAC National Accelerator Laboratory

SLC
SLAC Linear Collider

SNAP/JDEM
SuperNova Acceleration Probe/Joint Dark Energy Mission

SNO
Sudbury Neutrino Observatory

SNU
Seoul National University

SoC
System on a Chip

SPEAR
Stanford Positron Electron Accelerating Ring

SQMS
Superconducting Quantum Materials and Systems Center

SRF
superconducting radio frequency

SSC
Superconducting Super Collider

STEM
Science, Technology, Engineering, and Mathematics

STFC
Science and Technology Facilities Council (in the U.K.)

SULI
Science Undergraduate Laboratory Internship

SuperCDMS
Super Cryogenic Dark Matter Search

Super-Kamiokande
Super-Kamiokande Neutrino Detection Experiment

SuperKEKB
an upgraded KEKB electron-positron collider

SURF
Sanford Underground Research Facility

T2K
Tokai-to-Kamiokande experiment

TAPO
Trusted Access Program Office

TEAM-UP
Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (in the AIP)

TESSERACT
Transition Edge Sensors with Sub-EV Resolution And Cryogenic Target

TJNAF
Thomas Jefferson National Accelerator Facility

TMVA
Tool for MultiVariate Analysis

TSMC
Taiwan Semiconductor Manufacturing Company

UC Berkeley
University of California, Berkeley

UC Santa Barbara
University of California, Santa Barbara

UC Santa Cruz
University of California, Santa Cruz

U.K.
United Kingdom

U.S.
United States of America

URM
underrepresented minority

US-AUP
U.S. Accelerator Upgrade Project

USPAS
U.S. Particle Accelerator School

VALOR
Veteran Applied Laboratory Occupational Retraining

VetTech
military veteran internship program

VFP-Student
Visiting Faculty Program-Student

WIMPs
weakly interacting massive particles

XENON-nT
Direct Search for Dark Matter with Liquid Xenon Deep Underground

XFEL
X-ray free-electron laser

μeV
microelectron volt

Appendix D

International benchmarking charge

U.S. Department of Energy
and the
National Science Foundation

Dr. JoAnne Hewett
Chair, High Energy Physics Advisory Panel
Theory Group, MS 81
SLAC National Accelerator Laboratory
2575 Sand Hill Road
Menlo Park, California 94403

Dear Dr. Hewett:

We are grateful to the High Energy Physics Advisory Panel (HEPAP) for their many contributions to the development of the 2014 Particle Physics Project Prioritization Panel ("P5") Report, which successfully laid out a compelling research program that employed world-leading facilities and exciting new capabilities. HEPAP's 2019 review of P5 implementation demonstrated that many of the report's recommendations are being realized and the community is making excellent progress on the P5 science drivers. As we approach again a community-led "Snowmass" process to consider the most exciting particle physics opportunities for the coming decades, we think it is timely to consider more closely the unique international context of particle physics, and how we can best position the U.S. program and its researchers for success in this evolving landscape.

A core tenet of the P5 Report is that particle physics is fundamentally a global enterprise. The close connections of U.S.-based researchers to major international facilities, as well as the many international scientists conducting their research in the U.S., speak to how the enterprise of particle physics is tightly interwoven across multiple borders and time zones. Today, the international particle physics community is larger and more diverse than ever before, expanding opportunities for collaboration and partnership.

Looking to the future, we want to ensure that the U.S. continues to be a leader in particle physics internationally and remains one of the best places to conduct research, as well as preserving its ability to collaborate effectively at leading facilities hosted elsewhere. We want to be the best partner we can be for the international scientific community.

To that end, we must develop and maintain world-leading capabilities in key technologies, especially particle accelerators and detectors, as well as high performance computing; and also provide compelling, inclusive, and equitable opportunities for all those who want to explore the secrets of the universe at their most fundamental level.

Therefore, the Department of Energy and the National Science Foundation request that HEPAP develop a report providing further input on possible P5 implementation strategies, particularly in the unique international context of particle physics noted above. Specifically, we ask HEPAP to address the following questions:

- How can the U.S. particle physics program maintain critical international cooperation in an increasingly competitive environment for both talent and resources? In areas where the U.S. is leading, how can we sustain our roles and attract the best international partners? In other areas, how can the U.S. build and maintain its reputation as a "partner of choice"? In general, are there barriers that can hinder our ability to form effective and enduring international partnerships?

- Identify key areas where the U.S. currently has, or could aspire to, leadership roles in High Energy Physics (HEP) via its unique or world-leading capabilities (i.e., advanced scientific facilities and tools), or leading scientific and technical resources, including highly trained personnel and supporting infrastructure. This may include emerging areas or opportunities that offer significant promise for leadership. To preserve and foster U.S. leadership roles within reasonable resource constraints, are there particular technical areas or capabilities that could be emphasized? Are there other technical resources and capabilities that could be leveraged in to achieve these goals, possibly through collaborations within and beyond the HEP community?

- How can programs and facilities be structured to attract and retain talented people? What are the barriers to successfully advancing careers of scientific and technical personnel in particle physics and related fields, and how can U.S. funding agencies address those barriers? A complete answer to these questions must address how we can ensure that we are recruiting, training, mentoring, and retaining the best talent from all over the world, including among traditionally underrepresented groups within the U.S.

We would appreciate receiving a written report by July 1, 2022.

Sincerely,

JOHN BINKLEY
Digitally signed by JOHN BINKLEY
Date: 2022.02.04 13:15:10 -05'00'

J. Stephen Binkley
Acting Director
Office of Science
U.S. Department of Energy

Sean L. Jones
Digitally signed by Sean L. Jones
Date: 2022.02.18 14:47:18 -05'00'

Sean L. Jones
Assistant Director
Directorate for Mathematical and Physical Sciences
National Science Foundation

Appendix E

Guide to report terminology

This report discusses experiments, facilities, accelerators, telescopes, projects, and collaborations.

An *experiment* refers to a physical apparatus that produces data which is analyzed to yield new scientific results. A particle physics experiment may, and usually does, perform more than one measurement or study.

A *facility* refers to physical infrastructure at which experiments are performed. For instance, a particle accelerator such as the LHC (Large Hadron Collider) at CERN (European Laboratory for Particle Physics Research) is a facility at which experiments such as ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid), LHCb (Large Hadron Collider beauty), and ALICE (A Large Ion Collider Experiment) are performed.

Particle *accelerators* are not the only type of facility used for particle physics experiments. For instance, the DUNE (Deep Underground Neutrino Experiment) experiment will be mounted at LBNF (Long-Baseline Neutrino Facility), which consists of neutrino-producing accelerator beamlines at Fermilab as well as infrastructure, both underground and on the surface, at SURF (Sanford Underground Research Facility) in South Dakota.

We consider *telescopes* used by cosmic surveys studying dark energy and cosmic inflation as facilities at which many scientific studies will be performed; however, in this case there are no experiments separate from the telescope. For example, the Vera C. Rubin Observatory, constructed by NSF (National Science Foundation) and DOE (Department of Energy) in Chile, and its Simonyi Survey Telescope is a facility, one at which a vast wealth of particle physics and astronomy studies will be performed.

We use the term *projects* to refer to any major undertaking, be it a facility, accelerator, telescope, or experiment, and we use the expression construction project to refer to any project in its construction phase. Most large facilities in the future are likely to be constructed through international partnerships to consolidate the proper resources and expertise.

The term *collaboration* usually refers to the research activities for experiments or R&D (research and development) and are usually based on memoranda of understanding. Collaborations are often based on multilateral agreements. Partnerships are based on more formal agreements that are used to define work on construction projects and bilateral agreements between agencies. The term partnership is also used to describe strong collaborations that share financial responsibilities, share ownership, and share risk.

Typical lifecycle of an experiment

A concept for a new experiment or facility, particularly one demanding state-of-the-art techniques, will likely require an R&D phase to develop the technologies needed to implement the concept. At about the same time, but proceeding longer, is a design phase that will evolve the concept through a sequence of design stages, for instance conceptual design, technical design, and engineering design. Only when the design is complete and the resources needed to implement the design are understood can the construction start.

In an international construction project, components are often constructed in parallel at laboratories around the world as in-kind contributions and then assembled into one experiment or facility. The assembled apparatus is then installed at the location at which it will operate. The equipment is then commissioned, *i.e.*, it is brought into operation via a process that carefully checks that all components operate as designed. Once the equipment has been commissioned, the operations phase begins. In this phase, the experiment acquires data, the data is analyzed, and scientific results based on the data analysis are produced and disseminated. Even for a simple experiment, this lifecycle spans years, and for the field's largest experiments, it consumes decades. Moreover, for many experiments and facilities, this cycle largely repeats, with improvements or upgrades (*e.g.*, to produce more precise data or to implement a new generation of the experiment or facility to address the scientific objective more insightfully).

Although collaboration may not be demanded for the early conceptual steps, collaboration during the conceptual, R&D, and early design phases can already produce better concepts and designs. Building collaborations early in the lifecycle (*e.g.*, from the start) generates stronger, more scientifically productive collaborations that subsequently produce better science.

Appendix F

The nature of particle physics experiments

Accelerator-based experiments and facilities

Many particle physics experiments exploit particle beams produced by particle accelerators to probe the nature of fundamental particles and their interactions. These experiments detect and measure the interactions of colliding particles and the results, either in a fixed target or in a beam. For this purpose, experiments employ complex, state-of-the-art particle detectors to measure trajectories, energies, and identities of charged and neutral particles. The ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) experiments at the LHC (Large Hadron Collider) are examples of accelerator-based experiments, using colliding beams of protons to produce particle interactions. The U.S. currently has one dedicated accelerator facility located at Fermilab (Fermi National Accelerator Laboratory). Fermilab hosts international experiments like LBNF/DUNE (Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment) and Muon g-2 which use neutrino and muon beams and detectors, respectively. The most prominent accelerator facilities worldwide are currently housed at CERN (European Laboratory for Particle Physics Research) and at Japan's KEK (High Energy Accelerator Research Organization) and J-PARC (Japan Proton Accelerator Research Complex).

Underground experiments and facilities

Underground experiments and facilities help create controlled conditions to measure particles like neutrinos, which only weakly interact with matter. Isolating detectors underground removes interference from cosmic rays and other background radiation. Major investments have been made to SURF (Sanford Underground Research Facility) in South Dakota over the last ~15 years in order to prepare it for sensitive new experiments. SURF hosts portions of LBNF/DUNE, the flagship program for neutrino physics in the U.S. Hyper-Kamiokande (Hyper-Kamiokande Neutrino Observatory), under construction in Japan, is a competing effort.

Underground laboratories are also key to next-generation searches for dark matter. For example, LZ (LUX-ZEPLIN experiment), also housed at SURF, requires low background. Future facilities experiments will have stricter radioactivity requirements, host larger cleanrooms, and increase contaminant monitoring capabilities. Underground facilities also present opportunities for synergies with other fields, like quantum information science and nuclear astrophysics.

Cosmic surveys and facilities

Large cosmic survey experiments[53] are carried out by large world-wide collaborations. Some examples of these collaborations are DES (Dark Energy Survey) which used a 570-megapixel camera installed on a 4-meter telescope in Chile; the DESI (Dark Energy Spectroscopic Instrument) collaboration which uses a system of 5,000 robotic fiber positioners on a 4-meter telescope in Kitt Peak, Arizona; and the Rubin LSST (Legacy Survey of Space and Time) DESC (Dark Energy Science Collaboration) which will use a 3.2-gigapixel camera on a 8.5-meter telescope at the Vera Rubin Observatory in Chile. Cosmic survey datasets can be used to address multiple P5 science drivers simultaneously.

Appendix G

Findings and Recommendations

Chapter 3

Scientific breadth and application

KEY FINDING

Particle physics theory and experiments address deep mysteries of the universe while advancing concepts and technology that are vital to other research fields as well as society at large.

KEY RECOMMENDATION

Strengthen investments to advance particle physics discoveries as well as benefits to other scientific disciplines and society.

FINDING

The strategic plan for particle physics is developed through a community planning process culminating in the report of the HEPAP subpanel called P5.

RECOMMENDATION

The U.S. should continue to play leadership roles in the key scientific areas defined as science drivers by P5.

FINDING

Particle physics pushes the boundaries of technology in ways that enable research in other fields of science and that benefit society at large.

RECOMMENDATION

Continue to invest in technology R&D that enables new discoveries in particle physics and other scientific fields and that will lead to applications that benefit society at large.

KEY FINDING

The field of particle physics is a vibrant research ecosystem, built by an international network of partnering nations, facilities, experiments, and people. To be a leader, the U.S. must continuously produce scientific results, build facilities and experiments for the future, and advance new ideas and technologies that enable the discoveries of tomorrow.

KEY RECOMMENDATION

Maintain a comprehensive program at home and abroad, with a range of experiment scales and strategic balance among construction projects, operations of experiments and facilities, and core research activities, including the development of future facilities.

FINDING

Decline in support for core research threatens U.S. leadership in particle physics.

RECOMMENDATION

Reinvigorate the U.S. core research program to restore U.S. leadership in the next generation of ideas, experiments, and discoveries.

FINDING

U.S. leadership entails leading on small experiments as well as leading on medium and large experiments.

RECOMMENDATIONS

Continue to support small projects as a component of a balanced national portfolio of experiments at all scales.

Establish a funding mechanism under which scientifically compelling, well-conceived small projects can be initiated and executed in a timely and competitive fashion.

FINDING

The U.S. particle physics program is part of a global research ecosystem. More scientific advances can be realized through international partnerships.

RECOMMENDATION

The U.S. strategic planning processes should take into consideration the global particle physics ecosystem in setting priorities. International partnerships that create a compelling scientific program with a healthy global balance among the lifecycle stages—construction, operations, and core research activities—should be sought.

Collaborating across the globe

KEY FINDING

Frontier research in particle physics necessitates international collaboration and cooperation. The combined expertise and resources from nations around the world enable discoveries and technological advances impossible to achieve by any single nation. It is the global particle physics program that collectively addresses the burning scientific questions across the breadth of the field.

KEY RECOMMENDATION

Continue support for and actively seek engagement with international collaborations and partnerships of all sizes.

FINDING

Strong collaborations exhibit common characteristics. Shared scientific objectives and a shared sense of responsibility are overarching common characteristics.

RECOMMENDATION

Collaborations should strive to establish an organizational structure and governance model that enables and cultivates the shared characteristics of current and past successful strong collaborations.

FINDING

International partnerships are strongest when partners are engaged starting from the early conceptual development of projects.

RECOMMENDATIONS

DOE and NSF should support involvement of U.S. scientists and institutions starting from the early conceptual development and R&D phase for future international experiments and accelerator projects.

Future U.S.-hosted experiments and accelerator projects should seek to engage scientists and institutions of potential international partners in the projects' early conceptual design and R&D phase while remaining open to additional partners who may want to join later.

FINDING

Shared governance and shared responsibility are principles observed in successful partnerships and large collaborations.

RECOMMENDATION

Formally agree among partners on an international governance structure early during the formation of the international project.

FINDING

International partnership on construction of major particle physics accelerator facilities is growing. International partnerships yield more powerful capabilities for scientific discovery.

RECOMMENDATIONS

The U.S. particle physics program should 1) strive to engage as partners in the construction and operation of major future particle physics accelerator facilities constructed outside the U.S. and 2) actively seek international partners to engage in the construction and operation of major future particle accelerator facilities constructed in the U.S.

Establish a collaborative U.S. national accelerator R&D program on future colliders to coordinate the participation of U.S. accelerator scientists and engineers in global energy frontier collider design studies as well as maturation of technology.

FINDING

International experiments and accelerator projects hosted outside the U.S. seek U.S. participation. U.S. participation in programs hosted outside the U.S. enables U.S. scientists to participate in the best science wherever it is done.

RECOMMENDATION

Continue to enable and facilitate the participation of U.S. scientists and institutions in experiments and accelerator projects hosted outside the U.S.

FINDING

Mechanisms to support both the physical and remote participation of U.S. scientists collaborating on experiments hosted outside the U.S. are essential.

RECOMMENDATION

To maintain an active presence and intellectual leadership in experiments outside the U.S., support for faculty teaching buyouts or during a sabbatical should be expanded, and laboratory and university groups should support members to be based at experimental sites.

Being a partner of choice

KEY FINDING

Success in hosting and participating in international collaborations requires tailored approaches to collaboration governance and project management, host lab environments that are conducive to international research teams, and the ability to make reliable agreements with international partners.

KEY RECOMMENDATION

Implement structures for hosting strong international collaborations, act with timeliness, consistently meet obligations, and facilitate open communication with partners.

FINDING

The governance of international partnerships on particle physics projects can be broadly characterized as following either the host-led model or the CERN model. The principal distinction between the two models is that the host usually carries the largest responsibility in the host-led model, whereas sharing of responsibility is more distributed in the CERN model. Both models have been successful, and the CERN model is found to work well when the project's degree of financial sharing is high.

BaBar was a highly successful U.S.-hosted international partnership.

DESI is a current example of a successful U.S.-hosted international partnership.

The PIP-II accelerator project has established an effective governance structure for international partnership for accelerator facility construction.

LBNF/DUNE, the first U.S.-hosted international particle physics mega-project, has been launched successfully as a project with broad international participation. Nevertheless, its inception encountered new organizational challenges which offer instructive experience.

RECOMMENDATION

DOE and NSF should convene a task force to study and recommend project management and oversight procedures that facilitate and cultivate international and interagency partnerships on large scientific research infrastructures for particle physics.

FINDING

Partnerships between DOE High Energy Physics and NSF Astronomy have produced pathfinding advances and capabilities in the study of dark matter, dark energy, and inflation.

RECOMMENDATION

Future cosmic survey projects should engage with U.S. agencies to develop a plan for strong strategic international partnerships across all stages of the project lifecycle, including conceptual design and construction, in order to realize next-generation capabilities and scientific opportunities. Plans should include sharing of responsibilities and leadership opportunities with international partners.

FINDING

Being a reliable partner is essential to international collaboration and especially to hosting international partnerships.

RECOMMENDATION:

Discuss and communicate with international partners before making decisions that affect partners. Seek ways to mitigate the impact of necessary U.S. decisions on international partners.

FINDING

The uncertainty of the annual U.S. appropriations process is an impediment to good international partnership, whether the partnership's project is hosted in the U.S. or abroad. Continuity of funding is especially important for U.S.-hosted experiments in both the construction and operations phases because of its importance to international partners.

RECOMMENDATION

Stakeholders in the U.S. executive branch and in Congress should understand the negative consequences—both immediate and long term—of abrupt reductions in funding, including the negative impact on international partners.

FINDING

A welcoming environment is critical for hosting an international experiment or facility.

RECOMMENDATION

U.S. laboratories hosting international experiments should provide an environment that encourages and supports international collaboration.

Chapter 4

Strengthening critical capabilities

KEY FINDING

It is our state-of-the-art expertise in the tools, technology, and techniques of particle physics that makes the U.S. a sought-after partner and gives us the ability to impact future experiments at home and abroad.

KEY RECOMMENDATION

Continuously develop critical technologies to maintain and grow U.S. leadership in particle physics at home and abroad.

FINDING

Theory is a foundational pillar of particle physics, and declining investment threatens U.S. leadership.

RECOMMENDATION

Invest in a strong and innovative theory program.

FINDING

Areas of AS&T (accelerator science and technology) in which the U.S. is identified as a leader and is sought as a partner in accelerator projects outside the U.S. include superconducting magnets, superconducting and normal radio frequency high brightness particle sources, and advanced beam physics, including modeling and techniques of high intensity and brightness beam physics.

RECOMMENDATION

In the AS&T areas in which the U.S. is identified as a leader and a partner of choice, R&D investment should keep pace with the increasing performance demands, technological challenges, and investments in other regions.

FINDING

Funding for AS&T R&D in Europe is growing. Key areas of AS&T in which the U.S. was formerly a leader and in which the U.S. is now falling behind or in which U.S. leadership is now being seriously challenged include 1) collider beam physics, technology, and operation, 2) plasma wakefield acceleration R&D, and 3) fabrication of accelerator components and systems.

RECOMMENDATIONS

Establish a collaborative U.S. national accelerator R&D program on future colliders to coordinate the participation of U.S. accelerator scientists and engineers in global energy frontier collider design studies as well as maturation of technology.

Develop a strategic plan to maintain leadership in plasma wakefield acceleration as needs for R&D facilities evolve and research programs abroad grow.

FINDING
The manufacturing supply chain for key accelerator components and systems is dominated by foreign companies.

RECOMMENDATIONS
Increase the investments in supply chain development for accelerator components and systems in the challenge areas identified by the DOE Office of Accelerator R&D and Production.

Renew investments to revitalize DOE HEP AS&T R&D.

FINDING
U.S. scientists and institutions will be partners of choice and will have the greatest impact in future international experiments hosted at home and abroad if they maintain state-of-the-art expertise in instrumentation.

RECOMMENDATION
DOE HEP and NSF Physics should support an active, continuous program of instrumentation R&D and facilitate the development of instrumentation R&D collaborations at home and abroad.

FINDING
The U.S. is globally recognized as a leader in software and computing for the field of particle physics.

RECOMMENDATION
U.S. particle physics should capitalize on its deep experience as leaders in scientific software and computing development as well as the country's emerging high-performance computing and cloud systems of unprecedented scale. The field should also leverage its potential to create national scale collaborations for software and computing spanning experiments, DOE national laboratories, and universities. Collaborations should leverage computer and data science expertise beyond the field of particle physics.

Advancing national initiatives

KEY FINDING
The national initiatives in artificial intelligence and machine learning, quantum information science, and microelectronics are accelerating new research avenues in particle physics, and particle physics contributions to these initiatives are bringing new ideas and new technologies to a range of disciplines.

KEY RECOMMENDATION
Enhance and leverage the innovative role that particle physics plays in artificial intelligence and machine learning, quantum information science, and microelectronics to advance both particle physics and these national initiatives.

FINDING
Artificial intelligence is impacting every element of the cycle of inquiry in particle physics.

RECOMMENDATION
To retain U.S. leadership in the application of artificial intelligence and machine learning to particle physics, enhance funding in this area as it is an important driver of discovery.

FINDING
Quantum information science is driving innovation in particle physics, which in turn creates new capabilities and new ideas for quantum information science.

RECOMMENDATION
Establish a funding mechanism for a suite of small-scale experiments that have the potential to advance the scientific goals of the U.S. particle physics program to capitalize on the recent investments made in quantum sensing. These small experiments should be at the technical cutting edge of this rapidly progressing international field and world leading. Funding should be timely, recognize the interdisciplinary character of this field, and be sufficient to ensure the rapid, successful completion of these experiments.

FINDING

Application Specific Integrated Circuits (ASICs) are ubiquitous in particle physics, in other scientific disciplines, and in society. ASICs are an essential part of almost every detector technology in particle physics.

RECOMMENDATIONS:

DOE HEP and NSF Physics should regenerate and maintain at a leadership level expertise in microelectronics for particle physics instrumentation. Efforts should include support of both targeted and generic R&D in microelectronics to advance microelectronics applications as well as to maintain expertise and to attract talent. DOE HEP and NSF Division of Physics should exploit synergies with the needs of other parts of the DOE Office of Science and NSF programs.

The agencies and the community should work together to establish a program providing cost-effective access to design licenses and tools and to foundries for national laboratories and universities. Consider a program that extends across the DOE Office of Science and the NSF Directorate for Mathematical and Physical Sciences.

Chapter 5

Building a robust workforce

KEY FINDING

Attracting, inspiring, training, and retaining a diverse workforce is vital to the success of all particle physics endeavors and more broadly to U.S. science and technology. A robust particle physics workforce will both leverage and be representative of the diversity of the nation.

KEY RECOMMENDATION

Explore frontier science using cutting-edge technologies to inspire the public and the next generation of scientists while opening new pathways to diversify the workforce and realize the full potential of the field.

FINDING

The U.S. particle physics program is enriched by international contributions but still suffers from a lack of gender and ethnic diversity, including among students and workers that are U.S. citizens.

RECOMMENDATION

The U.S. particle physics program should strive to attract a diverse community in all senses of that word to secure leadership and innovation. In particular, the U.S. should do more to provide compelling, inclusive, and equitable opportunities for U.S. citizens. Some concrete actions include:

1. Create a program to send national laboratory and university researchers to colleges and universities that do not have particle physics programs to excite students about the field and waiting career opportunities. Include visits to MSIs and small two- and four-year colleges.
2. Increase the number of university joint/bridge faculty positions that DOE funds at the 50% level, with the goal of increasing particle physics positions at MSIs.
3. Significantly increase the numbers of both undergraduate and graduate internships and other longer-term opportunities in particle physics at the national laboratories and universities. Ensure that participation in one program during one year does not preclude participation in another program during another year.
4. Place a high priority on best practices for ensuring the cultural competency of managers at the national laboratories to hire, promote, and retain a diversity of researchers in the particle physics workforce. DOE should continue its commitment to develop and implement best practices in the area of diversity, equity, and inclusion.
5. Collect and report statistics on the particle physics workforce, and track its evolution over time across levels: laboratories, collaborations, and nationwide. The DOE SC Office of Scientific Workforce Diversity,

Equity, and Inclusion should work with the NSF Office of Equity and Civil Rights, as well the leadership of the national laboratories and large collaborations to align categorizations for consistent comparison across different datasets.

FINDING

There are many impediments faced by the U.S.'s international collaborators who come to the U.S. to conduct their research. These barriers hamper the whole research enterprise.

RECOMMENDATION

To lessen the burden on international collaborators, DOE and NSF should coordinate with all relevant stakeholders, including the U.S. Department of State, to reduce the impediments caused by agency compliance, visa delays, and on-site security.

FINDING

Progress in particle physics relies on advances in the state of the art in enabling technologies. Advances in technology rely, in turn, on the ability of particle physics to attract, train, and retain a highly skilled technical workforce.

RECOMMENDATION

Develop a framework to attract, train, and retain a highly skilled technical workforce.

FINDING

The U.S. needs to significantly increase the numbers of U.S. researchers and the country's workforce development capacity in key technologies of particle physics, especially instrumentation, large-scale computing, and particle accelerators.

FINDING

More long-term career opportunities are needed for specialists in instrumentation.

FINDING

The current standard for software and computing training is project-specific on-the-job training. Career path limitations within the field diminish retention rates.

FINDING

Over 50% of the U.S. accelerator science and technology workforce is trained by U.S. universities. Yet, accelerator science and technology training programs are only available at a small fraction of all U.S. universities and have limited overall support.

RECOMMENDATION

Attract, nurture, recognize, and sustain the careers of physicists, engineers, and technicians dedicated to the development of instrumentation, accelerator science and technology, and large-scale computing. Recommended actions include:

1. Conduct a comprehensive study to identify areas of inadequate expertise in the U.S. particle physics workforce, such as instrumentation, accelerators, and large-scale computing.
2. Shore up deficiencies by encouraging more students to pursue those areas of study.
3. Establish more university programs offering degrees in accelerator science and technologies.

FINDING

Too few artificial intelligence/machine learning (AI/ML) and quantum information science (QIS)/quantum sensing students remain in particle physics after receiving their degrees.

RECOMMENDATION

Develop new career frameworks to grow and retain the U.S. AI/ML and QIS/quantum particle physics workforce.

1. Establish new and attractive career frameworks in AI/ML and QIS/quantum sensing, such as allowing those working in particle physics to take sabbaticals in private companies and *vice versa* and enhancing opportunities for particle physics employees to create spin-offs.
2. To compete more effectively with industry in the recruitment and retention of the best talent, national laboratories should provide

opportunities for engineers and technicians to work with scientists on blue sky research and provide the possibility for national laboratory researchers to launch private companies via spin-off technologies.

FINDING

Microelectronics, and ASICs (Application Specific Integrated Circuits) in particular, are ubiquitous in particle physics. In the U.S. particle physics community, there is a shortage of both specialist ASIC design engineers and particle physicists sufficiently knowledgeable in ASIC design to work effectively with ASIC designers and to review systems designed with ASICs. These factors limit U.S. leadership in this crucial area of the field.

RECOMMENDATION

DOE should fund and work with universities to create an enhanced integrated program to train university Ph.D. and Master's students in system design of the experiment and subsystem design of the detector and readout and appropriate implementation and design of ASICs for the detector readout.

FINDING

Frontier large-scale research facilities offer the most comprehensive method of answering fundamental questions while exciting and inspiring a whole new STEM workforce.

RECOMMENDATION

A next-generation international flagship particle physics facility based in the U.S. would attract a whole new generation of scientists while boosting opportunities to train students and sustain a leading scientific workforce. The U.S. should not wait until DUNE is commissioned to embark upon its next major particle physics initiative but should move quickly to intensify its R&D program with the aim of accelerating progress in this direction to enable a timely decision.

Appendix H

Methods for Chapter 3

Collaboration

To investigate the science enabled by partnerships in particle physics, the members of the subpanel worked in three subgroups: 1) Large collaborations and large facilities, 2) Small experiments and small projects, and 3) Accelerators. Each subgroup interviewed members of the particle physics and/or accelerator community. These interviews focused on the questions in the charge to the subpanel, such as the following:

- How can the U.S. particle physics program maintain critical international cooperation in an increasingly competitive environment for both talent and resources?
- In areas where the U.S. is leading, how can we sustain our roles and attract the best international partners?
- In other areas, how can the U.S. build and maintain its reputation as a "partner of choice"?
- In general, are there barriers that can hinder our ability to form effective and enduring international partnerships?

Both U.S. leaders and non-U.S. leaders were interviewed, and the consultations included interviews with leaders from both U.S.-hosted experiments and accelerator projects and experiments and accelerator projects hosted abroad. Semi-structured interviews were conducted starting from similar lists of questions tailored to whether the experiment or accelerator project was hosted at home or abroad and whether the interviewee was a U.S. or non-U.S. scientist. Interviews were typically about one hour in length. Most were conducted via Zoom with two or three subpanel members present, and a small number were conducted in person. A sample standard pair of lists of questions concerning experiments is included below, *i.e.*, the lists used for U.S. leaders and international leaders of U.S.-hosted experiments as well as the list of topics discussed regarding accelerator projects. The subpanel interviews were supplemented by additional consultations via email with leaders of a suite of both present and recent experiments and facilities of a variety of sizes. Initial consultations via email with a given experiment usually started with the same list of questions as used for in-person or Zoom interviews. Interviews and/or consultations were conducted with approximately 35 experiments and facilities, with additional interviews being conducted for some of the largest present experiments: ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid), and LBNF/DUNE (Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment). Most interviews were conducted during the second half of 2022. The report also draws upon the first-hand experience of the subpanel members.

The experiments and facilities consulted were:

- CERN (European Laboratory for Particle Physics Research): ATLAS, CMS, and LHCb (Large Hadron Collider beauty);
- China: Daya Bay;
- Italy: XENON-nT (Direct Search for Dark Matter with Liquid Xenon Deep Underground);
- Japan: Belle (experiment at KEKB electron-positron collider) and Belle II (experiment at SuperKEKB electron-positron collider), K0TO (an experiment at J-PARC,

Japan Proton Accelerator Research Complex, to measure a rare decay of the neutral long-lived kaon subatomic particle to a neutral pion — a neutrino and an anti-neutrino — to search for new physics beyond the standard model), nEXO (next Enriched Xenon Observatory), Super-Kamiokande (Super-Kamiokande Neutrino Detection Experiment), T2K (Tokai-to-Kamiokande experiment), Hyper-Kamiokande (Hyper-Kamiokande Neutrino Detection Experiment), and GADZOOKS! (Gadolinium Antineutrino Detector Zealously Outperform Old Kamiokande Super!); and

- U.S.: ADMX (Axion Dark Matter Experiment), *BaBar*, CCM (Coherent CAPTAIN Mills), CMB-S4 (Cosmic Microwave Background-Stage 4), COHERENT (A collaboration at Oak Ridge National Laboratory Spallation Neutron Source aiming to make a first direct measurement of CEvNS, coherent elastic neutrino-nucleus scattering), DESI (Dark Energy Spectroscopic Instrument), DM Radio (Dark Matter Radio), D0 (an international collaboration that conducted experiments at Fermilab's Tevatron), LNBF/DUNE (Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment), IsoDAR (Isotope Decay-At-Rest), LDMX (Light Dark Matter Experiment), LZ (LUX-ZEPLIN experiment), Muon g-2, MINERvA (Main Injector Neutrino ExpeRiment to study v-A interactions), Mu2e (Muon-to-Electron experiment), OSCURA (Observatory of Skipper CCDs, Charged Coupled Devices, Unveiling Recoiling Atoms), Project-8 (a neutrino mass experiment), Vera C. Rubin Observatory (Rubin) and DESC (Dark Energy Science Collaboration), and TESSERACT (Transition Edge Sensors with Sub-EV Resolution And Cryogenic Target).

The accelerators consulted were:

- CERN: LHC and HL-LHC (High-Luminosity LHC);
- Germany: HERA (Hadron-Electron Ring Accelerator); and
- U.S.: EIC (Electron-Ion Collider), PIP-II (Proton Improvement Plan-II), and RHIC (Relativistic Heavy Ion Collider).

Sample list of questions for U.S.-hosted experiments

Questions for U.S. leaders:

- In what areas did you seek international participation? Why these areas?
- To what areas were international contributions key or critical? (consider construction, operation, physics analysis, collaboration leadership)
- Generally speaking, were international construction contributions spread widely or did they concentrate in particular areas. Did international partners take responsibility for, or the lead on, entire detector systems? If so, did these tend to group along national lines?
- How is physics analysis organized within your experiment, *e.g.*, by physics topic or along national lines? Are international contributions to physics analysis clustered in certain areas or are they spread widely? Do international scientists tend to work together in groups or are analysis teams quite international?
- Did you perceive obstacles that constrained the degree or quality of international participation, either generally or in nation-specific ways?
- How is your experiment governed, and how did your governance model affect (*i.e.*, facilitate or hinder) international participation?

- Do you feel that you were successful in engaging international partners? What were shortcomings, if any?
- If you were to approach the issue of international participation again, what would you do differently?

Questions for international leaders:

- To what areas were your (and other) international contributions key or critical?
- Generally speaking, were international construction contributions spread widely or did they concentrate in particular areas. Did international partners take responsibility for, or the lead on, entire detector systems? If so, did these tend to group along national lines?
- How is physics analysis organized within your experiment, *e.g.*, by physics topic or along national lines? Are international contributions to physics analysis clustered in certain areas or are they spread widely? Do international scientists tend to work together in groups or are analysis teams quite international?
- Were you (and other international collaborators) able to contribute in the fashion and to the degree that you sought?
- How did the experiment's governance model affect (*i.e.*, facilitate or hinder) international participation?
- What were the obstacles to better collaboration?

Sample list of topics concerning international partnership discussed with leaders of large-scale accelerator facility projects

- Their experience in forming international partnerships. What do these leaders look for?
- Their experience and input of the U.S. as a partner for a non-U.S. hosted facility/project.
- Their experience and input of the U.S. as a host working with international partners.

Appendix I

Methods for Chapter 4

Enabling Capabilities and Technologies

To "identify key areas where the U.S. currently has, or could aspire to, leadership roles" in particle physics, as requested in its charge, the subpanel formed a working group to study 1) particle theory, 2) accelerator science and technology, 3) instrumentation development, 4) software and computing, 5) artificial intelligence and machine learning, 6) quantum information science, and 7) microelectronics. The working group considered advanced facilities, resources, infrastructure, and highly trained personnel. Particular consideration was given to "recruiting, training, mentoring, and retaining the best talent from all over the world, including among traditionally underrepresented groups within the U.S." Some workforce results were incorporated into Chapter 5. Given the charge, the working group also considered how to leverage U.S. capabilities through international collaboration.

The working group's study included consultations with U.S. and international experts in the subject areas above. It also included surveys of larger numbers of experts via email. For the topics in accelerator science and technology, the Snowmass summary report of the Accelerator Frontier[54] was studied by the working group. The GARD (General Accelerator R&D) program manager and ARDAP (Office of Accelerator R&D And Production) program director were also interviewed. The working group additionally interacted closely with subject matter experts as the draft of the report was developed. Where appropriate, the study also drew from the interviews of leaders of experiments conducted by the subpanel's working group studying collaboration on experiments, facilities, and accelerators (see Appendix H).

Sample questions for U.S. experts

In consulting and discussing with experts, the charge was shared, and the working group considered questions for each of the subject areas above. Example questions for instrumentation asked of U.S. experts are listed below:

- How is the instrumentation community organized in the U.S.?
- How is the instrumentation community funded in the U.S., and what is the balance between blue sky/proof-of-principle/strategic/project instrumentation research?
- What are the U.S. strengths in instrumentation?
- What are the international strengths in instrumentation?
- What are examples of international collaboration on instrumentation within and outside projects? What are the U.S. and international collaborator roles, and are there areas where U.S. contributions are key, critical, or unique?
- Are there barriers to international collaboration?
- Is the U.S. instrumentation community healthy? What is the derivative? What would you change if you could?
- Is the international instrumentation community healthy? What is the derivative? What would you change if you could? (answer for selected countries or regions, *e.g.*, Europe, with which you are familiar).

- Given your answers to the last two questions, can you compare and contrast the U.S. instrumentation community to the international instrumentation community (pick selected countries or regions, *e.g.*, Europe, with which you are familiar.) Do the derivatives differ, and if so, how and why?

Corresponding questions were asked to colleagues from the international community.

Survey questions to the U.S. theory community

The questions used to survey the American Physical Society Division of Particles and Fields (DPF) particle theory leadership and DPF Snowmass conveners (a combined group that numbered about 12) in the period late 2022 to early 2023 were:

- Describe how the U.S. community is funded for particle theory.
- What do you perceive as the U.S. strengths/weaknesses in particle theory?
- Which other countries/regions have strengths in particle theory, and what strengths do they have?
- Is the U.S. particle theory community healthy? What is the derivative? What would you change if you could?
- How would you compare and contrast the U.S. theory community to the international theory community (choose selected countries or regions that you are familiar with). Do the derivatives in involvement and strength differ? If so, how and why? Are there generally accepted benchmarks for assessing the impact and relative strength of particle theory efforts?
- How do you collaborate with other theorists? Do you perceive differences/challenges in collaborating with other theorists in the U.S. and outside the U.S.?
- How do you collaborate with experimentalists? Do you perceive differences in collaborating with experimentalists in the U.S. and outside the U.S.? What could be improved?
- Please provide any concluding thoughts you wish to share.

Survey questions to the U.S. accelerator community

The survey questions sent out to the representatives in DOE (Department of Energy) HEP (Office of High Energy Physics) GARD programs as well as universities were:

- Are the current R&D topics well suited for addressing the needs of HEP missions? In what areas of accelerator science and technology does the U.S. have the leadership and continue to be the key partner in large-scale projects?
- What areas in the accelerator field does the U.S. no longer hold its leadership? Are there areas that the U.S. should strategically focus on?
- In comparison to European accelerator R&D, where are the strengths and weaknesses of the U.S. accelerator R&D program? How do the programs compare in terms of scope, how cross-cutting topics are supported, the level of support, *etc.*? Should the U.S. only focus on the accelerator R&D topics that neither Europe nor Asia would like to fund?
- Should the U.S. still consider hosting or being the key partner of the next energy frontier collider (Higgs factory)? What about the next-to-next collider (10-TeV scale)? If so, are there areas in accelerator R&D that should be added to the current GARD portfolio?

Appendix J

Methods for Chapter 5

To analyze the composition and status of the U.S. particle physics workforce, a large quantity of data was collected from AIP[55] (American Institute of Physics), NSF[56] (National Science Foundation), U.S. national laboratories (BNL[57], Brookhaven National Laboratory; FNAL/Fermilab[58], Fermi National Accelerator Laboratory, LBNL[59], Lawrence Berkeley National Laboratory; and SLAC[60], SLAC National Accelerator Laboratory), international research collaborations (ATLAS[61], A Toroidal LHC ApparatuS; CMS[62], Compact Muon Solenoid; and DUNE[63], Deep Underground Neutrino Experiment), and foreign organizations (IOP[64], Institute of Physics; and DESY[65], Deutsches Elektronen-Synchrotron). The categories of requested data included 1) gender, 2) ethnicity, 3) citizenship (U.S. and non-U.S.), 4) Ph.D.s received for students based at the national laboratories, 5) undergraduate and graduate internships, and 6) faculty visitors at the national laboratories. For the AIP and NSF, data were requested for the number of Ph.D.s awarded for the various demographics. For the national laboratories, data were reported in various ways. For example, some national laboratories only collect binary gender information (male or female).

Workforce data regarding U.S. accelerator science and technology were gathered from 1) an ad hoc survey hosted by Cornell University[66], 2) BELLA[67] (Berkeley Lab Laser Accelerator), AWA[68] (Argonne Wakefield Accelerator), and FACET[69] (Facility for Advanced Accelerator Experimental Tests), and 3) several DOE national laboratories (BNL[70], FNAL[71], SLAC[72], and TJNAF[73], Thomas Jefferson National Accelerator Facility).

A number of interviews fed into the Findings and Recommendations found in Chapter 5. These included the top administrators from Accelerator R&D at DOE (Department of Energy), HL-LHC (High-Luminosity LHC) at CERN (European Laboratory for Particle Physics Research), EIC (Electron-Ion Collider) at BNL, DUNE at Fermilab, and DUNE-UK. Information from the Head of DUNE-UK highlighted the visa and other difficulties that hinder collaborations with the U.S. In addition, information gathered for Chapter 4 (see Appendix I) that addressed “recruiting, training, mentoring, and retaining the best talent from all over the world, including among traditionally underrepresented groups within the U.S.” was used to support findings and recommendations related to the workforce for enabling technologies.

Sample workforce interview questions

- Are you satisfied that you are attracting the best international talent? Explain.
- What impediments, such as visa issues, hamper the involvement of international collaborators?
- To what extent are African Americans, Latino Americans, Native Americans, and Pacific Islanders involved in your particle physics program?

Appendix K

Workforce Data

Table 1

FNAL Internships

UNDERGRADUATE

SIST (Summer Internships in Science and Technology)
FEMI (Fermilab Environmental Management Internship)
LBNF/DUNE in South Dakota FSCF (Far Site Conventional Facilities) Internship
Helen Edwards Summer Internship
CCI (Community College Internship)
SULI (Science Undergraduate Laboratory Internship)
VFP-Student (Visiting Faculty Program-Student)
QCIPU (Quantum Computing Internship for Physics Undergraduate) Program
SQMS (Superconducting Quantum Materials and Systems Center) Undergraduate Internship
VetTech (military veteran) Internship Program
VALOR (Veteran Applied Laboratory Occupational Retraining) Program
U.S. CMS (Compact Muon Solenoid) Undergraduate Internship

GRADUATE

FCSI (Fermilab Computational Science Internship)
NSF Mathematical Sciences Graduate Internship
Italian Student Program

FNAL Fellowships

UNDERGRADUATE

ASPIRE (Accelerator Science Program to Increase Representation in Engineering)
Lee Teng
Undergraduate Cooperative Education Program

GRADUATE

CSGF (Computational Science Graduate Fellowship)
SCGSR (Office of Science Graduate Student Research) Program
GEM (Graduate Fellowships for Minorities in Engineering and Science)

NOT LISTED ON INTERNSHIPS SITE - FOR UNDERGRADUATE VISITORS

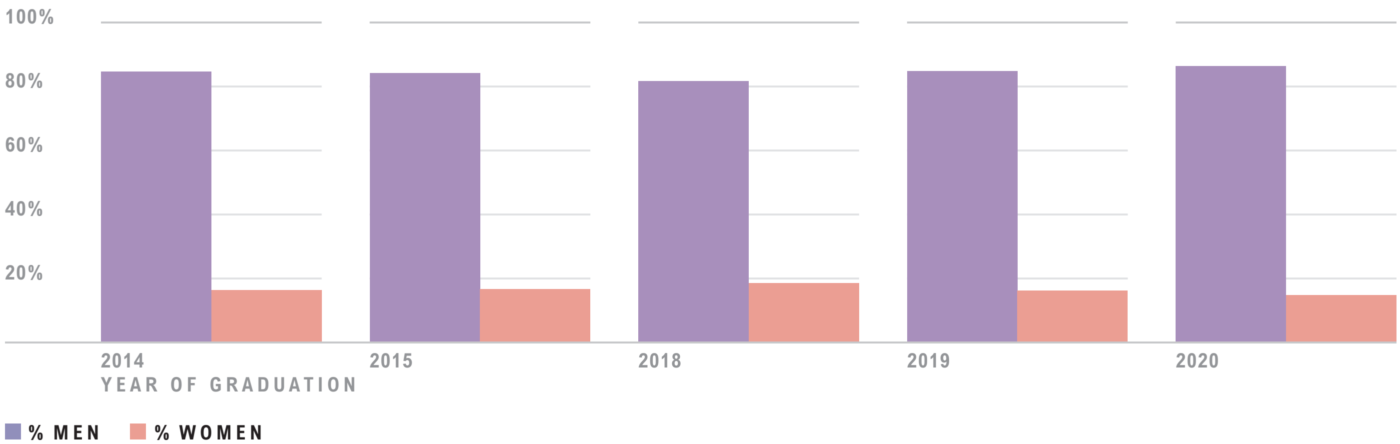
University of Chicago Metcalf, Odyssey, and Provost Scholars
DOE Omni Technology Alliance
OQI (Open Quantum Initiative) Fellowship

Not included: Gates Fellowship, Parker Fellowship, Wilson Fellow, Lederman Fellow, Peoples Fellow, Neutrino Physics Center Fellowship, Bardeen Engineering Leadership Program

Figure 1

AIP: Gender distribution of Ph.D. graduates in particle physics

	2014	2015	2018	2019	2020
Total Ph.D.s	289	295	309	257	206
Men	244	247	252	216	177
Women	45	48	57	41	29



The fractions of male (purple bars) and female (orange bars) Ph.D. graduates in particle physics by year (2014, 2015, 2018, 2019, and 2020) are given on the y-axis. Total counts of Ph.D.s given by gender and year are listed above. Data were obtained from the AIP.+

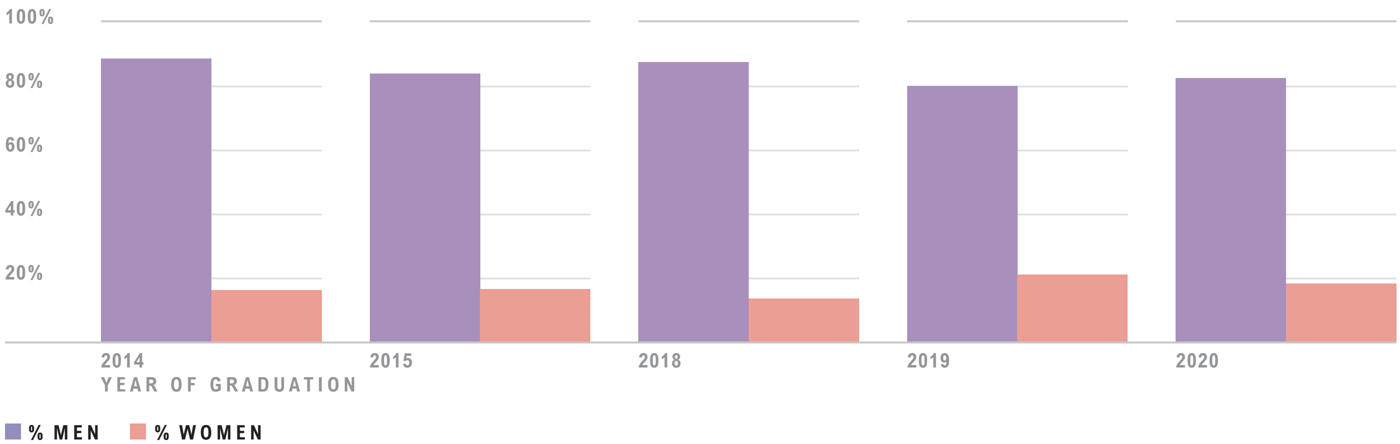
+Class of 2021 data were not yet available from AIP.

AIP collects binary gender data (male and female) only.

Figure 2

NSF: Gender distribution of Ph.D. graduates in particle physics

Total Ph.D.s	245	243	232	234	198
Men	215	203	201	186	162
Women	30	40	31	48	36



The fractions of male (purple bars) and female (orange bars) Ph.D. graduates in particle physics by year (2014, 2015, 2018, 2019, and 2020) are given on the y-axis. Total counts of Ph.D.s given by gender and year are listed above. Data were obtained from the NSF.+

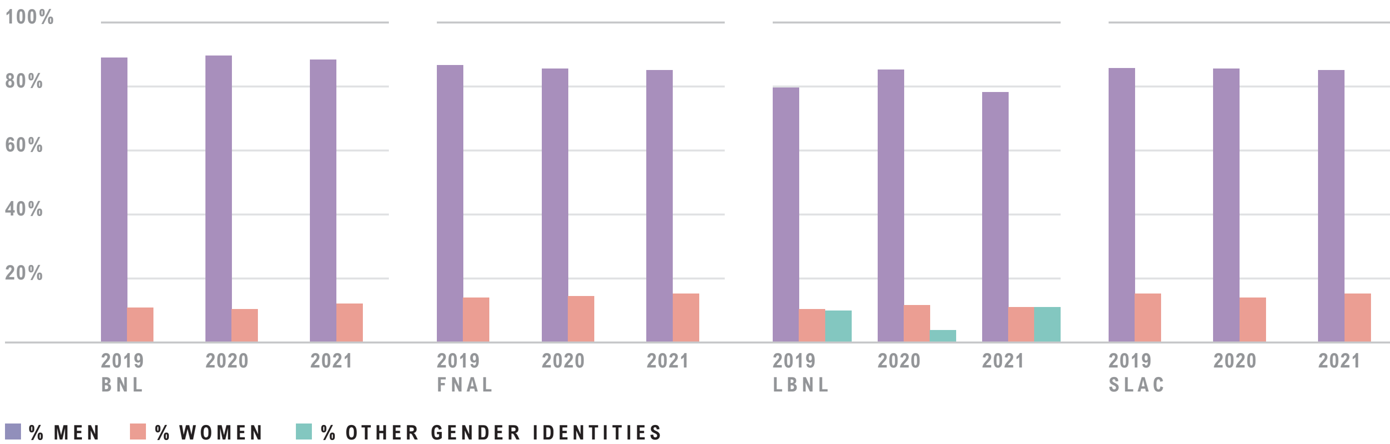
+Class of 2021 data were not available yet from NSF.

NSF data do not include a category for other gender identities.

Figure 3

DOE national laboratories: Gender distribution of particle physics staff

	BNL			FNAL			LBNL			SLAC		
Total staff size	147	151	159	837	867	897	201	213	233	187	162	165
Men	131	135	140	721	740	760	160	181	182	159	138	140
Women	16	16	19	116	127	137	21	24	26	28	24	25
Other gender identities	0	0	0	Data not available			20	8	25	0	0	0



The fractions of male (purple bars) and female (orange bars) particle physics staff at BNL,+ FNAL,† LBNL,‡ and SLAC‡ for the years 2019–2021 are given on the y-axis. Where data are available, the fractions of particle physics staff identifying as other gender identities (green bars) are shown. Total particle physics staff size by DOE national laboratory, year, and gender are given above.

+BNL staff: Scientific, Professional, Technicians, and Postdocs.

†FNAL research staff: Scientists, Postdocs, Engineers, Technicians.

‡LBNL research staff: Scientists, Engineers, Technicians.

‡SLAC and Stanford University faculty and staff identified as ≥0.5 full-time employed (FTE) on HEP funds: Scientists, Engineers, Postdocs and Technicians.

Figure 4

DESY: Gender distribution of particle physics staff

Total staff size	164.1	171.1	171.8
Men	124.8	131.1	130.2
Women	39.3	40.0	41.6

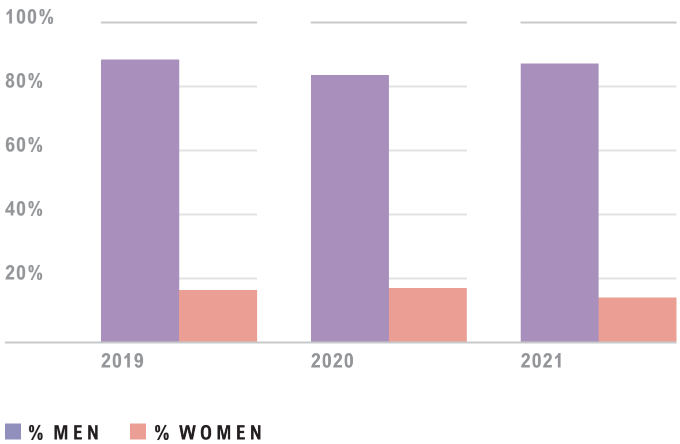


Figure 4: The fractions of male (purple bars) and female (orange bars) particle physics staff at DESY⁺ for the years 2019–2021 are given on the y-axis. Total particle physics staff counts by gender and year are listed above. DESY counts fractions of positions for part-time staff.

⁺DESY research staff include scientists with limited AND unlimited contracts.

No data were available for other gender identifications.

Figure 5

IOP: Gender distribution of the High Energy Physics Special Interest Group

Total staff size	860
Men	671
Women	181
Other gender identities	8

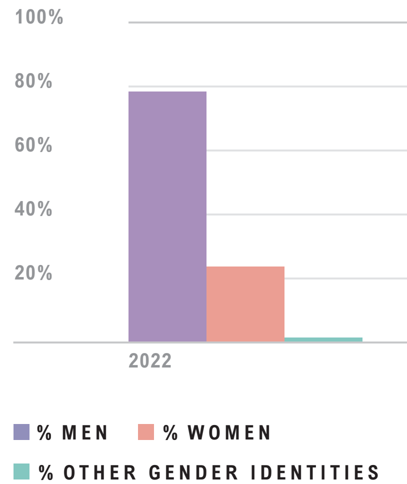
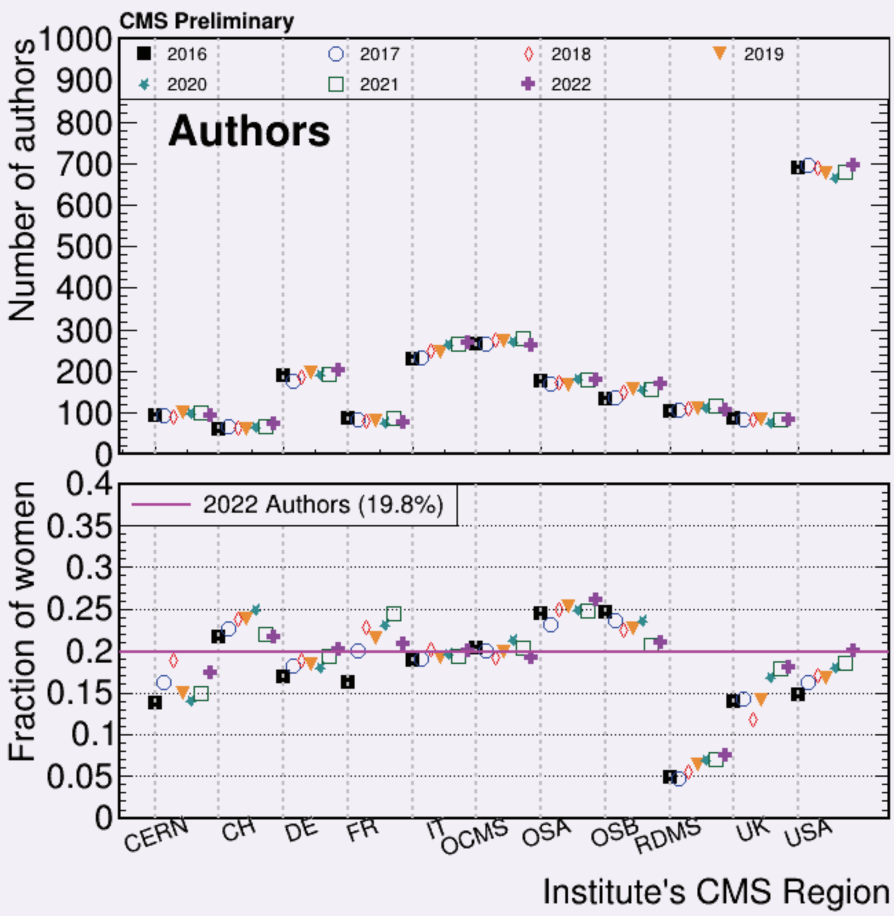


Figure 5: The fractions of the members of the IOP particle physics special interest group identifying as male (purple bar), female (orange bar), or Other gender identities/Unknown (green bar) in 2022 are given on the y-axis. Total counts are listed above.

Figure 6

CMS authors by region



CMS⁺ evolution of the number of authors (top) and fraction of women (bottom) from 2016–2022 by region.

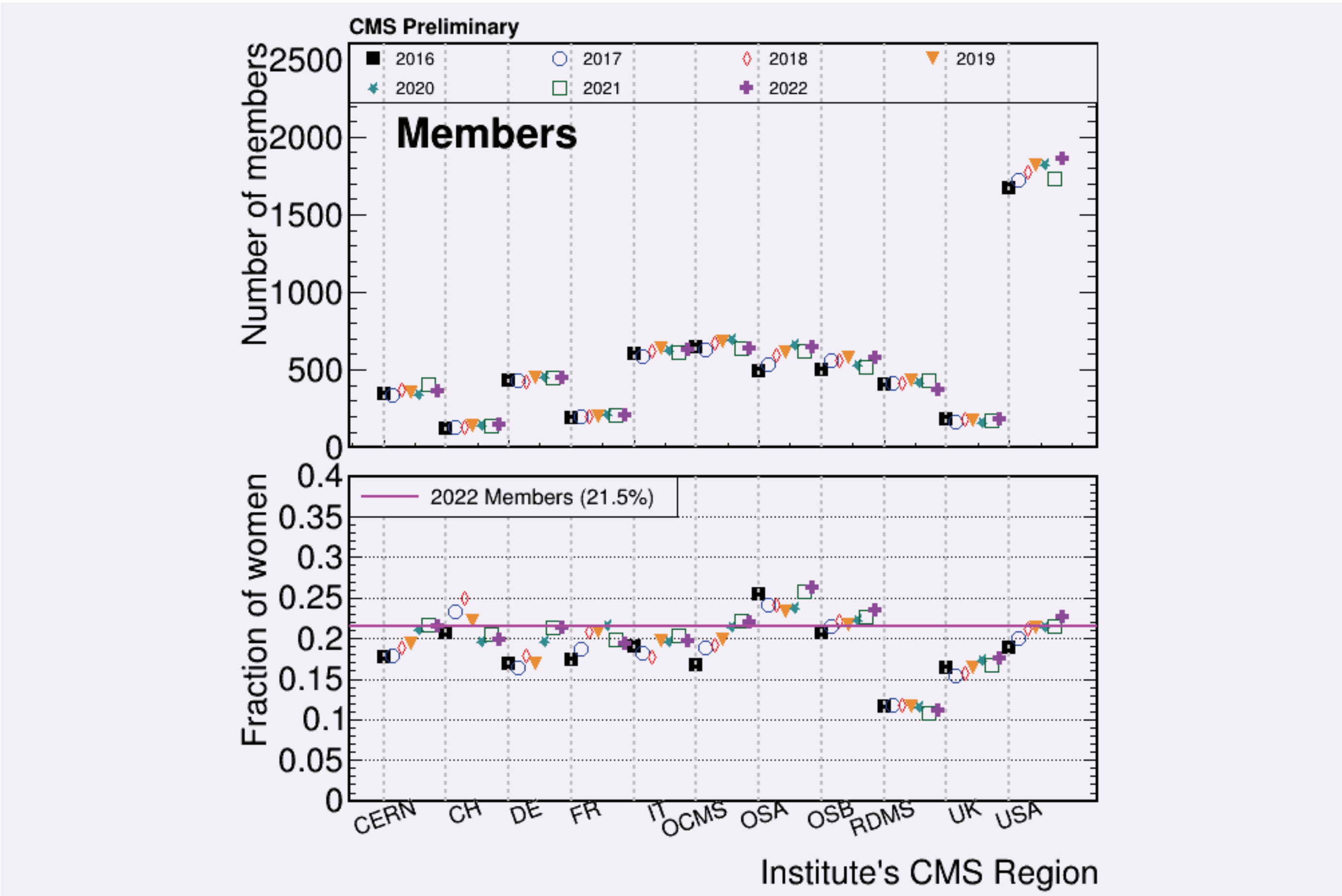
⁺Region: CERN; Switzerland (CH); Germany (DE); France (FR); Italy (IT); Other CERN member states (OCMS): Austria, Belgium, Bulgaria, Finland, Greece, Hungary, Norway, Poland, Portugal, Serbia, Spain; Other States A (OSA): China, India, Iran, Korea, Malaysia, New Zealand, Pakistan, Sri Lanka, Taiwan, Thailand; Other States B (OSB): Bahrain, Brazil, Colombia, Croatia, Cyprus, Ecuador, Egypt, Estonia, Ireland, Kuwait, Lebanon, Lithuania, Mexico, Montenegro, Oman, Qatar, Saudi Arabia, Turkey, Ukraine; Russia and Dubna member states (RDMS): Armenia, Belarus, Czechia, Georgia, Russia, Uzbekistan; United Kingdom (UK); United States of America (USA).

Figures obtained from: CMS Collaboration. “Approved Plots for Diversity and Inclusion Statistics (August 2023).” CERN (2023). Accessed 25 October 2023.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Public_plots_Aug2023.

Figure 7

CMS members by region



CMS+ evolution of the number of members (top) and fraction of women (bottom) by region from 2016–2022.

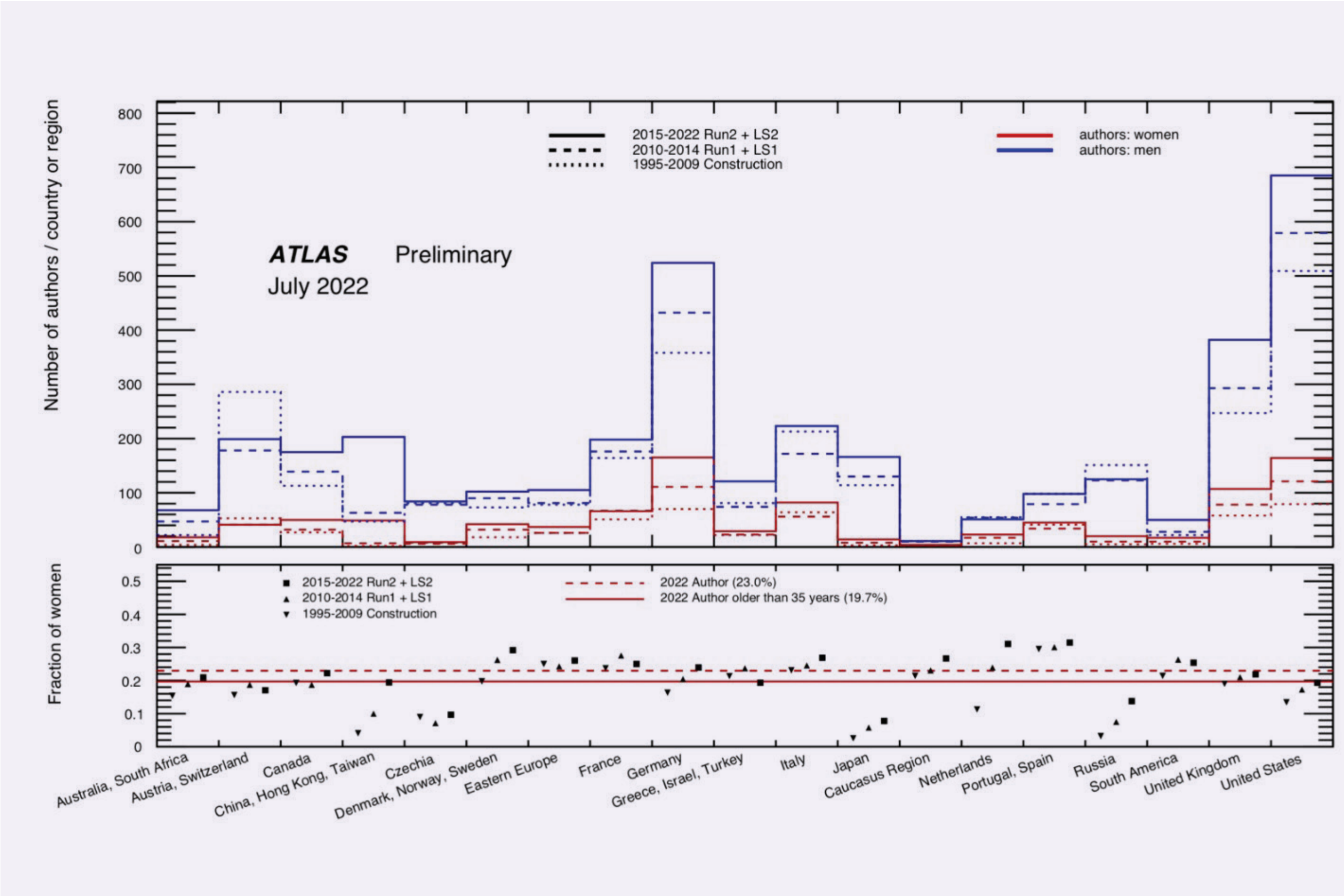
+Region: CERN; Switzerland (CH); Germany (DE); France (FR); Italy (IT); Other CERN member states (OCMS): Austria, Belgium, Bulgaria, Finland, Greece, Hungary, Norway, Poland, Portugal, Serbia, Spain; Other States A (OSA): China, India, Iran, Korea, Malaysia, New Zealand, Pakistan, Sri Lanka, Taiwan, Thailand; Other States B (OSB): Bahrain, Brazil, Colombia, Croatia, Cyprus, Ecuador, Egypt, Estonia, Ireland, Kuwait, Lebanon, Lithuania, Mexico, Montenegro, Oman, Qatar, Saudi Arabia, Turkey, Ukraine; Russia and Dubna member states (RDMS): Armenia, Belarus, Czechia, Georgia, Russia, Uzbekistan; United Kingdom (UK); United States of America (USA).

Figures obtained from: CMS Collaboration. "Approved Plots for Diversity and Inclusion Statistics (August 2023)." CERN (2023). Accessed 25 October 2023.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Public_plots_Aug2023.

Figure 8

ATLAS authors by country



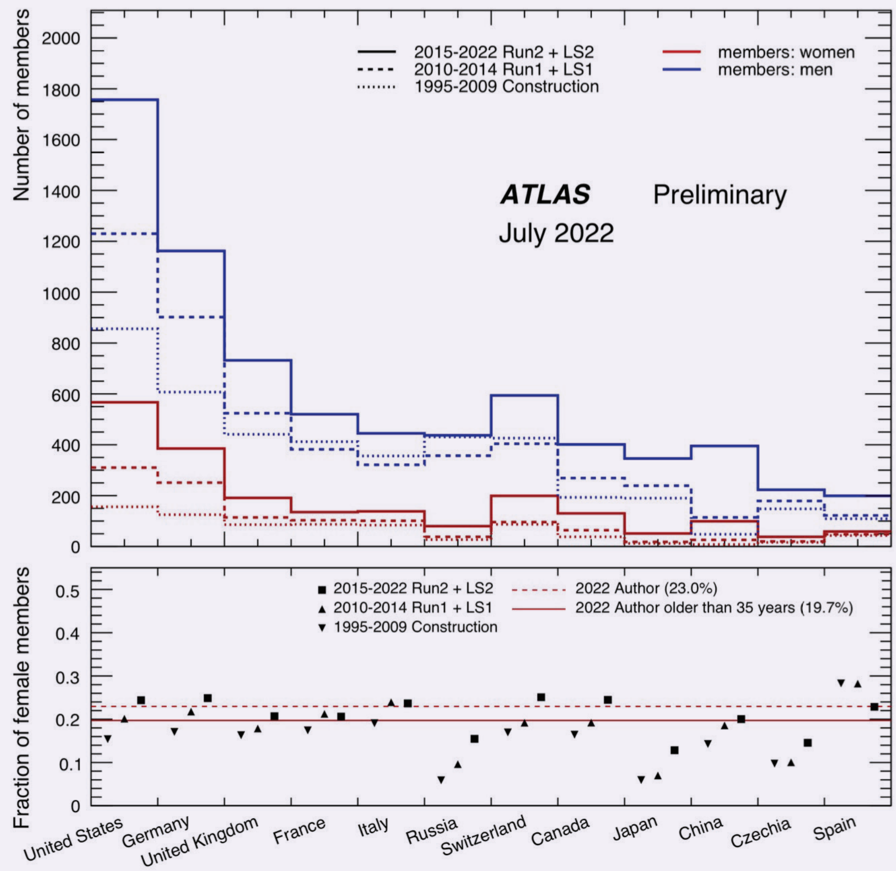
ATLAS number of authors (top) by country or region and fraction of female authors (bottom).

Figures obtained from: ATLAS Collaboration. Studies related to gender and geographic diversity in the ATLAS Collaboration. ATLAS Experiment (2022). Accessed 25 October 2023.

https://cds.cern.ch/record/2202392

Figure 9

ATLAS members by country



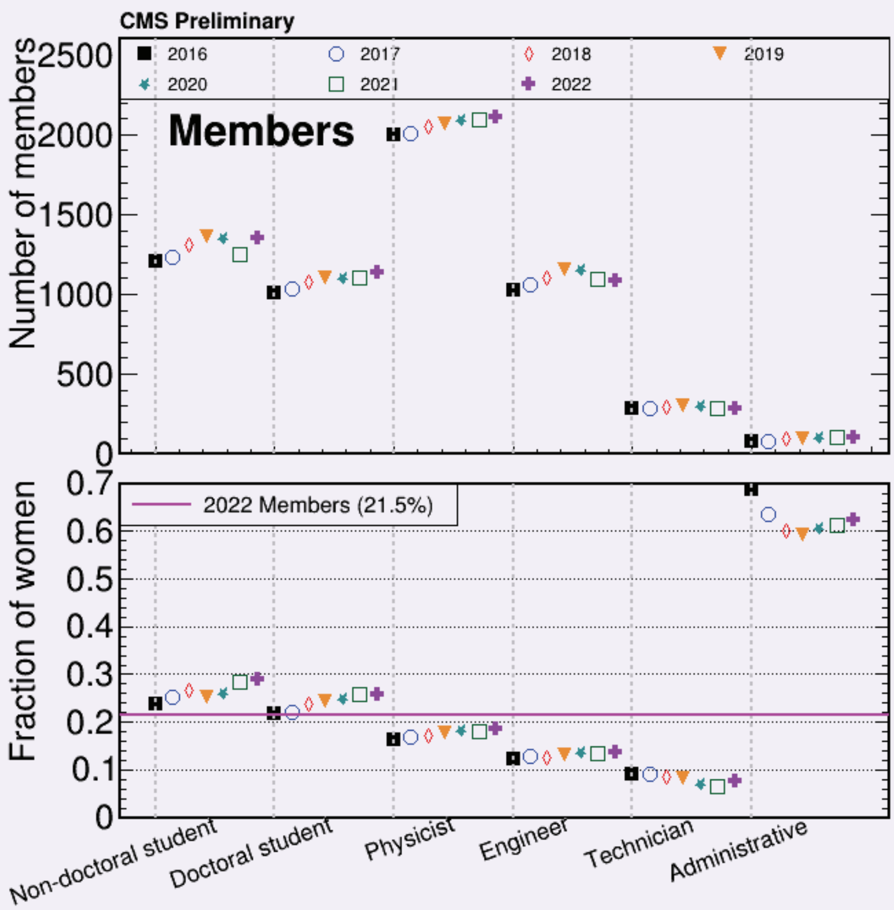
ATLAS number of members by country (top) and fraction of female members (bottom).

Figures obtained from: ATLAS Collaboration. Studies related to gender and geographic diversity in the ATLAS Collaboration. ATLAS Experiment (2022). Accessed 25 October 2023.

https://cds.cern.ch/record/2202392

Figure 10

CMS members by profession



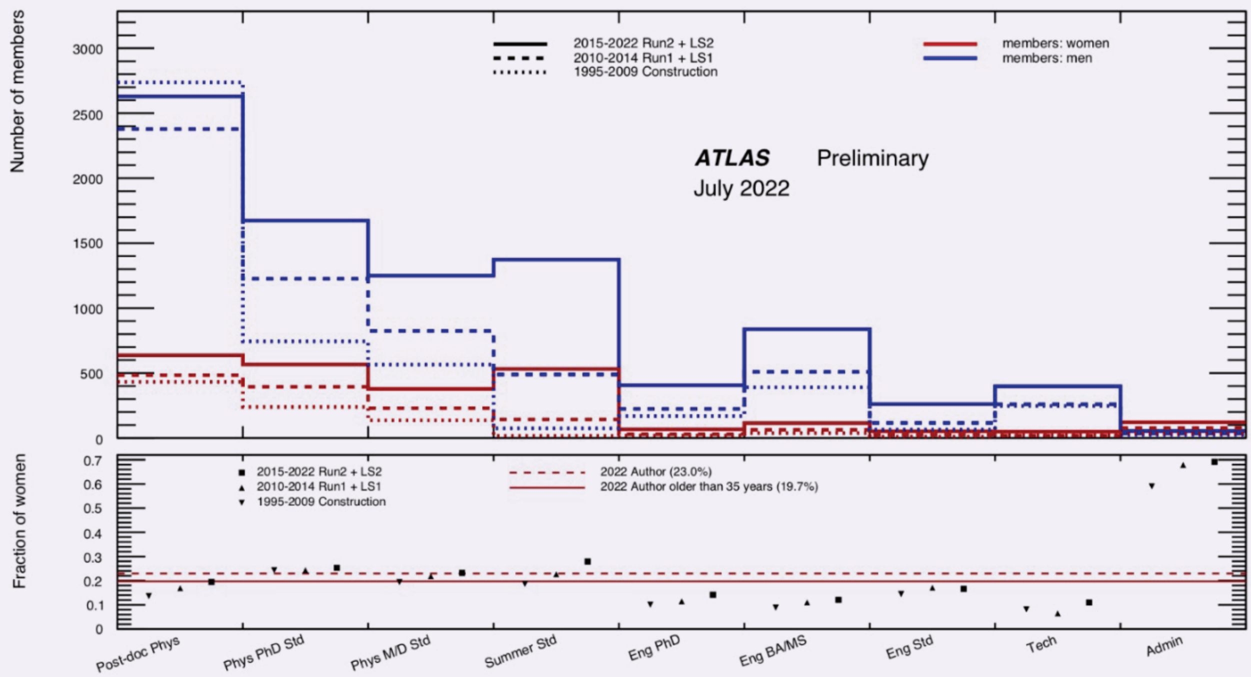
CMS evolution of the number of members (top) and fraction of women (bottom) as a function of professional category from 2016–2022.

Figures obtained from: CMS Collaboration. "Approved Plots for Diversity and Inclusion Statistics (August 2023)." CERN (2023). Accessed 25 October 2023.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Public_plots_Aug2023.

Figure 11

ATLAS members by profession



ATLAS number of members (top) by professional category and fraction of women (lower).

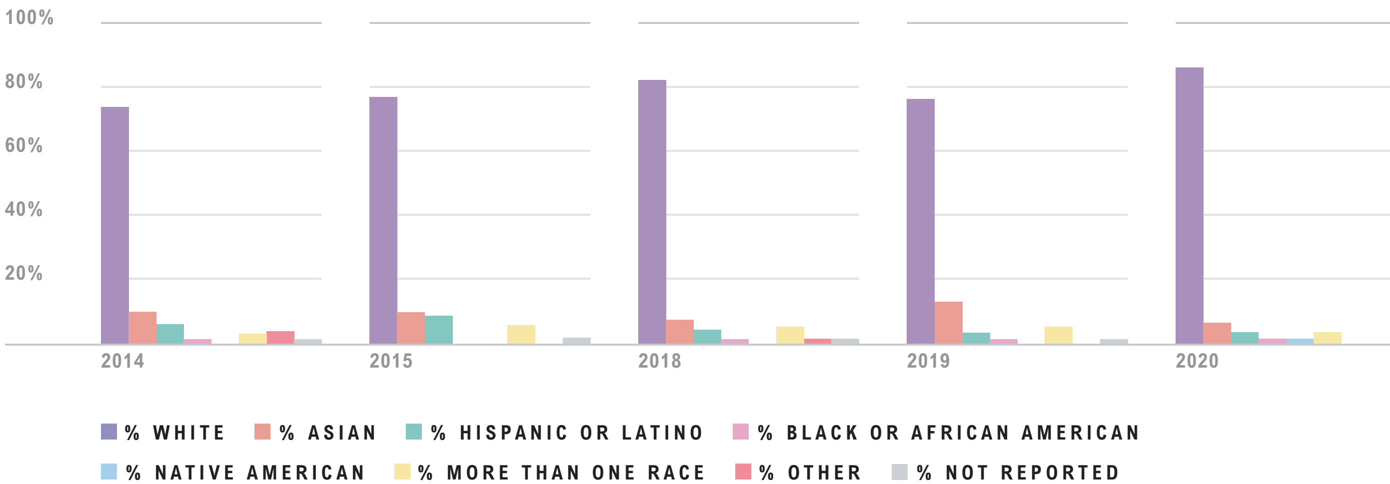
Figures obtained from: ATLAS Collaboration. Studies related to gender and geographic diversity in the ATLAS Collaboration. ATLAS Experiment (2022). Accessed 25 October 2023.

https://cds.cern.ch/record/2202392

Figure 12

NSF: Ethnicity distribution of Ph.D. graduates in particle physics

	2014	2015	2018	2019	2020
White	104	119	113	92	93
Asian	14	14	10	15	7
Hispanic or Latino	9	12	5	4	3
Black or African American	2	0	1	1	1
Native American	0	0	0	0	1
More than one race	4	7	7	6	3
Other	5	0	1	0	0
Not reported	1	2	1	1	0



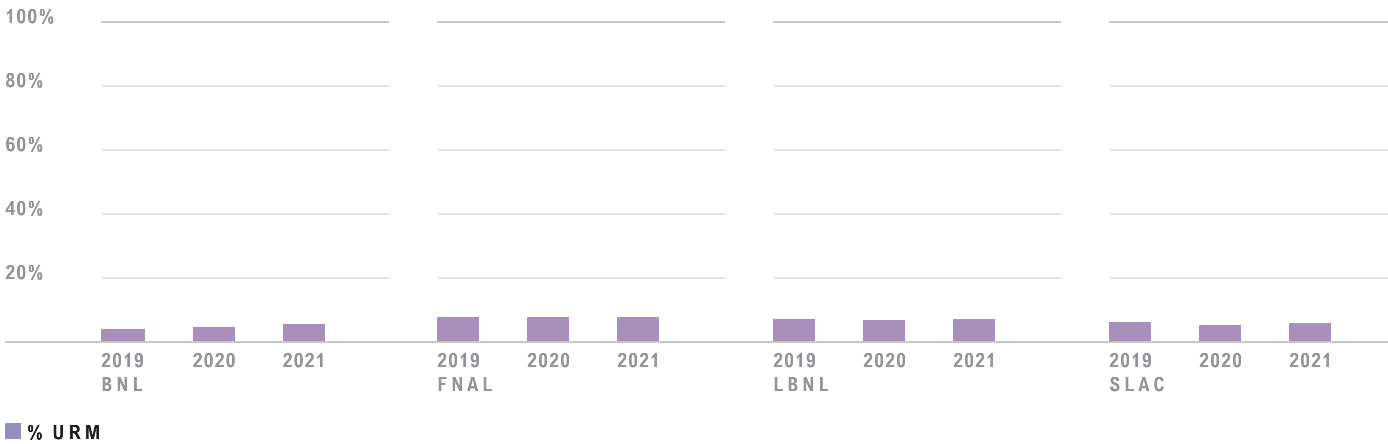
The fractions of Ph.D. graduates in particle physics by ethnicity (% White-purple, % Asian-orange, % Hispanic or Latino-green, % Black or African American-pink, % Native American-blue, % More than one race-yellow, % Other-red, and % Not reported-grey) for each year (2014, 2015, 2018, 2019, and 2020) are given on the y-axis. Total counts of Ph.D.s given by ethnicity and year are listed above. Data were obtained from the NSF.+

+Class of 2021 data were not available yet from NSF.

Figure 13

DOE national laboratories: URM distribution of particle physics staff

	BNL			FNAL			LBNL			SLAC		
Total staff	147	151	159	837	867	897	201	213	233	187	162	165
URMs	7	8	10	69	71	72	15	15	18	12	9	10



The fractions of particle physics staff that are URMs (purple bars) at BNL,[+] FNAL,[†] LBNL,[‡] and SLAC[*] for the years 2019–2021 are given on the y-axis. Total particle physics staff size by DOE national laboratory and year are given above.

[+]BNL staff: Scientific, Professional, Technicians, and Postdocs.

URMs: Hispanic or Black

[†]FNAL research staff: Scientists, Postdocs, Engineers, Technicians.

URMs: Data requested for African American/Black, Native American, Hispanic/Latinx, Pacific Islanders.

[‡]LBNL staff: Scientists, Engineers, Technicians.

URMs: African American/Black, Native American/Alaskan Native, Hispanic/Latinx. There may be a significant percentage who decline to state ethnicity.

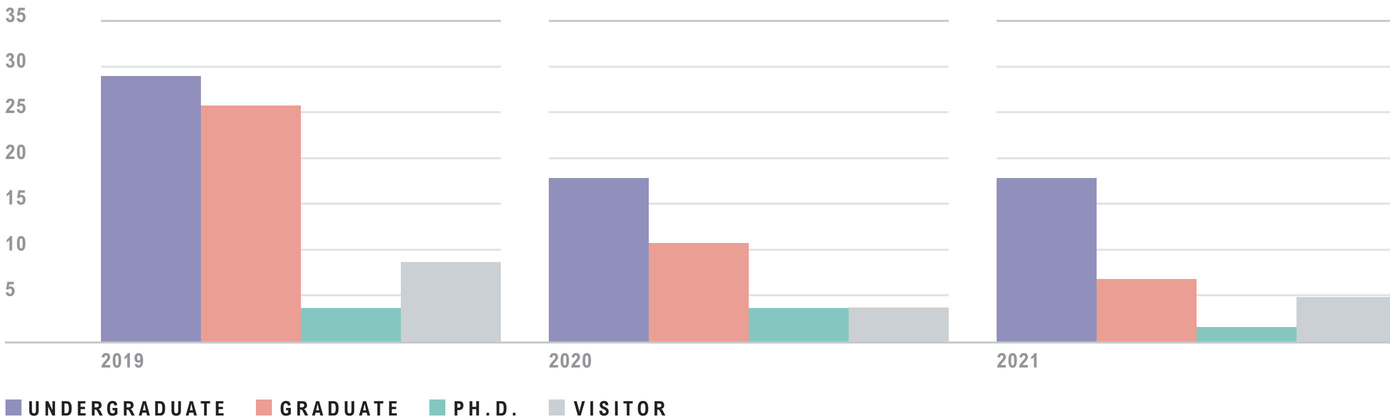
[*]SLAC and Stanford University faculty and staff identified as ≥0.5 FTE (full-time employed) on HEP funds: Scientists, Engineers, Postdocs and Technicians.

URMs: African-, Latino-, Native-Americans, and Pacific Islanders

Figure 14

BNL: Non-staff particle physics workforce counts

Total non-staff workforce	68	37	32
Undergraduate	29	18	18
Graduate	26	11	7
Ph.D.	4	4	2
Visitor	9	4	5



Non-staff particle physics workforce counts for undergraduate (purple bars), graduate (orange bars), Ph.D. (green bars), or visitor (grey bars) demographic groups at BNL[+] for the years 2019–2021 are given on the y-axis and above.

[+]BNL undergraduate students: those student interns from SULI, the African School for Physics, and other programs.

BNL graduate students: those students that BNL hosted for extended periods of time, supported financially, or for which BNL played advisory roles.

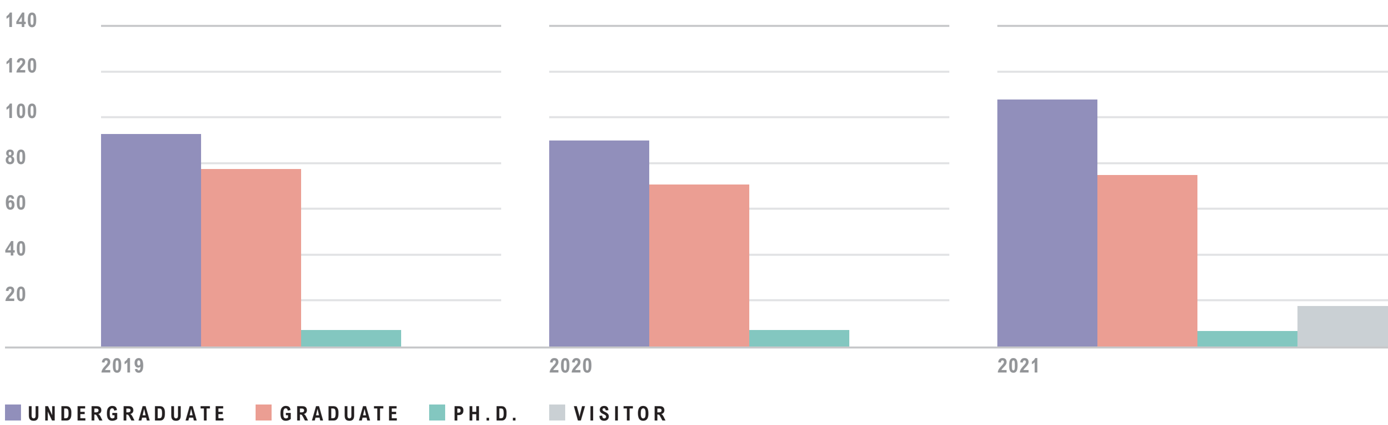
BNL Ph.D.s: doctoral degrees received by those in particle physics programs in which BNL participated, even if the experiments were located at other places.

BNL visitors: those postdocs and faculty who visited BNL for at least one month.

Figure 15

LBNL: Non-staff particle physics workforce counts

Total non-staff workforce	179	169	208
Undergraduate	93	90	108
Graduate	78	71	75
Ph.D.	8	8	7
Visitor	0	0	18



Non-staff particle physics workforce counts for undergraduate (purple bars), graduate (orange bars), Ph.D. (green bars), or visitor (grey bars) demographic groups at LBNL⁺ for the years 2019–2021 are given on the y-axis and above.

⁺LBNL undergraduate and graduate students: those students who are salaried and those in internship programs.

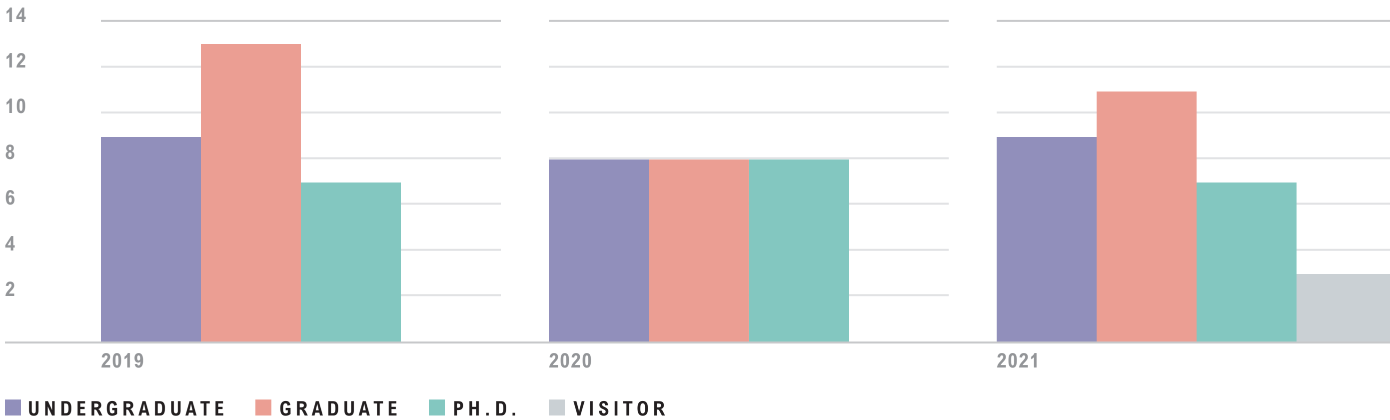
LBNL Ph.D.s: those students supported by LBNL.

LBNL visitors: Faculty who visited LBNL for at least one month.

Figure 16

SLAC: Non-staff particle physics workforce counts

Total non-staff workforce	29	24	30
Undergraduate	9	8	9
Graduate	13	8	11
Ph.D.	7	8	7
Visitor	0	0	3



Non-staff particle physics workforce counts for undergraduate (purple bars), graduate (orange bars), Ph.D. (green bars), or visitor (grey bars) demographic groups at SLAC+ for the years 2019–2021 are given on the y-axis and above.

+SLAC undergraduate and graduate students: those who participated in internships.

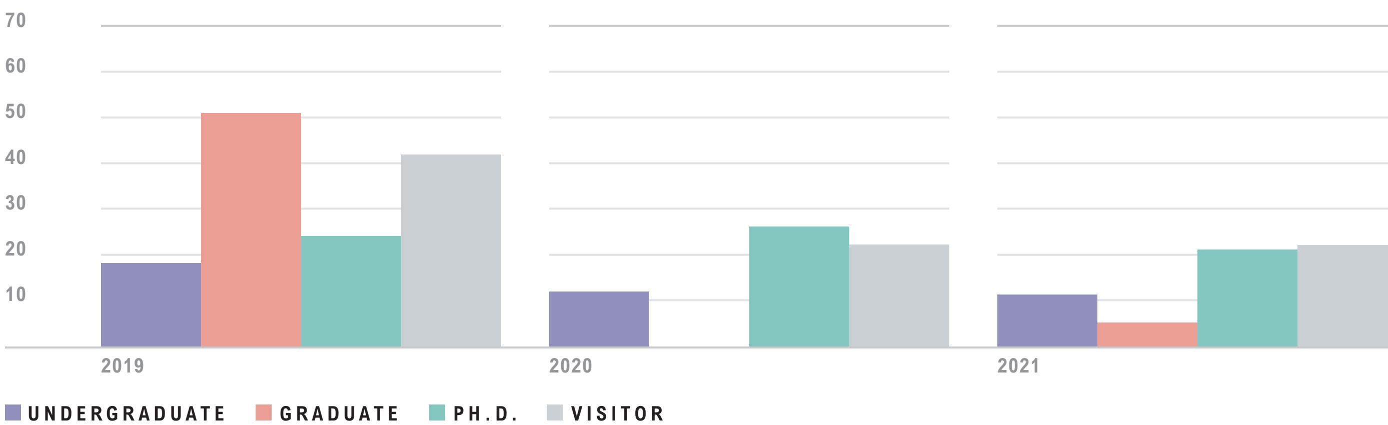
SLAC Ph.D.s: those received for students based at SLAC.

SLAC visitors: those faculty who visited for at least one month.

Figure 17

DESY: Non-staff particle physics workforce count

Total non-staff workforce	135	60	58
Undergraduate	18	12	11
Graduate	51	0	5
Ph.D.	24	26	21
Visitor	42	22	22



Non-staff particle physics workforce counts for undergraduate (purple bars), graduate (orange bars), Ph.D. (green bars), or visitor (grey bars) demographic groups at DESY+ for the years 2019–2021 are given on the y-axis and above.

+DESY undergraduate students were heavily impacted by the COVID-19 pandemic. A number of undergraduates were not allowed to come on campus.

DESY graduate students were heavily impacted by the COVID-19 pandemic. The Summer Student Program was online (fully/partial).

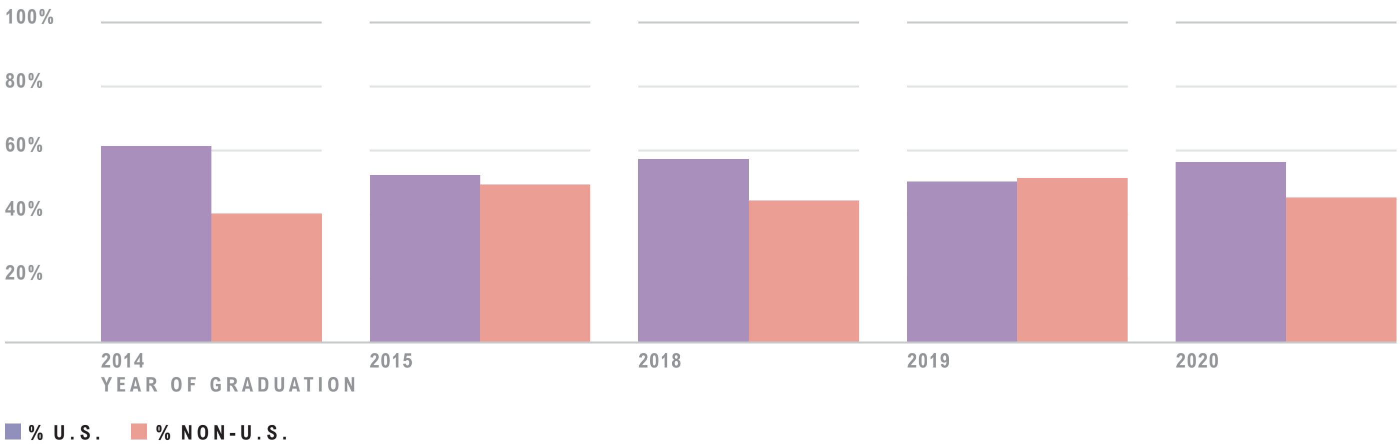
DESY Ph.D.s: those Ph.D. students who were employed by DESY. Ph.D. students from Hamburg University are not counted.

DESY visitors: those faculty who visited for at least an uninterrupted month. Visitors were heavily impacted by the COVID-19 pandemic. A number of guests we not allowed to come on campus or allowed to travel.

Figure 18

AIP: Citizenship of Ph.D. graduates in particle physics

Total Ph.D.s	289	295	309	258	206
U.S.	175	152	175	127	114
Non-U.S.	114	143	134	131	92



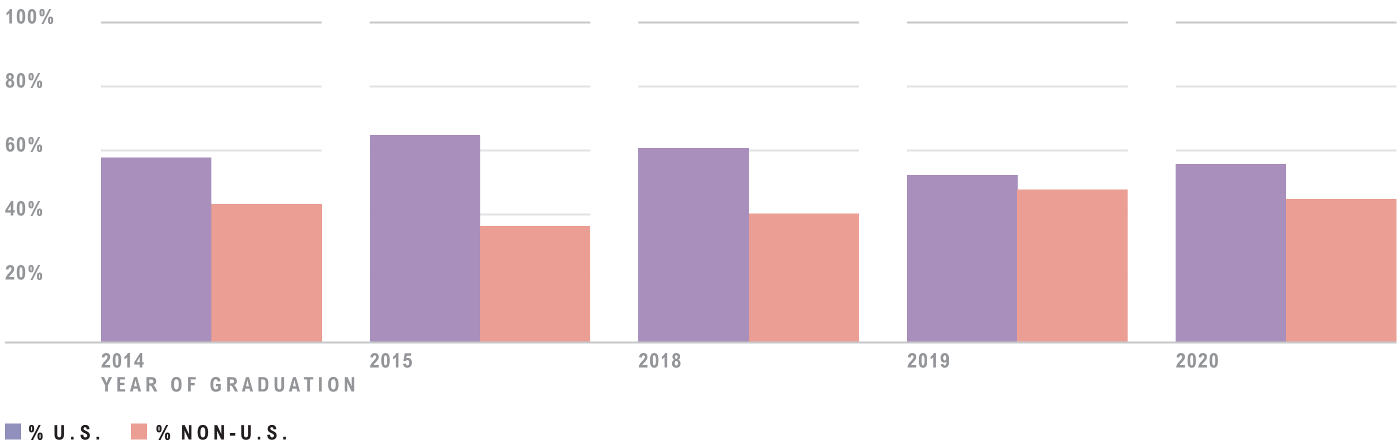
The fractions of U.S. citizens (purple bars) and non-U.S. nationals (orange bars) receiving a Ph.D. in particle physics by year (2014, 2015, 2018, 2019, and 2020) are given on the y-axis. Total counts of Ph.D.s by citizenship and year are listed above. Data were obtained from the AIP.+

+Class of 2021 data were not yet available from AIP.

Figure 19

NSF: Citizenship of Ph.D. graduates in particle physics

	2014	2015	2018	2019	2020
Total Ph.D.s	243	243	230	228	196
U.S.	139	156	138	119	108
Non-U.S.	104	87	92	109	88



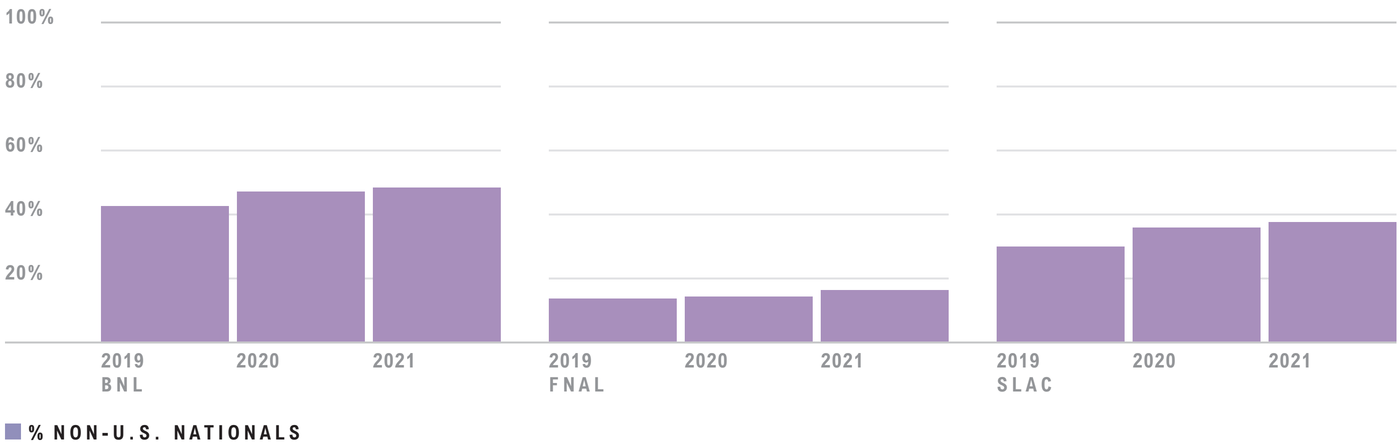
The fractions of U.S. citizens (purple bars) and non-U.S. nationals (orange bars) receiving a Ph.D. in particle physics by year (2014, 2015, 2018, 2019, and 2020) are given on the y-axis. Total counts of Ph.D.s by citizenship and year are listed above. Data were obtained from the NSF.+

+Class of 2021 data were not available yet from NSF.

Figure 20

DOE national laboratory data: Citizenship of particle physics staff

	BNL			FNAL			SLAC		
Total staff	147	151	159	837	867	897	187	162	165
Non-U.S. Nationals	63	71	77	115	125	147	57	58	62



The fractions of particle physics staff that are non-U.S. nationals (purple bars) at BNL,[+] FNAL,[†] and SLAC[⁎] for the years 2019–2021 are given on the left y-axis. Total particle physics staff size by DOE national laboratory and year are given above.

[+]BNL staff: Scientific, Professional, Technicians, and Postdocs.

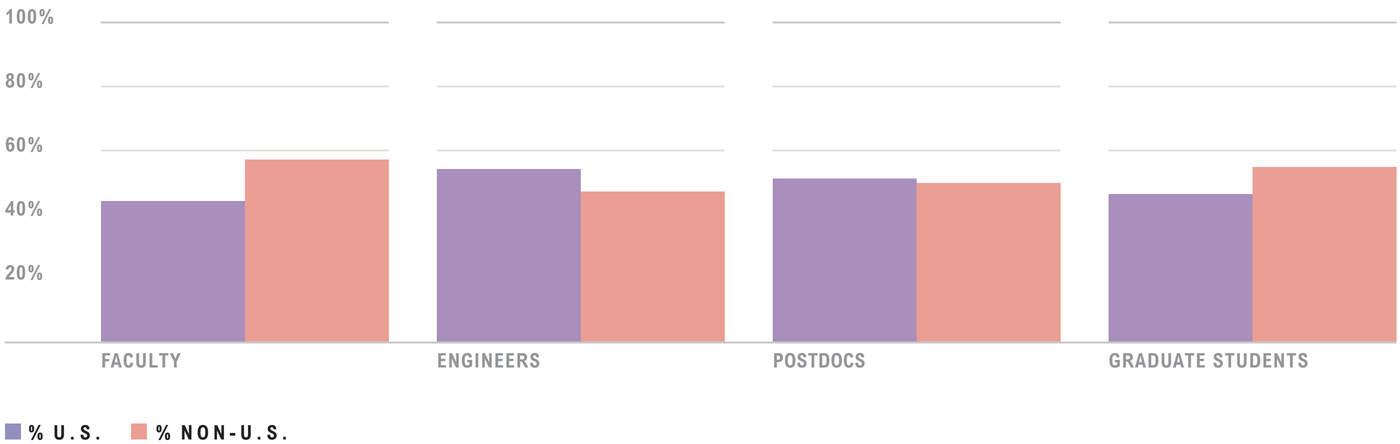
[†]FNAL research staff: Scientists, Postdocs, Engineers, Technicians.

[⁎]SLAC and Stanford University faculty and staff identified as ≥0.5 full-time employed (FTE) on HEP funds: Scientists, Engineers, Postdocs and Technicians.

Figure 21

DUNE: Citizenship of staff

	FACULTY	ENGINEERS	POSTDOCS	GRADUATE STUDENTS
Total staff	668	153	255	329
U.S.	290	82	129	151
Non-U.S.	378	71	126	178

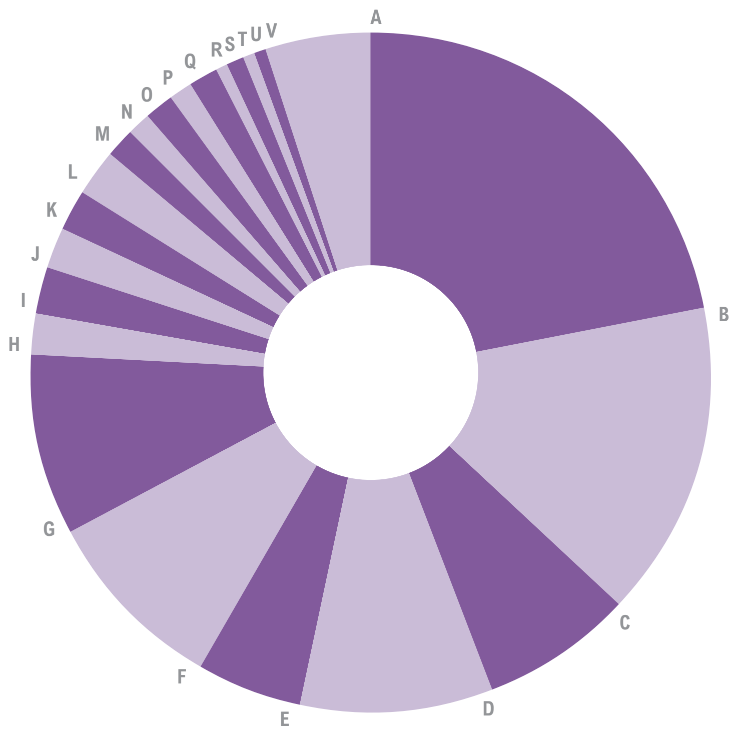


The fractions of DUNE staff that are U.S. citizens (purple bars) and non-U.S. nationals (orange bars) in 2022 are given on the y-axis. Total staff counts by citizenship are listed above.

Figure 22

AS&T Ph.D.s from U.S. universities

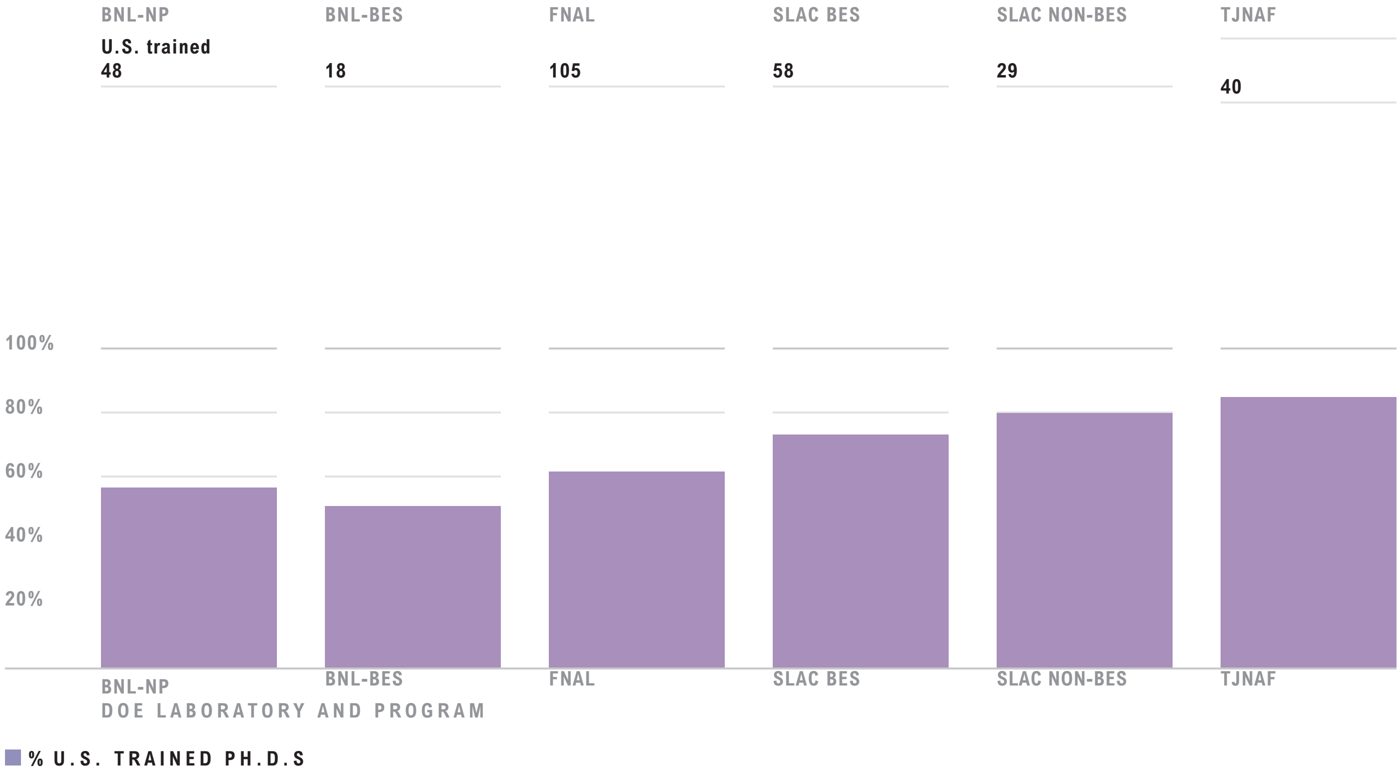
A **Cornell University** 65
B **Indiana University** 45
C **Stanford University** 21
D **Stony Brook University** 27
E **University of Maryland** 15
F **Northern Illinois University** 26
G **UCLA** 26
H **University of Colorado** 6
I **University of Chicago** 6
J **UC Berkeley** 6
K **Duke University** 6
L **Old Dominion University** 6
M **University of Tennessee** 4
N **University of New Mexico** 4
O **Michigan State University** 4
P **UT Austin** 3
Q **MIT** 4
R **Florida State University** 2
S **Carnegie Mellon University** 2
T **UC Irvine** 2
U **University of Mississippi** 2
V **Other** 14



U.S. universities from which accelerator science and technology professionals in the current workforce received their Ph.D.s. Counts of doctoral degrees are listed under each university.

Figure 23

DOE national laboratories: Percent of AS&T staff with Ph.D.s trained by U.S. universities



The percents of Ph.D.s trained in the U.S. working in the field of accelerator science and technology at BNL, FNAL, SLAC, or TJNAF with training funding provided by DOE NP, DOE BES or other source are given on the y-axis. Counts of individuals are given above.

Figure 24

Sectors in which former students and postdocs are currently working

A National Laboratory 31

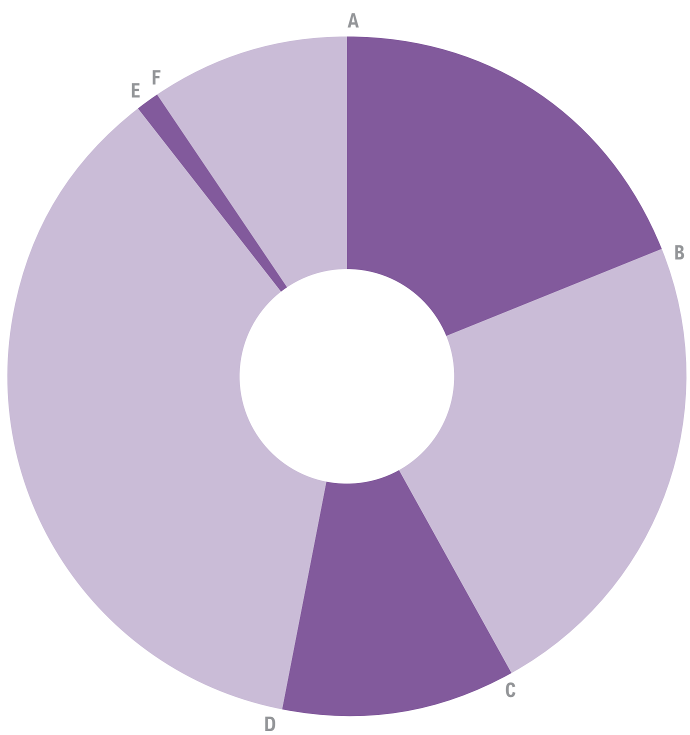
B Research University 37

C International Research Institute 18

D Private Company 59

E Government 2

F Unknown 15



Current employment sectors for former students and postdocs at FACET (from 2011–2016), BELLA (from 2015–present), and AWA (from 2015–present). Counts of individuals are combined across projects.

Appendix L

Acknowledgements

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Acosta, D. (Rice University)
Allport, P. (University of Liverpool, U.K.)
Aprile, E. (Columbia University)
Artuso, M. (Syracuse University)
Ballarino, A. (CERN, European Laboratory for Particle Physics Research)
Beckford, B. (DOE, Department of Energy)
Belomestnykh, S. (FNAL, Fermi National Accelerator Laboratory)
Bernstein, B. (FNAL)
Bertolucci, S. (Bologna, IT, Italy)
Bermudez, S.L. (FNAL)
Blucher, E. (University of Chicago)
Bouman, K. (California Institute of Technology, Caltech)
Bousso Dieng, A. (Princeton University)
Boutigny, D. (Annecy, FR, France)
Browder, T. (University of Hawaii)
Bruning, O. (CERN)
Budker, D. (University of California, Berkeley, UC Berkeley and University of Mainz)
Butler, J. (FNAL)
Calafiura, P. (Lawrence Berkely National Laboratory, LBNL)
Canelli, F. (University of Zurich, CH)
Carlstrom, J. (University of Chicago)
Childs, L. (IOP, Institute of Physics, U.K.)
Chivukula, S. (University of California, San Diego)
Colby, E. (DOE)
Cousins, B. (University of California, Los Angeles)
Cousineau, S. (ORNL, Oak Ridge National Laboratory)
Craig, N. (University of California, Santa Barbara, UC Santa Barbara)
Csaki, C. (Cornell University)
De, K. (NSF, National Science Foundation)
Demarteau, M. (ORNL)
Denisov, D. (BNL, Brookhaven National Laboratory)
Doser, M. (CERN)
Esarey, E. (LBNL)
El Kahdra, A. (University of Illinois Urbana-Champaign)
Elmer, P. (Princeton University)
Estrada, J. (FNAL)
Ferrari, A. (Helmholtz-Zentrum Dresden-Rossendorf, DE)
Fisher, P. (MIT, Massachusetts Institute of Technology)
Formaggio, J. (MIT)
Fischer, W. (BNL)
Fisk, I. (Flatiron Institute)
Fleischer, M. (Deutsches Elektronen-Synchrotron, DESY, DE)
Forti, F. (Pisa, IT)
Frieman, J. (University of Chicago)
Geddas, C. (LBNL)
Gianotti, F. (CERN)
Gladney, L. (Yale University)
Gordon, H. (BNL)
Gottlieb, S. (Indiana University)
Grannis, P. (Stony Brook University)
Gratta, G. (Stanford University)
Han, T. (University of Pittsburgh)
Hao, Y. (Facility for Rare Isotope Beams, FRIB/Michigan State University, MSU)
Harris, D. (FNAL)
Harrison, M. (BNL)
Heinemann, B. (DESY, DE)
Hertzog, D. (University of Washington)

Hitlin, D. (Caltech)
Huang, Z. (SLAC National Accelerator Laboratory, SLAC)
Jakobs, K. (Albert Ludwig University of Freiburg, DE)
Jawahery, H. (University of Maryland)
Jenni, P. (Albert Ludwig University of Freiburg, DE and CERN)
Jung, C.K. (Stony Brook University)
Kearns, E. (Boston University)
Kraus, H. (University of Oxford, U.K.)
Lahav, O. (University College London, U.K.)
Lancaster, M. (The University of Manchester, U.K.)
Lee, S.Y. (Indiana University)
Lefleur, M. (Institute for Artificial Intelligence and Fundamental Interactions, IAIFI, MIT)
Levi, M. (LBNL)
Lockyer, N. (Cornell University)
Luk, K.B. (UC Berkeley)
Mandelbaum, R. (Carnegie Mellon University)
Marken, K. (DOE)
Marsiske, H. (in a personal capacity)
McKinsey, D. (UC Berkeley)
Merminga, L. (FNAL)
Miahnahri, R. (SLAC)
Miscetti,,S. (INFN, Instituto Nazionale di Fisica Nucleare, IT)
Mossey, C. (FNAL)
Mulvey, P. (AIP, American Institute of Physics)
Nakada, T. (EPFL, École Polytechnique Fédérale de Lausanne, CH)
Nakaya, T. (Kyoto, JP)
Nelson, H. (UC Santa Barbara)
Nelson, T. (SLAC)
Nessi, M. (CERN)
Newcomer, M. (University of Pennsylvania)
Nomura, T. (KEK, High Energy Accelerator Research Organization, JP)
Palmer, M. (BNL)
Patwa, A. (DOE)
Patterson, R. (Cornell University)
Pierini, M. (CERN)
Power, J. (ANL, Argonne National Laboratory)
Prestemon, S. (LBNL)
Quigg, C. (FNAL, retired)
Rameika, R. (FNAL, retired)
Ritz, S. (University of California, Santa Cruz, UC Santa Cruz)
Lee Roberts, B. (Boston University)
Roe, N. (LBNL)
Sabbi, G. (FNAL)
Sadrozinski, H. (UC Santa Cruz)
Shaftan, T. (BNL)
Seiden, A. (UC Santa Cruz)
Seryi, A. (TJNAF, Thomas Jefferson National Accelerator Facility)
Shiltsev, V. (FNAL)
Scholberg, K. (Duke University)
Schroeder, C. (LBNL)
Shank, J. (NSF)
Smith, W. (University of Wisconsin-Madison)
Soldahl, C. (SLAC)
Sonnenschien, A. (FNAL)
Spitz, J. (University of Michigan)
Strait, J. (LBNL)
Svodoba, R. (University of California, Davis)
Tait, T. (University of California, Irvine)
Thaler, J. (MIT)
Thomson, M. (STFC, Science and Technology Facilities Council, U.K.)
Trivedi, S. (MIT)
Turner, K. (DOE)
Turner, M. (CERN)
Ushiroda, Y. (KEK, JP)
Vagins, M. (Kavli-IPMU, Kavli Institute for the Physics and Mathematics of the Universe, JP)
Valishev, A. (FNAL)
Van de Water, R. (FNAL)
Venanzoni, G. (University of Liverpool, U.K.)
Wah, Y.W. (University of Chicago)
Wang, Y. (Institute of High Energy Physics, IHEP, CN)
Wascko, M. (University of Oxford, U.K.)
Watts, G. (University of Washington)
Wenaus, T. (BNL)
Willett, R. (University of Chicago)
Winkelehner, D. (MIT)
Yeck, J. (BNL)
Yoo, J. (SNU, Seoul National University, KR)
Zdeborova, L. (EPFL, CH)
Zlobin, A. (FNAL)

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