HEPAP Facilities Subpanel Report

Draft Report

Dear Dr. Kung,

This letter and the report that follows are written in response to Dr. Behre's charge letter dated December 1, 2023 requesting an assessment of new and upgraded facilities to "position the Office of Science at the forefront of discovery" (reproduced in Appendix A). It is submitted on behalf of the High Energy Physics Advisory Panel (HEPAP), whose Chair, Professor Sally Seidel, empanelled a special HEPAP Facilities subpanel, consisting of the members listed in Appendix B. The subpanel members have deep expertise spanning the scientific breadth of the field of high energy physics, are representative of the field demographically, and include university as well as national laboratory researchers, supported by both NSF and DOE.

The P5 Report, HEP scientific goals and future HEP facilities

The subpanel benefitted enormously from the recent Particle Physics Project Prioritization Panel (P5) Report, "Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics". This report was presented to HEPAP on December 9, 2023, after more than one year of work that included multiple community town halls, white papers and individual inputs. The P5 report in turn was built on the consensus reports developed for the two week "Snowmass" community workshop that was held in Seattle in July 2022. The Snowmass meeting itself was the culmination of two years of community organization, including hundreds of white papers and dozens of working groups who produced consensus reports for each sub-field of high energy physics, as well as other topics such as the needs of early career scientists, diversity and outreach efforts, connections with other fields, and so on. Thus our report builds on four years of work by the entire high energy physics community to develop, assess and prioritize future facilities.

The scientific priorities outlined in the 2023 P5 report are:

- Reveal the Secrets of the Higgs Boson
- Elucidate the Mysteries of Neutrinos
- Search for Direct Evidence of New Particles
- Pursue Quantum Imprints of New Phenomena
- Determine the Nature of Dark Matter
- Understand What Drives Cosmic Evolution

The P5 subpanel was charged with prioritizing facilities and projects within the constraints of realistic budget scenarios over the next ten years, and they had to make many difficult choices. The projects that we considered in this subpanel have all been recommended by P5 and have therefore already gone through a rigorous down-select process. P5 identified the most important projects that could be supported over the next ten years within a twenty-year vision for the field. Some of these projects will not realistically make a construction start within ten years, but significant investments in R&D leading up to a project start are still necessary in the next decade. Therefore, we have included some projects beyond the ten-year horizon in our list, given the need for long-term planning for such large and ambitious projects. This list of projects, selected based on the P5 report in consultation with DOE's HEP Associate Director, includes:

1. New projects recommended by P5:
    a. Cosmic Microwave Background Stage 4 (CMB-S4)
    b. Generation 3 Dark Matter (G3 DM)
    c. Advanced Accelerator Test Facilities (AATF)
    d. Spectroscopic Survey Stage 5 (Spec-S5)
2. Completion of the LBNF/DUNE pre-CD3 sub-projects:
    a. Far Detectors and Cryogenics
    b. Near Site Conventional Facilities and Beamline
    c. Near Detectors
3. LBNF/DUNE Phase 2 projects:
    a. Accelerator Complex Evolution - Main Injector, Ramp and Target (ACE-MIRT)
    b. Far Detector 3 (FD3)
    c. More Capable Near Detector (MCND)
4. Future LBNF/DUNE upgrades beyond Phase 2:
    a. Far Detector 4 (FD4)
    b. Accelerator Complex Evolution - Booster Replacement (ACE-BR)
5. Future Large Accelerator Projects:
    a. Off-shore Higgs Factory
    b. 10 TeV parton center of mass collider

These large (>$100M) facilities that advance high-energy physics and address the P5 scientific goals fall into two general categories: accelerators and experiments. Accelerators provide the high energy and/or high-intensity beams needed to study the smallest scales, the highest energies, and/or the most subtle effects in particle physics. Experiments are major detector systems comprising sensors of various kinds, readout electronics, DAQ, and software systems designed for a variety of measurements ranging from particle detection at accelerators to large cosmological surveys and searches for rare events such as dark matter or neutrino interactions. Both accelerators and experiments typically serve large communities of scientists, with broad collaborations spanning US national labs and universities and international participation. These collaborations range from hundreds to thousands of scientists, and they provide excellent environments for the training of graduate students and postdoctoral fellows.

High energy physics is a global field with major facilities around the world supporting large international collaborations of scientists. Some of the facilities we consider in this report are likely to be based in other countries, with substantial US participation and investment, while others are planned to be located in the US with significant international participation. However, given the current barriers to participation, we did not include facilities planned in countries of risk. Thus, for example, we do not consider the plans for future accelerators and experiments in China when evaluating the uniqueness of facilities that will be based in the US, Europe, or Japan.

The HEPAP facilities subpanel process

The subpanel convened for the first time on January 29, 2024, and subsequently held 10 meetings; a list of meetings is provided in Appendix C. The subpanel requested short-form answers for each facility under consideration to a list of questions regarding their scientific goals, cost and schedule overview, community endorsements, technical maturity, major R&D needed to establish feasibility, etc. In addition to virtual meetings, the subpanel met in person for 2 days at Fermilab on March 5-6, 2024. At the Fermilab meeting, we had the opportunity to hear presentations from most of the facilities in open sessions, interact with proponents, and ask questions in closed sessions; for a few facilities, the presentations and Q&A sessions took place later in virtual meetings.

In formulating our assessments of these projects, we used the following definitions:

- The potential to contribute to world-leading science:
    - ***Absolutely central:*** addresses the most important scientific questions of the field, is unique in its capabilities (among facilities accessible to the US scientific community), and serves a broad community of users.
    - ***Important:*** addresses important scientific questions and has unique aspects.
    - ***Lower priority:*** scientific goals are lower priority and/or the facility is redundant with other existing or planned facilities.
    - ***Don’t know***: scientific goals not yet well defined.

- The readiness for construction:
    - ***Ready to initiate construction:*** could be ready soon to initiate the DOE Critical Decision process (starting with conceptual design review and selection of alternatives); beyond the basic R&D stage.
    - ***Significant scientific/engineering challenges remain:*** Initiation of the Critical Decision process is at least several years away; pending selection of alternatives and/or demonstration of basic feasibility of some aspects.
    - ***Mission and technical requirements not fully defined:*** scientific goals are not well defined and/or more R&D is needed to define technical requirements.

Cross-cutting Interests and Connections

While the HEP facilities we consider here are focused on the goals of particle physics as outlined above in the recent P5 report, the technological advances achieved in the course of designing and building HEP facilities have often benefited a much broader range of science and society. In particular, HEP has been the major federal steward of accelerator science and technology, which has enabled not only powerful colliders, but also the most intense coherent X-ray beams, bright, ultra-short electron beam probes, neutron sources, as well as beams for medical use and industrial applications such as semiconductor fabrication. Continued basic accelerator research will both enable future colliders employing new technologies and approaches, and benefit a wide range of other applications.

HEP support for accelerator R&D also provides training for many scientists who go on to work on light sources, neutron sources and nuclear physics accelerators. The work to advance the future accelerators and test facilities included in this report will continue to advance the field of accelerator science and technology and train the future workforce, keeping the US at the forefront of this highly important and competitive field.

The recent HEP International Benchmarking study commissioned by HEPAP pointed out that “Tools developed for particle physics experiments now power next-generation technologies with diverse applications.” The report describes many applications of HEP developed technologies including national security, nuclear reactor monitoring, medical imaging, computing technologies, advances in microelectronics and even applications to geoscience and climate studies.

HEP has also benefited greatly from some of the facilities constructed by other offices in the DOE Office of Science. In particular, HEP scientists make very good use of the computing and networking resources supported by ASCR, especially NERSC and ESNet. ESNet provides essential services for transporting data, e.g. from CERN’s

Large Hadron Collider to US computing facilities and from experiments such as DESI (in Kitt Peak, Arizona) and LZ (in South Dakota) to NERSC. NERSC computing resources are used extensively by multiple HEP collaborations, including those at the LHC, for processing data and generating large-scale simulations. HEP scientists also heavily utilize leadership computing facilities at ANL and ORNL for computing-intensive activities such as large-scale cosmological simulations and lattice QCD calculations. The future High-Performance Data Facility (HPDF) is also of great interest to HEP, given the large data sets generated by particle physics and cosmology experiments.

HEP users are often early adopters of new computing, network and software technologies, and work closely with their ASCR colleagues to ensure that computing facilities are well integrated into their research. We greatly appreciate the close partnership with ESNet and NERSC, for example when they solicit input from the HEP research community in developing requirements for their next generation facilities, as well as providing the opportunity to have early access as “beta testers” as the new facilities come online.

Respectfully submitted,

Natalie Roe, Chair
on behalf of the HEP Facilities Subpanel

HEPAP Facilities Subpanel Report

Executive Summary

The HEPAP Facilities subpanel considered twelve facilities, summarized in the table below, together with our assessments. As described in the letter above, these are facilities expected to cost >$100M that have been recommended by the 2023 P5 report, which selected these from a much more extensive list of potential future facilities. Our scientific assessments are primarily informed by this report and as a result most of these projects are assessed as "absolutely central", with the exception of two long-term detector and accelerator upgrades where we "don't know" enough yet; these projects will be informed by the results of planned near-term experiments and R&D efforts.

		Science Assessment				Technical Readiness		
		Absolutely central	*Important*	*Lower priority*	*Don't know*	*Ready to initiate construction*	*Significant scientific/ engineering challenges*	*Mission and technical requirements not fully*
		A	B	C	D	A		
	CMB-S4	●				●		
	G3 Dark Matter	●						
	kBELLA	●						
	Spec-S5	●				●		
	LBNF/DUNE Phase 1	●				●		
LBNF/DUNE Phase 2 and beyond	ACE-MIRT	●				●		
	FD3	●				●		
	MCND	●						
	FD4				●			
	ACE-BR				●			
	Off-Shore Higgs Factory	●				●		
	10 TeV pCM Collider	●						●

1. CMB-S4

1.1. Project Description

The particle physics community conceived the Cosmic Microwave Background Stage IV Experiment (CMB-S4) as a next-generation facility to realize the enormous potential of cosmic microwave background (CMB) measurements for understanding the origin of the Universe and the fundamental physics that drives its evolution. CMB-S4 is planned to be joint DOE-NSF project that will use telescopes sited both in Chile and Antarctica to study the oldest light from the beginning of the universe. Small aperture telescopes located at the South Pole will monitor a small patch of sky that is always visible, drilling deeply to achieve the best sensitivity to polarization signals that would provide evidence of primordial gravitational waves from a period of exponential inflation. Large aperture telescopes located at both the South Pole and in Chile will survey the sky to create a legacy map for a rich program of fundamental astrophysical measurements, and to characterize backgrounds to the inflation signal. The CMB-S4 project was launched in 2019 and includes a strong scientific collaboration that has grown to include over 500 cosmologists, particle physicists and astronomers from about 120 institutions in 23 countries.

1.2. Scientific Goals

CMB-S4 will enable a major advance in our ability to study the cosmic microwave background, crossing critical discovery thresholds in cosmology, astrophysics, and fundamental physics. It will continue the groundbreaking history of U.S. leadership in CMB research. It presents an exciting opportunity to discover gravitational waves produced by inflation in the extremely early universe, thus providing a direct window to this previously inaccessible epoch in cosmic history and the highest energy scales in the universe. This transformative science includes the search for primordial gravitational waves, constraints on relic particles, setting the neutrino mass scale, probing the sum of neutrino masses (information that can be directly compared with the mass ordering measured by DUNE), unique and complementary insights into dark energy and tests of gravity on large scales, elucidating the role of baryonic feedback on galaxy formation and evolution, opening up a window on the transient Universe at millimeter wavelengths, and even the exploration of the outer solar system.

The CMB-S4 survey is poised to have a profound and lasting impact on astronomy and astrophysics. It will also provide powerful synergies to surveys at other wavelengths, such as the currently operating Dark Energy Spectroscopic Instrument (DESI), the Vera Rubin Observatory Legacy Survey of Space and Time (LSST), the Nancy Grace Roman Space Telescope, the proposed Spec-S5, and others yet to be imagined. In addition, given the planned landscape of ground and space-based CMB experiments, CMB-S4 presents an important opportunity for the field of particle physics using demonstrated technology and a unique two-site survey capability that is crucial for addressing key science goals and discovering cosmic inflation.

1.3. Scientific Impact

We rate this project as ***"absolutely central"***. Community input through the Snowmass process and the P5 planning process identified CMB-S4 as an essential element of the U.S. particle physics program. The P5 report recommends:

> "*CMB-S4, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals*."

The 2023 P5 ranked CMB-S4 as the highest priority for future HEP construction projects without reduction in scope in any funding scenario. Prior to this, the 2014 P5 [4] also recommended CMB-S4 under all budget scenarios. We concur with this evaluation.

CMB-S4 will significantly extend the reach of the current Stage 3 experiments, including the Simons Observatory (SO), situated in the Atacama Desert in Chile and the South Pole Observatory, comprising the BICEP Array and the South Pole Telescope, both located at the South Pole. CMB-S4 also provides important synergies with the Japanese-led LiteBIRD CMB satellite mission which aims to launch in the next decade and carry out a program of complementary measurements..

1.4. Technical Readiness

We rate this project as ***"ready to initiate construction***" given its level of maturity and overall design approach. CMB-S4 builds on decades of experience from U.S.-led ground-based CMB experiments but with increased sensitivity made possible by scaling up to nearly 500,000 detectors. There are no beyond the state-of-the-art technologies required for CMB-S4. All technologies for CMB-S4 have been demonstrated on-sky in previous CMB experiments (e.g., BICEP, ACT, SPT), and the project has a clear pathway for achieving the necessary steps in scalability.

CMB-S4 received DOE CD-0 (Mission Need) in 2019 in recognition of the "*need for the U.S. to continue to lead research in particle physics, dark matter, dark energy, and inflation by mounting a stage 4 CMB discovery-focused project*". CMB-S4's current design maturity is beyond conceptual and the CMB-S4 project is ready to initiate the gateway review processes of the two funding agencies (DOE, NSF).

CMB-S4 is technically ready to start construction and will require installing telescopes in both Chile and the South Pole. Each are proven sites with excellent observing conditions and infrastructure. Access to the Chilean site will depend on agreements with the Parque Astronómico Atacama which are already being negotiated and are based on the successful experience with other observatories in Chile. Access to the Antarctic will depend on future commitments from the NSF Office of Polar Programs (OPP) and Division of Astronomical Sciences (AST) to provide sufficient infrastructure and logistics support at the South Pole Station in the 2030s. In particular, the 2023 P5 report commented that "*the South Pole, a unique site that enables the world-leading science of CMB-S5 and IceCube-Gen2, must be maintained as a premier site of science to allow continued U.S. leadership in these areas*" and that "*coordination between DOE-HEP, NSF-AST, and NSF-OPP is critical for the success of CMB-S4."*

2. Generation 3 Dark Matter

2.1. Project Description

Determining the nature of dark matter is one of the highest priorities articulated by the recent P5 report which recommends an "*ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners and preferably sited in the US."* Generation 3 dark matter experiments are envisioned to be two-phase liquid noble detectors with active target masses of order 100 tonnes. They would extend sensitivity for direct detection of a galactic halo of weakly interacting massive particles (WIMPs) by an order of magnitude in interaction strength, reaching a level at which interactions from astrophysical neutrinos produce a limiting background source. That background is called the neutrino fog; extending sensitivity beyond it would require new techniques and ideas. As such, the G3 dark matter experiments will be the ultimate probe of WIMP dark matter in the next decade.

The G3 DM experiments must operate deep underground to reduce backgrounds from cosmic rays at the surface; there are a number of underground laboratories available that are suitable for the Generation 3 experiments, including the Sanford Underground Research Laboratory (SURF) in South Dakota, SNOLAB in Canada, the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, the Boulby mine in the UK, and Kamioka in Japan. P5 recommended DOE support for additional expansion of SURF to accommodate an on-shore G3DM experiment.

The current Generation-2 dark matter experiments with U.S. participation include the liquid argon based Darkside-20k experiment, the liquid xenon based LZ and XENONnT experiments, and the SuperCDMS experiment composed of detectors made from germanium and silicon crystals. LZ and XENONnT are operational at SURF and LNGS, respectively, and producing world leading scientific results. SuperCDMS and Darkside-20k are under construction at SNOLAB and LNGS, respectively.

Two Generation-3 dark matter experiments are under development with U.S. participation. The ARGO experiment would bring together more than 400 scientists from the U.S., Italy, Canada, France, and the UK. It builds on the expertise of the Darkside-20k collaboration. The argon for the 400-tonne experiment would be sourced underground to avoid an otherwise dominant background from argon-39 decays. It will utilize state-of-the-art photon sensors and cryogen handling facilities. Two host underground laboratories are under consideration, SNOLAB and SURF.

The XLZD experiment will bring together more than 350 scientists from over 60 institutions. It builds on the expertise of the XENONnT and LZ collaborations to build a 100-tonne two-phase liquid xenon experiment. The XLZD collaboration has started a process to select a final site but a final siting decision will also require international negotiations among funding agencies. The XLZD collaboration has prioritized R&D on the high voltage distribution systems and on radon reduction, areas where the current Generation 2 experiments have encountered issues.

Outside of ARGO and XLZD, one potential experiment with competing sensitivity is PandaX-30T, which is proposed to use 30-50 tonnes of liquid xenon at the China Jinping Underground Laboratory (CJPL).

2.2. Scientific Goals

While we do not yet understand the underlying nature of dark matter, we do know that it is not described by the subatomic structures in the Standard Model of particle physics. Revealing the nature of dark matter will dramatically change the landscape of our current understanding of the Universe. The primary goal of Generation 3 Dark Matter experiments is to extend discovery potential for WIMP-nucleon interactions over the full range of cross-sections down to the “neutrino fog,” where interactions of neutrinos become an irreducible background. There are also a number of secondary scientific goals made possible by the exquisitely low background. These include sensitivity to neutrinoless double beta decay, the ability to detect solar neutrinos, and the detection of the diffuse supernova neutrino background as well as neutrinos from nearby supernova explosions.

2.3. Scientific Impact

We rate this project as ***“absolutely central”*** because dark matter, which makes up a significant portion of the universe’s mass and energy, has been one of the most enduring mysteries in modern physics. Current and previous experiments conducted worldwide have placed limits on the interaction of galactic-halo WIMPs. A large Generation-3 WIMP dark matter search would build on the most successful designs of the current G2 experiments, providing sensitivity to dark matter-Standard Model interactions that are small enough that neutrinos become an irreducible background (the "neutrino fog").

2.4. Technical Readiness

The G3 dark matter program currently has "***significant scientific/engineering challenges"*** to resolve before initiating construction. The two proposed detectors, one with a liquid xenon target and one with a liquid argon target, both face challenges in the procurement of large amounts of noble liquid. The Xenon program has demonstrated longer-term operations with precursor experiments that point to required R&D on radon mitigation and stable high voltage operation. The Argon program requires a demonstration of longer-term operations with a precursor experiment, planned to begin operations in about 2026, in order to identify areas that might require further research.

3. Spec-S5

3.1. Project Description

The Stage 5 Spectroscopic Instrument (Spec-S5) would utilize two existing 4-meter telescopes, each upgraded with a 6-meter mirror and instrumented with a spectrographic system capable of mapping the high-redshift universe with significantly improved sensitivity. The spectrographic system is based on the DESI system, currently taking data, with improved multiplexing capabilities. By utilizing the Mayall telescope at Kitt Peak National Observatory (KPNO) in the northern hemisphere and the Blanco telescope at Cerro Tololo Inter-American Observatory (CTIO) in the southern hemisphere, Spec-S5 would provide a full-sky large-volume map of the universe to high redshift. This would require an upgrade of the existing DESI instrument at the Mayall telescope, while a duplicate of the upgraded instrument would need to be installed at the Blanco telescope.

In addition to operating at two sites, the primary improvement relative to DESI is an increase in the multiplexing of the fiber system at the focal plane of each telescope. Spec-S5 would utilize 14,300 fibers (per telescope), a nearly x3 increase relative to the 5000 fibers employed by DESI. Each fiber is positioned via computer-controlled robotic actuators. The multiplexing of the fibers into packages called 'rafts' will need to be improved to accommodate the larger fiber density of Spec-S5. The fibers are read-out by CCDs that can be based largely on the DESI CCDs. Improvements in sensitivity on the blue portion of the spectrograph may be possible by utilizing new skipper CCD technologies with lower noise performance. Additional spectrographs will be fabricated based on the existing DESI design. Modifications to the optical corrector, cage, and barrel systems will be required at the Blanco telescope. The control and data management systems will utilize the DESI systems as-is at the Mayall location and replicate those systems at the Blanco telescope.

The R&D for the higher-density fiber multiplexing is well advanced, with small numbers of prototypes having been produced that satisfy Spec-S5 performance requirements. The R&D for the low-noise skipper CCDs has demonstrated viability via multiple vendors with small numbers of prototypes. For fiber multiplexing and skipper CCDs, the next R&D stage will focus on scaling production to the numbers and throughput required for Spec-S5. The design for the optical corrector system for the Blanco telescope has been recently completed. The corrections can be accomplished using a system of spherically shaped mirrors that are well within the demonstrated capabilities of industry. Some low-risk R&D remains to validate vendors for the standard readout CCDs and the required spectrograph gratings since the vendors that DESI used for these components are no longer available.

Both the Mayall and Blanco sites are NSF facilities operated by NOIRLab. Operation at both sites will require a formal agreement with NOIRLab as well as an interagency agreement between the DOE and NSF. These agreements could be modeled on those used for the DESI and DECam experiments and the Mayall and Blanco telescopes, respectively.

The project is in a pre-CD0 stage. Several international partners have expressed interest in making contributions to Spec-S5. Discussions are at an early stage and no formal agreements are in place.

3.2. Scientific Goals

Spec-S5 will create a 3-dimensional map of more than 100 million galaxies with redshift z<2 universe, 60 million galaxies and quasars with redshift z>2 universe, and 50 million dark matter tracer stars. With this extensive data set, Spec-S5 will provide significantly improved sensitivity to advance our understanding of the origins and evolution of the universe – specifically in inflationary physics, cosmic expansion, light relics, neutrino masses, and dark matter.

The Snowmass Cosmic Frontier report emphasizes that Spec-S5's sensitivity to inflationary physics enables it to "go beyond discovery of the energy scale of inflation… to conclusively probing [inflationary] physics via precision measurements". The map produced by Spec-S5 will be a factor of ten more sensitive than its predecessors and will probe the primordial power spectrum, primordial non-Gaussianity, and evidence for non-standard Dark Energy behavior affecting cosmic expansion. The 2023 P5 report endorsed Spec-S5 “to advance our understanding and reach key theoretical benchmarks in several areas” relevant to our understanding of the universe. Spec-S5 would maintain US and DOE global leadership in the cosmic frontier through the 2030s.

3.3. Scientific Impact

We rate Spec-S5 as ***“absolutely central”.*** Community input through the Snowmass process and the P5 planning process identified Spec-S5 as an important component of the US particle physics program. We concur.

3.4. Technical Readiness

We rate Spec-S5 as ***“ready to initiate construction”*** within the next decade assuming success of the near-term R&D program discussed above and once formal agreement is reached with NOIRlab and NSF for use of the Mayall and Blanco telescopes.

4. Advanced Accelerator Test Facilities - kBELLA

4.1. Project Description

The most recent P5 report has called out an ambitious future collider concept of 10 TeV pCm to search for direct evidence and quantum imprints of new physics at unprecedented energies. While the technology required for building such an accelerator in a cost-effective and socially sustainable way does not yet exist, the P5 report recommended carrying out the extensive R&D that is required and pointed out that “Possibilities include proton beams with high-field magnets, muon beams that require rapid capture and acceleration of muons within their short lifetime, and conceivably electron and positron beams with wakefield acceleration. All three approaches have the potential to revolutionize the field.” For the mid- and large scale test and demonstrator facilities in accelerator and collider portfolio, P5 has recommended a targeted panel review with broad membership across particle physics later this decade to make decisions on the US accelerator-based program.

A plasma wakefield based multi-TeV electron-positron collider has been the core focus of the Advanced Acceleration Concept program (AAC), one of the five thrusts of the current HEP Generic Accelerator R&D program (GARD). The related Advanced Accelerator Test facilities are BELLA at LBNL, FACET-II at SLAC and AWA at Argonne. While all three facilities have upgrade plans, i.e. kBELLA, FACET-II positron and GeV wakefield structure at AWA, kBELLA is the only one that is currently estimated at the >$100M level. For this reason, we describe kBELLA here in more detail.

While the wakefield based acceleration concept R&D has shown several orders of magnitude higher gradient within a short distance compared to conventional RF technology based accelerators, the overall technical feasibility for these advanced acceleration concepts to become a reliable accelerator facility requires rigorous R&D demonstrate the full set of accelerator and beam performance that is compatible and superior to conventional RF technology accelerators. Hence, P5 has called out the highest priority for the wakefield based collider concept is to deliver an end-to-end design concept, including cost scales, with self-consistent parameters throughout.

The current Laser Plasma wakefield Acceleration (LPA) R&D has encountered challenges in furthering its R&D towards demonstrating overall technical feasibility towards collider-like beam and accelerator performance, such as precision control of the laser-driven plasma performance and acceleration at kHz repletion rate. kBELLA aims to fill this technology gap in the R&D towards a multi-kHz rate GeV class laser plasma accelerator.

The kBELLA project aims to extend the current capability of BELLA with a kHz-kW class ultrafast laser to develop the critical technologies, in laser, controls, and diagnostics that are critical for the envisioned plasma based 10 TeV parton center of mass (pCM) collider. The scope of the project consists of developing the kW-KHz short pulse laser with 3 J and 30 fs, and construction of a test facility with spaces for experimental beamlines for addressing technology gaps needed in developing multi-kHz-rate GeV-class plasma accelerators. The project spans over 10 years and proposes to commence the laser pre-project R&D in 2025.

In addition, this cost effective kW kHz ultrafast laser technology that kBELLA aims to develop can be of interest to many other fields as well as applications such as security, medicine, etc. Furthermore, the ML/AI based precision control of an ultra-fast and short beam exhibits strong synergies with current state of the art accelerators (4th generation light source, X-FEL), as well as the future ones. The targeted beam parameters of kBELLA, i.e. A high brightness Gev electron beam with 100pC bunch intensity, is also highly desired for next generation X-FEL. Its success could pave the way for future compact light sources, which in turn provides a much-needed stepping stone towards future colliders.

4.2. Scientific Goals

The main goal of KBELLA is to fill the core capability technology gap for advancing the ongoing laser driven plasma acceleration concept R&D towards user facilities including multi-kHz-rate GeV-class plasma accelerators for HEP future energy frontier collider. Among them, the key objective is to translate the ongoing high energy and high repetition rate laser technology to a 3J, 30fs kilohertz class laser. At the same time, kBELLA also aims to develop the ML/AI based precision control that is required for reaching the beam performance for user applications, including a future 10 TeV pCM collider.

4.3. Scientific Impact

We rate the scientific impact of kBELLA as ***"absolutely central"*** for the Advanced Acceleration Concept Thrust of the HEP Generic Accelerator Research and Development program (GARD). kBELLA is an examplar of the test facilities that will be included in a panel review of the AATF portfolio later this decade.

4.4. Technical Readiness

We rate the project technical readiness as ***"needs significant development"***.
The core mission of the kBELLA project is to develop cost-effective kW-kHz class laser technology. Such technology is not currently available. Ongoing research and development efforts have shown promising outcomes. The recent R&D on coherent combination of multiple fiber lasers has demonstrated it is feasible to achieve a high power high repetition rate laser. However, to meet the stringent requirements of kBELLA — specifically, a 3J 30fs laser at kilohertz repetition rates — further progress is required. This necessitates concerted efforts in simultaneously combining multiple fiber lasers spatially, spectrally, and temporally. High power optical components and system integration are also required.

5. LBNF/DUNE Phase 1 Subprojects

5.1. Project Description:

DUNE (Deep Underground Neutrino Experiment) will use massive, cryogenic liquid-argon (LAr) time-projection chambers (LArTPCs) and an intense neutrino beam delivered from Fermilab to the underground SURF laboratory in South Dakota to comprehensively determine the structure of neutrino mixings and the pattern of their masses. DUNE's ultimate neutrino oscillation physics goals are precision measurement of all parameters governing long-baseline neutrino oscillation, sensitivity to deviations from standard three-flavor neutrino mixing, unambiguous determination of the neutrino mass ordering and discovery of CP violation, the latter providing a second example of nature's differentiation between matter and antimatter.

The dominance of matter over antimatter in the universe remains one of the fundamental puzzles of particle physics, given that most mechanisms of particle production create equal amounts of matter and antimatter. The known exceptions to this are processes that exhibit the violation of the symmetries of charge conjugation and parity, known as “CP violation”. While CP violation has been observed in interactions in the quark sector, it has not been seen at a large enough level to explain the level of matter dominance we observe. Thus it is important to probe the lepton sector for CP violating effects. The DUNE experiment has sensitivity to these effects, with Phase I of the project expected to provide evidence for CP violation should there be a maximal amount of it in the neutrino sector. A definitive exploration of CP violation requires the DUNE Phase II upgrades.

DUNE also has a broad physics program beyond three-flavor oscillation physics that includes multi-messenger astronomy and astrophysics, searches for a wide variety of Beyond Standard Model (BSM) signatures including proton decay, and precision Standard Model (SM) measurements. DUNE and the Long Baseline Neutrino Facility (LBNF) consists of several subprojects. There are three sub-projects for the Far Site, the excavation, the buildings and site infrastructure, and the far detectors and cryogenics. For the Near Site there are two subprojects, the conventional facilities and beam line, and the near detector. Together, these projects will establish a world-leading program for precision neutrino studies.

5.2. Scientific Goals:

The LBNF and DUNE Phase 1 projects will be able to establish the neutrino mass ordering at the 5σ level for 100% of δ_{CP} values with 100 kt-MW-years exposure and can make strong statements even with significantly shorter exposures depending on the true values of other oscillation parameters. DUNE Phase I can also observe CP violation with 3σ significance with 100 kt-MW-years exposure for maximal CP violation ($\delta_{CP} = -\pi/2$). DUNE Phase I will also make measurements of the disappearance parameters Δm^2_{32} and $\sin^2 2\theta_{23}$ that improve on current measurements. DUNE’s large underground liquid argon detectors also have unique sensitivity to the electron neutrino component of a supernova neutrino burst. They will therefore complement measurements by other underground neutrino detectors, such as Hyper-Kamiokande in Japan, that is primarily sensitive to electron antineutrinos from supernova, as well as all-flavor measurements by the Antarctic neutrino observatory IceCube and future direct dark matter detectors that constrain the overall burst energetics.

5.3. Scientific Impact

The LBNF/DUNE Phase 1 projects’ scientific impact is ***“absolutely central”***. These facilities will usher in the era of precision neutrino physics with the ability to determine the neutrino mass ordering, establish CP violation if CP violation is near maximal, improve measurements of the disappearance parameters Δm^2_{32} and $\sin^2 2\theta_{23}$, and search for new physics in the neutrino sector. The P5 report recommends the completion of DUNE and LBNF as the highest priority in any funding scenario stating "The first phase of DUNE and PIP-II to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science." The Phase 1 projects set the stage for future upgrades that will enable further precision studies of neutrino physics.

5.4. Technical Readiness

We rate this project as ***"ready to initiate construction***". The Phase 1 project is technically advanced: the Building and Site Infrastructure subproject operates under CD-3 approval, the Far Detectors and Cryogenics Systems subproject has CD-3b approval and the Near Site Conventional Facilities has CD-3a approval. The Beamline and Near Detector subprojects have CD-1 approval. All of these projects are well advanced and technically mature.

DUNE Phase 2 - Introduction

The recent P5 report recommended a "re-imagined" DUNE Phase 2 consisting of upgrades to the beam (Accelerator Complex Evolution - Main Injector Ramp and Target, or ACE-MIRT) that will enable an increase in stages from 1.2 MW to 2.1MW beam power, an additional 10 kiloton Far Detector 3 (FD3), and a More Capable Near Detector (MCND) which will be essential for systematics control to keep up with the increased statistics from the previous two upgrades. The goal for DUNE Phase 2 is to accumulate 600 MW-kt-years of exposure, reaching the figure of merit recommended for the LBNF/DUNE program by the previous 2014 P5 report. The 2023 P5 report summary of the impact stated: *"Phase 2 completion leaves DUNE poised to deliver the most precise measurement of the CP phase across a range of possible CP phase space."* The 2023 P5 committee ranks DUNE Phase 2 as second highest priority calling it "*the definitive long-baseline neutrino oscillation experiment of its kind."* All three Phase 2 projects are pre-CD-0.

6. Accelerator Complex Evolution - Main Injector + Target

6.1. Project Description

The Fermilab accelerator complex consists of three primary accelerators, the Linac, the Booster, and the Main Injector (MI). The current PIP-II project will replace the first accelerator in the chain, the warm linear accelerator, with a new superconducting accelerator that will improve reliability and enable 1.2 MW of beam power for the LBNF/DUNE neutrino program. The proposed Fermilab Accelerator Complex Evolution (ACE) Main Injector Ramp and Target (MIRT) program proposes to upgrade the last accelerator in the chain to provide a 75% increase in beam power beyond the 1.2 MW

PIP-II goal to 2.1 MW. The technical path for the beam power increase is to reduce the accelerator cycle time of the Main Injector to take full advantage of the upgraded proton flux provided by PIP-II. The project also aims to replace systems with significant reliability issues to increase beam delivery hours. A notable feature of this project is that it does not require the construction of a new accelerator, and does not increase the beam intensity per pulse.

The ACE-MIRT project is proposed as a series of staggered individual sub-projects aimed at either beam power increase or reliability improvement. These four essential subprojects are: 1) replacement of the MI quadrupole magnets to improve reliability of this system, 2) upgrade of the MI power system to provide faster beam accelerator and shorter cycle time, 3) upgrade of the MI RF accelerating system to allow faster beam acceleration, and 4) phased development and implementation of 2.1 MW capable targets and horns.

6.2. Scientific Goals

The scientific goal is to increase the beam flux on target thus enabling more rapid accumulation of neutrino beam statistics. The P5 report also stated that *"Early implementation of the accelerator upgrade ACE-MIRT advances the DUNE program significantly, hastening the definite discovery of the neutrino mass ordering."*

6.3. Scientific Impact

The scientific impact is rated as ***"absolutely central"***. The primary neutrino oscillation measurements of DUNE are expected to be statistics limited for many years with the anticipated 1.2 MW of beam power that will be provided by the PIP-II upgrade. Early implementation of ACE-MIRT would increase beam statistics and enable DUNE to achieve the statistical goals for the neutrino mass ordering sooner, while laying the foundation for the Phase 2 program.

In addition to its direct scientific impact on the HEP neutrino program, ACE-MIRT would modernize an important component of the Fermilab accelerator complex, which would pay dividends in years to come related to future HEP endeavors. Finally, the anticipated target R&D program would broadly serve the high power accelerator community both domestically and internationally.

6.4. Technical Readiness

The project is related as ***"ready to initiate construction***" because the first three of the four essential upgrade areas rely on established technologies that have a high level of technical readiness. However, the fourth area requires substantial R&D to develop the

2.1 MW capable targets, including possibly a materials R&D program that would benefit from collaboration with other DOE institutes and international partners. The target evolution would occur in two phases, with a 1.5 MW target as the middle step between the current 1.2 MW capable target and the final 2.1 MW capable target.

7. DUNE Far Detector 3

7.1. Project Description

The third DUNE Far Detector (FD3) is part of P5's recommended DUNE Phase 2 program. It will increase the fiducial target mass to 30 kt providing additional exposure and improved statistical precision. The baseline FD3 design is that of a vertical drift liquid argon time projection chamber (TPC) similar in concept to FD2, the second DUNE Far Detector currently under construction. Only modest upgrades are envisioned to the charge readout planes and the light collection system. R&D is ongoing to determine the baseline photon system readout electronics solution for FD3. The FD3 project is expected to receive significant international contributions including the cryostat and half of the detector. High level government-to-government and agency agreements are in place but no formal MOUs have been signed at this point in time. DOE's Fermi National Accelerator Lab is the host lab for the full scope of the DUNE project. FD3 also enhances DUNE's sensitivity to non-beam physics such as neutrinos produced in the Sun and nearby core-collapse supernovae.

7.2. Scientific Goals

The DUNE Far Detector 3 is a fundamental element of the DUNE science program. By itself, it will increase DUNE's exposure by 50%, but the real power of the Phase II program lies in the combination of the third far detector with a more capable near detector and the increased beam power from the ACE-MIRT project. Combined they will achieve the ability to establish CP violation in the lepton sector at more than 3 sigma for 75% of possible values of the CP phase and provide world-leading tests of the three-flavor neutrino model.

7.3. Scientific Impact

We rate this project as:***“absolutely central”.*** Understanding the three-flavor neutrino model and possible detection of CP violation is an essential component of the US HEP program and is of the highest importance. The full DUNE vision (Phase I and Phase II) has been strongly endorsed by the community and national and international advisory panels.

7.4. Technical Readiness

This project is ***“ready to initiate construction***”. The design is based on FD2 with only modest upgrades. R&D on improved photon detection and charge readout planes is ongoing and well advanced and expected to be ready on the timescale needed. An important upcoming step is to secure formal commitments from the international partners.

8. DUNE Phase 2 - Near Detector Upgrade

8.1. Project Description:

The DUNE “more capable near detector” (MCND) would be built at Fermilab as part of the DUNE Phase II upgrades. The MCND would, for example, replace the muon catcher in the Phase I near detector with a pressurized gaseous argon detector inside a magnetic field, complemented by calorimetry and muon detector systems. A baseline detector design was described in a Snowmass white paper, but a focused R&D program is required for complete design development. The project is in a pre-CD0 stage.

8.2. Scientific Goals:

The MCND allows for definitive observation of CP violation across the entire range of possible values, by reducing the systematic uncertainties associated with observations made with the far detector. Without this, the large DUNE dataset facilitated by ACE-MIRT and FD3 would reach a plateau in its sensitivity to CP violation. The use of gaseous argon will allow for an even more detailed understanding of argon-neutrino interactions. It also provides new opportunities for the observation of hypothetical particles such as neutral heavy leptons and axions.

8.3. Scientific Impact:

We rate this project as ***“absolutely central”***. Community input through the Snowmass process and the P5 planning process has identified the MCND as an essential element of the U.S. particle physics program. The P5 report states, *“With higher statistics, control of systematic uncertainties (such as those arising from the interaction of neutrinos and nuclei) becomes increasingly crucial. A more capable near detector (MCND), a gas target combined with a magnetic field and electromagnetic calorimeter, is indispensable for this purpose. In addition, by being exposed to the world’s most intense neutrino beam, it will create a unique laboratory for the discovery of novel particles and interactions, many of which could shed light on the nature of dark matter and possible hidden sectors.”* The MCND, along with ACE-MIRT and FD3, is included in the portfolio of recommended construction projects, ranked second behind only CMB-S4. We concur in this evaluation.

8.4. Technical Readiness:

We rate this project as “***significant scientific/engineering challenges to resolve before initiating construction”.*** While the scientific requirements are clear for achieving the necessary reductions in systematic uncertainties, significant R&D is still needed to fully define the technical specifications for the construction of the detector. R&D topics include how to operate a gaseous argon drift detector significantly above atmospheric pressure and the design of the superconducting magnet. At the moment there is limited support from DOE for this work, with the only funding coming from a detector R&D project. While there is interest in participation from several international partners, no formal agreements on contributions have been made yet. Cost estimates are based on experience from similar detectors, without any formal costing process initiated. Additional effort, including in project management, will be needed to bring the DUNE MCND to fruition.

9. DUNE Phase 2 - Far Detector 4

9.1. Project Description

DUNE Far Detector 4 (FD4) presents an opportunity to add a fourth detector module in the underground laboratory that has been excavated at SURF. This fourth module could incorporate new detector capabilities to extend the DUNE physics program, as recommended by P5. An R&D program in the next decade would study and prototype potential detector improvement ideas that include enhanced charge readout planes, expanded photon detector coverage, integrated charge-light pixel readout, and the potential for water-based liquid scintillators. The DUNE collaboration is currently evaluating different options and expects to arrive at a technology decision in 2028.

9.2. Scientific Goals

The increased detector volume from adding a fourth module has a small effect on the primary DUNE neutrino oscillation physics program, assuming the ACE-MIRT and FD3 upgrades proceed as planned, but the detector improvements aim to extend the detector sensitivity to much lower energy (MeV) scales. Providing sensitivity to interactions at that energy scale would open new opportunities for neutrino astrophysics, such as studies of solar and supernova neutrinos, as well as searches for physics beyond the Standard Model (BSM).

9.3. Scientific Impact

We rate this project’s scientific impact as “***don’t know enough yet.”*** The FD4 is noted as a “module of opportunity” in the P5 report. The extent of its scientific impact on the primary DUNE physics program will depend on the value of δCP, which shouldl become more clear early in the next decade. The impact on expanding the science reach into neutrino astrophysics and BSM physics will be clarified as the R&D effort determines the performance that can be obtained with the new detector technologies.

9.4. Technical Readiness

We assess the technical readiness of FD4 as "**significant scientific/engineering challenges to resolve before initiating construction**". The impact on the primary DUNE neutrino oscillation physics program will depend on the value of δ_{CP}. As DUNE Phase-I proceeds, that value will be clarified to resolve this scientific issue before the requirements can be well defined and the design and construction of FD4 could begin. Another scientific issue to resolve is the detector performance obtained from the R&D program and the corresponding reach for extending the neutrino program to probe lower energy processes. The proposed water-based liquid scintillator option could provide enhanced scientific opportunities in this respect, but could also require modifications to the near detector complex to handle systematics in the neutrino oscillation physics arising from a different target material. These engineering challenges will be addressed by the P5-recommended R&D program.

10. Accelerator Complex Evolution - Booster Replacement

10.1. Project Description

The Fermilab Booster ring is now over 50 years old and will be almost 70 years old by the time of DUNE Phase 2, posing a reliability risk. The ACE-BR project is a modernization effort aimed at construction of an entirely new accelerator to replace the Booster. The aim of this project is to enhance the scientific reach of the facility, improve the long term reliability, and serve as a platform for future HEP initiatives such as a muon demonstrator or a muon collider facility. The booster will also provide additional opportunities for experiments in the 8 GeV range, which will otherwise be limited due to the ACE-MIRT upgrade consuming most of the available beam flux in the post-PIP-II configuration.

The project is in its very early stages with multiple configuration options under consideration. Some configuration options are attractive from the standpoint of the US muon collider effort, as they could serve as a front-end proton driver for this collider.

10.2. Scientific Goals

The scientific goals are broad and range from providing higher reliability operation to support DUNE Phase 2, to supporting additional experiments with 8 GeV protons, to providing a demonstration facility for a muon collider facility.

10.3. Scientific Impact

The scientific impact is not yet well determined and will depend on the implementation options that are selected; therefore it is rated as ***"don't know".*** The project will at a minimum provide reliability improvements in support of DUNE, but could also support new science in the 8 GeV range and could even serve as the injector for a muon collider demonstration facility. The HEP far future goals are not well enough defined at this point to accurately assess the scientific impact.

10.4. Technical Readiness

We assess the technical readiness level of the ACE-BR project as ***"mission and scientific goals not yet well defined".*** The project is in its early conceptual design stages where major configuration decisions are still pending. All design configurations under consideration require substantial R&D. A number of these R&D items are of broad interest to the high power accelerator community.

11. Higgs Factory (ILC, FCC-ee)

11.1. Project Description

Defined as an electron-positron collider that can cover the center-of-momentum energy range of 90 GeV to 350 GeV, a future high energy e^- - e^+ collider facility – a Higgs factory – is the critical next step toward revealing the secrets of the Higgs boson. Substantial participation by the United States in the design and construction of accelerators and detectors for an off-shore Higgs factory is required for U.S. scientists to participate in this exciting science. Support for the development of the Future Circular Collider (FCC-ee) at CERN and the International Linear Collider (ILC) in Japan is essential for a U.S. leadership role in the design and construction of the Higgs factory and for the aspirational goal to potentially host the next high-energy collider facility beyond the Higgs factory in the United States.

11.2. Scientific Goals

A Higgs factory will produce large numbers of Higgs bosons with small backgrounds and enable more detailed studies of the Higgs boson properties and interactions. The Higgs boson is also a sensitive probe of the quantum imprints of new phenomena. It is possible that there is more than one type of Higgs boson, and the discovered particle is only the first one in a new family. Even if the masses of the additional Higgs bosons are too great to be observed directly by the High Luminosity Large Hadron Collider (HL-LHC), their existence affects the interaction of the first Higgs boson with various particles and can be inferred from the precise measurements of the Higgs couplings. Another possibility is that the Higgs boson is not an elementary particle but is composite, consisting of smaller constituents, and then the resulting finite size of the

Higgs boson can be inferred from the precise measurements of the Higgs couplings.

A Higgs factory could produce unprecedented numbers of Z bosons and a large sample of WW events. This would enable an exceptional program of precision studies of electroweak interactions, extending the probed energy scale by a factor of 3–10 beyond the HL-LHC. With a very large sample of Z and W bosons, one could obtain an extended exploration of quantum imprints of new phenomena. A successful Z program will involve challenging, high collision rate environments that will necessitate advances in accelerator and detector design, as well as imposing computing requirements an order of magnitude beyond those of the HL-LHC. In addition, the Z boson could produce large samples of bottom and charm hadrons, and tau leptons in their decays. These samples could exceed those from existing or soon-to-exist experiments.

Precision measurement of the top quark mass is an indirect measure of its interaction with the Higgs boson, which controls the quantum mechanical evolution of the Standard Model at high energies; a 350 GeV Higgs Factory stage will reduce the uncertainty in this crucial parameter by a factor of ten. Comparing the direct measurements of the top quark and Higgs boson masses at a Higgs factory to the precision measurements of Z and W boson properties can reveal hidden quantum imprints of new particles and phenomena at the 10 TeV energy scale.

11.3. Scientific Impact

We rate this project as ***"absolutely central"***. Community input through the Snowmass process and the P5 planning process has identified the off-shore Higgs factory as an essential element of the U.S. particle physics program. The P5 report recommends:
"An off-shore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies."
The Higgs Factory is included in the portfolio of construction projects recommended by P5 and is ranked third behind CMB-S4 and the Phase 2 DUNE program. We concur in this evaluation.

11.4. Technical Readiness

We rate this project as ***"ready to initiate construction."*** The designs of the ILC and FCC-ee are generally based on mature technologies. However, the scope of either project is very large and complex international agreements are needed to provide the design personnel, technical resources and financial support to initiate construction. The ILC and the FCC-ee could be ready in less than a decade to begin construction if international agreements are in place and resources are available. The P5 panel recommended an evaluation later this decade of the U.S. based accelerator program, to determine *"the level and nature of US contribution in a specific Higgs factory including an evaluation of the associated schedule, budget, and risks once crucial information becomes available."*

The design and technical development for the ILC has been underway for many years. A Technical Design Report (TDR) was completed in 2013. The International Committee for Future Accelerators (ICFA) established an ILC International Development Team (IDT) in 2020. Work is now underway under the auspices of the ILC Technology Network (ITN) initiated by the IDT and KEK in Japan. The ITN phase is proposed to continue development and optimization studies until 2026. The next phase is proposed to be an ILC Preparatory Laboratory phase until about 2030 at which time construction of the ILC facility could begin. The ILC design and plan has also been reviewed multiple times since the completion of the TDR. The report from the Snowmass 2021 Implementation Task Force on the Feasibility of Future Colliders noted the relatively very high technical readiness levels of key ILC accelerator systems.

The technical feasibility of a very high energy but correspondingly very large circular e^+e^- collider has been known for decades. The FCC-ee conceptual design study began at CERN in 2014 leading to a Conceptual Design Report at the end of 2018. A detailed Feasibility Study was launched in 2021, to be concluded in 2025. A decision by the CERN Council to proceed with FCC-ee could be taken as early as 2027-2028. A positive decision could lead to a construction start in the early 2030's. Operation of the FCC-ee would follow after completion of the HL-LHC program, currently foreseen to continue to about 2041. The tunnel constructed for FCC-ee and other systems could be utilized for a very high energy proton-proton collider, FCC-hh, on the timescale of the 2070's. The Task Force referenced in the previous paragraph rated the technical readiness of the key FCC-ee components to be high to very high.

12. 10 TeV pCM Collider (Muon Collider, FCC-hh)

12.1. Science Goals and Science Impact

Beyond the Higgs factory, the physics landscape that has shaped the P5 science drivers points to still higher energy scales, the 10 or more TeV parton center-of-mass (pCM) scale. Three technological approaches are under development that have the potential to enable physics exploration at this scale. They are a proton-proton collider based on very high field magnets, a muon collider, or possibly a linear collider based on advanced wakefield technology. All three of these technologies have different appealing features and must be developed further before a decision to begin construction can be made. Advanced accelerator test facilities can explore technology and concepts that could significantly reduce cost and risks associated with a 10 TeV pCM collider.

Realization of a future 10 TeV pCM collider will require resources and an organization at the global scale, first to carry out the R&D and then for the design, construction and operations of the most appropriate accelerator facility.

The time scale of a 10 TeV parton center-of-mass (pCM) collider is at least three decades away, with an R&D plan that spans 20-30 years. Significant R&D investment is needed to enable the development of the technologies for all options. The U.S. investment in this R&D and the associated facilities could exceed $100M over the coming decade. We describe briefly below two of the options for realizing a 10 TeV pCM collider: FCC-hh and a muon collider. A 10 TeV pCM collider based on plasma wakefield acceleration requires decades of R&D such as that described in Section 5 (AATF- kBELLA).

The scientific goals and science impact of a 10 TeV pCM collider, however realized, encompass a comprehensive physics portfolio that includes ultimate measurements in the Higgs sector and also a broad search program for new phenomena and particles. A unique aspect of a 10 TeV pCM collider is its potential to directly probe the causes of possible deviations in Higgs boson properties. At a Higgs factory, a deviation in the measured Higgs couplings would generally point to new physics outside the direct discovery reach of that collider. A 10 TeV pCM collider, on the other hand, would enable both precision measurements that illustrate indirect effects of new physics on Higgs properties and also direct discovery of the particles responsible. Overall, 10 TeV pCM colliders have a broad search program with a high potential for observing additional Higgs bosons if they exist. They can also directly probe hidden sector physics through Higgs exotic decays. Thus, the scientific impact of a future 10 TeV parton center-of-mass collider is rated ***"absolutely central".***

14.1.1 Project Description - FCC-hh

The FCC-hh would be the second stage of the FCC Integrated Project following the FCC-ee which is a candidate for the Higgs factory (Section 13). The FCC-hh would replace the FCC-ee, in the same underground tunnel, with a high energy proton-proton collider operating at about 100 TeV which meets the 10 TeV pCM criterion.

FCC-hh could also be upgraded to be a lepton-proton collider or enable operation as an ion-ion collider, providing for complementary physics.

14.1.2. FCC-hh Technical Readiness

We rate the technical readiness of the FCC-hh as ***"mission and technical requirements not yet fully defined"***. The FCC-hh is at a very early stage with operations necessarily following the completion of the FCC-ee scientific program, as well as requiring years of construction and installation. Scientific operation of the FCC-hh is foreseen to start in the 2070's.

The development of high-field, superconducting magnets is the key to realizing the FCC-hh and is anticipated to require decades of R&D. Significantly higher magnetic fields than are achievable in today's superconducting magnets (e.g. at the HL-LHC) are needed to enable a 100 TeV accelerator to be constructed in the FCC-ee tunnel. R&D on the continued development of superconducting magnets based on Nb_3Sn and on high temperature superconductors (HTS) is essential. There are many synergies with other potential uses for HTS magnets that make R&D in this direction especially compelling. The use of HTS magnets at the FCC-hh would potentially reduce costs, including power consumption. The Department of Energy supports a vigorous program in high field magnet development. Continuing and expanding this program ultimately for the FCC-hh would have many benefits to other DOE programs.

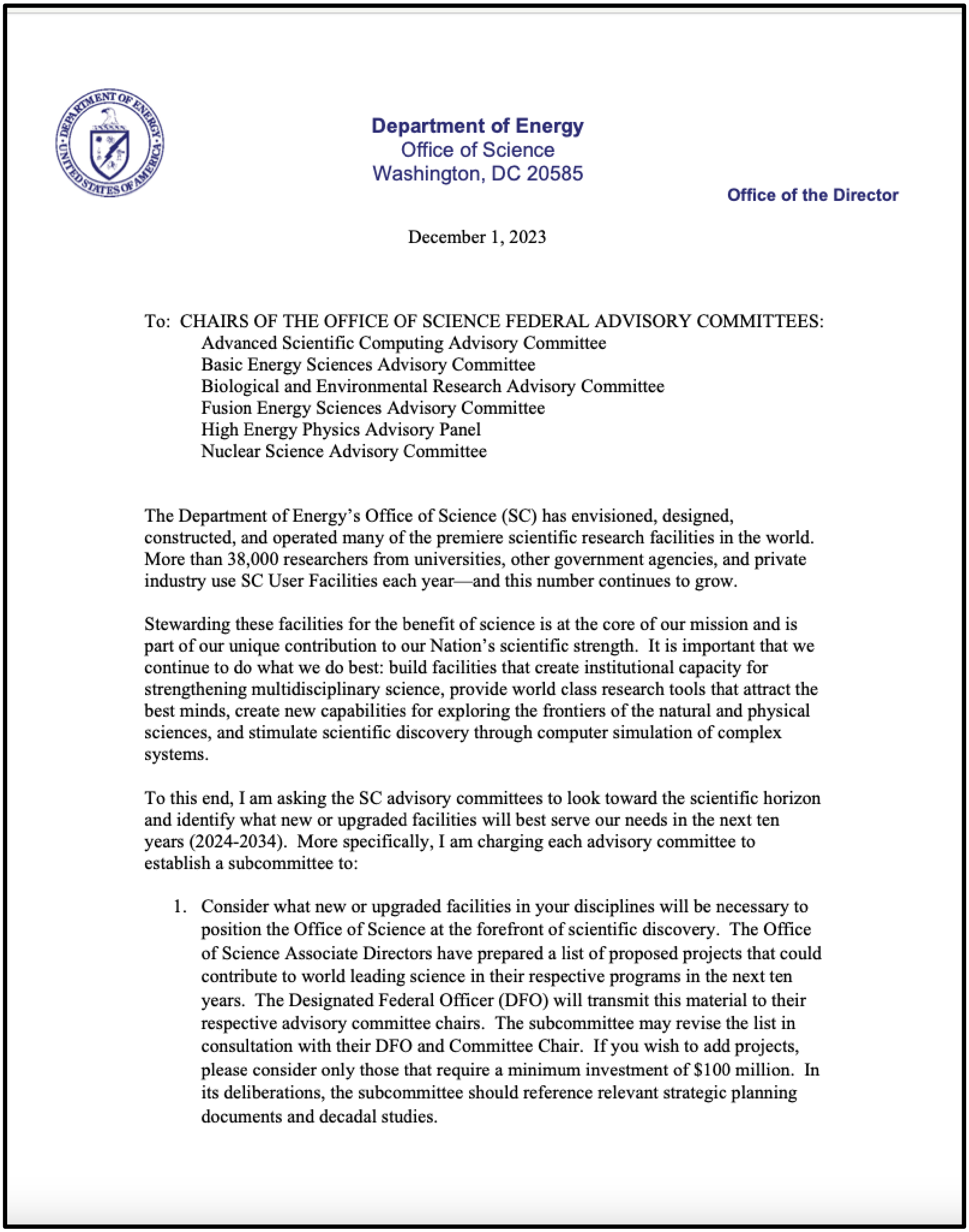
14.1.3 Project Description - Muon Collider

A muon collider presents an option both for substantial technological innovation and for bringing energy frontier colliders back to the United States. The footprint of a 10 TeV pCM muon collider would potentially fit on the existing Fermilab campus. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. The muons need to be captured and cooled (that is, directed into the appropriate channels in energy and space) before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses. The muons would be guided in a magnetic ring as is the case in other colliders.

14.1.4 Muon Collider Technical Readiness

We rate the technical readiness of the muon collider as ***"mission and technical requirements not yet fully defined."*** The basic concepts needed to realize a muon collider have been known for decades. However, each of the steps described above that create muon - muon collisions presents considerable technical challenges, many of which have never been confronted before. The P5 plan outlines and recommends an aggressive R&D program to determine the parameters for a muon collider demonstrator test facility by the end of this decade. This facility would test the feasibility of developing a muon collider in the following decade. The path toward a muon collider leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path could be an unparalleled global facility in the United States, bringing the world-wide community to the U.S.

Appendix A: Charge to the Subpanel



Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

December 1, 2023

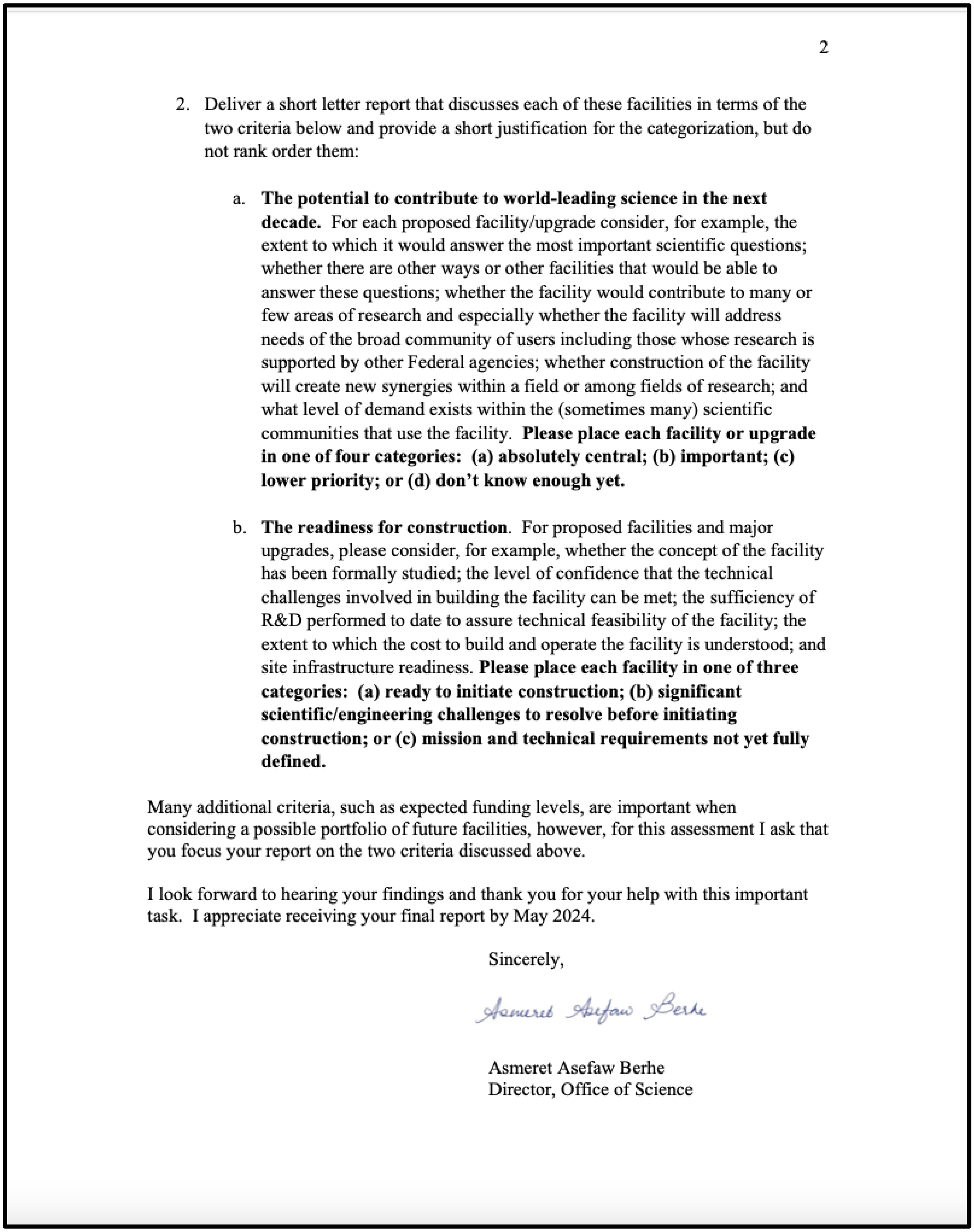
To: CHAIRS OF THE OFFICE OF SCIENCE FEDERAL ADVISORY COMMITTEES:
Advanced Scientific Computing Advisory Committee
Basic Energy Sciences Advisory Committee
Biological and Environmental Research Advisory Committee
Fusion Energy Sciences Advisory Committee
High Energy Physics Advisory Panel
Nuclear Science Advisory Committee

The Department of Energy's Office of Science (SC) has envisioned, designed, constructed, and operated many of the premiere scientific research facilities in the world. More than 38,000 researchers from universities, other government agencies, and private industry use SC User Facilities each year—and this number continues to grow.

Stewarding these facilities for the benefit of science is at the core of our mission and is part of our unique contribution to our Nation's scientific strength. It is important that we continue to do what we do best: build facilities that create institutional capacity for strengthening multidisciplinary science, provide world class research tools that attract the best minds, create new capabilities for exploring the frontiers of the natural and physical sciences, and stimulate scientific discovery through computer simulation of complex systems.

To this end, I am asking the SC advisory committees to look toward the scientific horizon and identify what new or upgraded facilities will best serve our needs in the next ten years (2024-2034). More specifically, I am charging each advisory committee to establish a subcommittee to:

1. Consider what new or upgraded facilities in your disciplines will be necessary to position the Office of Science at the forefront of scientific discovery. The Office of Science Associate Directors have prepared a list of proposed projects that could contribute to world leading science in their respective programs in the next ten years. The Designated Federal Officer (DFO) will transmit this material to their respective advisory committee chairs. The subcommittee may revise the list in consultation with their DFO and Committee Chair. If you wish to add projects, please consider only those that require a minimum investment of $100 million. In its deliberations, the subcommittee should reference relevant strategic planning documents and decadal studies.



2. Deliver a short letter report that discusses each of these facilities in terms of the two criteria below and provide a short justification for the categorization, but do not rank order them:

   a. **The potential to contribute to world-leading science in the next decade.** For each proposed facility/upgrade consider, for example, the extent to which it would answer the most important scientific questions; whether there are other ways or other facilities that would be able to answer these questions; whether the facility would contribute to many or few areas of research and especially whether the facility will address needs of the broad community of users including those whose research is supported by other Federal agencies; whether construction of the facility will create new synergies within a field or among fields of research; and what level of demand exists within the (sometimes many) scientific communities that use the facility. **Please place each facility or upgrade in one of four categories: (a) absolutely central; (b) important; (c) lower priority; or (d) don't know enough yet.**

   b. **The readiness for construction**. For proposed facilities and major upgrades, please consider, for example, whether the concept of the facility has been formally studied; the level of confidence that the technical challenges involved in building the facility can be met; the sufficiency of R&D performed to date to assure technical feasibility of the facility; the extent to which the cost to build and operate the facility is understood; and site infrastructure readiness. **Please place each facility in one of three categories: (a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; or (c) mission and technical requirements not yet fully defined.**

Many additional criteria, such as expected funding levels, are important when considering a possible portfolio of future facilities, however, for this assessment I ask that you focus your report on the two criteria discussed above.

I look forward to hearing your findings and thank you for your help with this important task. I appreciate receiving your final report by May 2024.

Sincerely,

Asmeret Asefaw Berhe

Asmeret Asefaw Berhe
Director, Office of Science

Appendix B: List of Committee Members

Natalie Roe, Chair
Lawrence Berkeley National Laboratory

Mei Bai
SLAC Accelerator National Laboratory

Mary Bishai
Brookhaven National Laboratory

Ken Bloom
University of Nebraska-Lincoln

Jodi Cooley
SNOLAB, Canada

Sarah Cousineau
Oak Ridge National Laboratory

Gil Gilchriese
Lawrence Berkeley National Laboratory

Doug Glenzinski
Fermi National Accelerator Laboratory

Klaus Honscheid
The Ohio State University

Reina Maruyama
Yale University

Anders Ryd
Cornell University

David Stuart
University of California, Santa Barbara

Sam Zeller
Fermi National Accelerator Laboratory

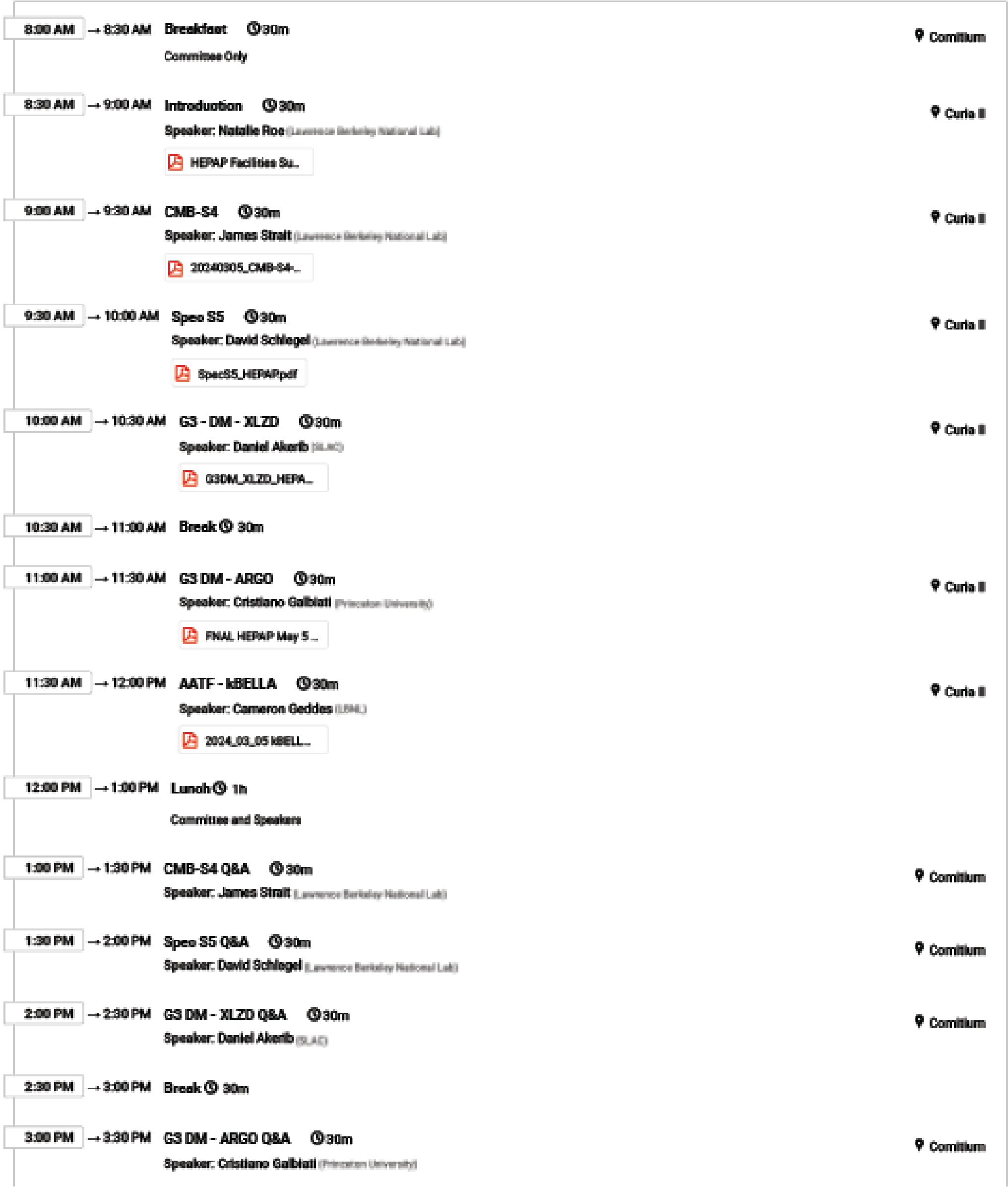
Appendix C: List of meetings and agenda for in-person meeting

The following meetings were held of the 2024 HEPAP Facilities Subpanel:

1. January 18, 2024, virtual
2. January 29, 2024, virtual
3. February 6, 2024, virtual
4. March 5-6, 2024, in-person meeting at Fermilab, see agenda below
5. March 12, 2024, virtual
6. March 20, 2024, FCC presentation by Frank Zimmerman (CERN), virtual
7. March 21, 2024, ILC presentation by Andy Lankford (UC Irvine), virtual
8. March 28, 2024, virtual
9. April 12, 2024, virtual
10. April 28 (TBD), 2024, virtual

Agenda for HEPAP Facilities Subpanel Meeting on March 5-6, 2024 at Fermilab:

Tuesday, March 5



8:00 AM → 8:30 AM **Breakfast** ⏱30m 📍 Comitium
Committee Only

8:30 AM → 9:00 AM **Introduction** ⏱30m 📍 Curia II
Speaker: Natalie Roe (Lawrence Berkeley National Lab)
HEPAP Facilities Su...

9:00 AM → 9:30 AM **CMB-S4** ⏱30m 📍 Curia II
Speaker: James Strait (Lawrence Berkeley National Lab)
20240305_CMB-S4-...

9:30 AM → 10:00 AM **Spec S5** ⏱30m 📍 Curia II
Speaker: David Schlegel (Lawrence Berkeley National Lab)
SpecS5_HEPAP.pdf

10:00 AM → 10:30 AM **G3 - DM - XLZD** ⏱30m 📍 Curia II
Speaker: Daniel Akerib (SLAC)
G3DM_XLZD_HEPA...

10:30 AM → 11:00 AM **Break** ⏱ 30m

11:00 AM → 11:30 AM **G3 DM - ARGO** ⏱30m 📍 Curia II
Speaker: Cristiano Galbiati (Princeton University)
FNAL HEPAP May 5 ...

11:30 AM → 12:00 PM **AATF - kBELLA** ⏱30m 📍 Curia II
Speaker: Cameron Geddes (LBNL)
2024_03_05 kBELL...

12:00 PM → 1:00 PM **Lunch** ⏱ 1h
Committee and Speakers

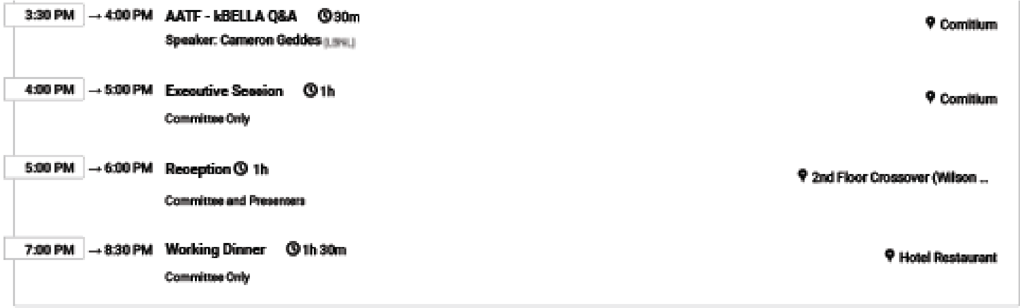
1:00 PM → 1:30 PM **CMB-S4 Q&A** ⏱30m 📍 Comitium
Speaker: James Strait (Lawrence Berkeley National Lab)

1:30 PM → 2:00 PM **Spec S5 Q&A** ⏱30m 📍 Comitium
Speaker: David Schlegel (Lawrence Berkeley National Lab)

2:00 PM → 2:30 PM **G3 DM - XLZD Q&A** ⏱30m 📍 Comitium
Speaker: Daniel Akerib (SLAC)

2:30 PM → 3:00 PM **Break** ⏱ 30m

3:00 PM → 3:30 PM **G3 DM - ARGO Q&A** ⏱30m 📍 Comitium
Speaker: Cristiano Galbiati (Princeton University)



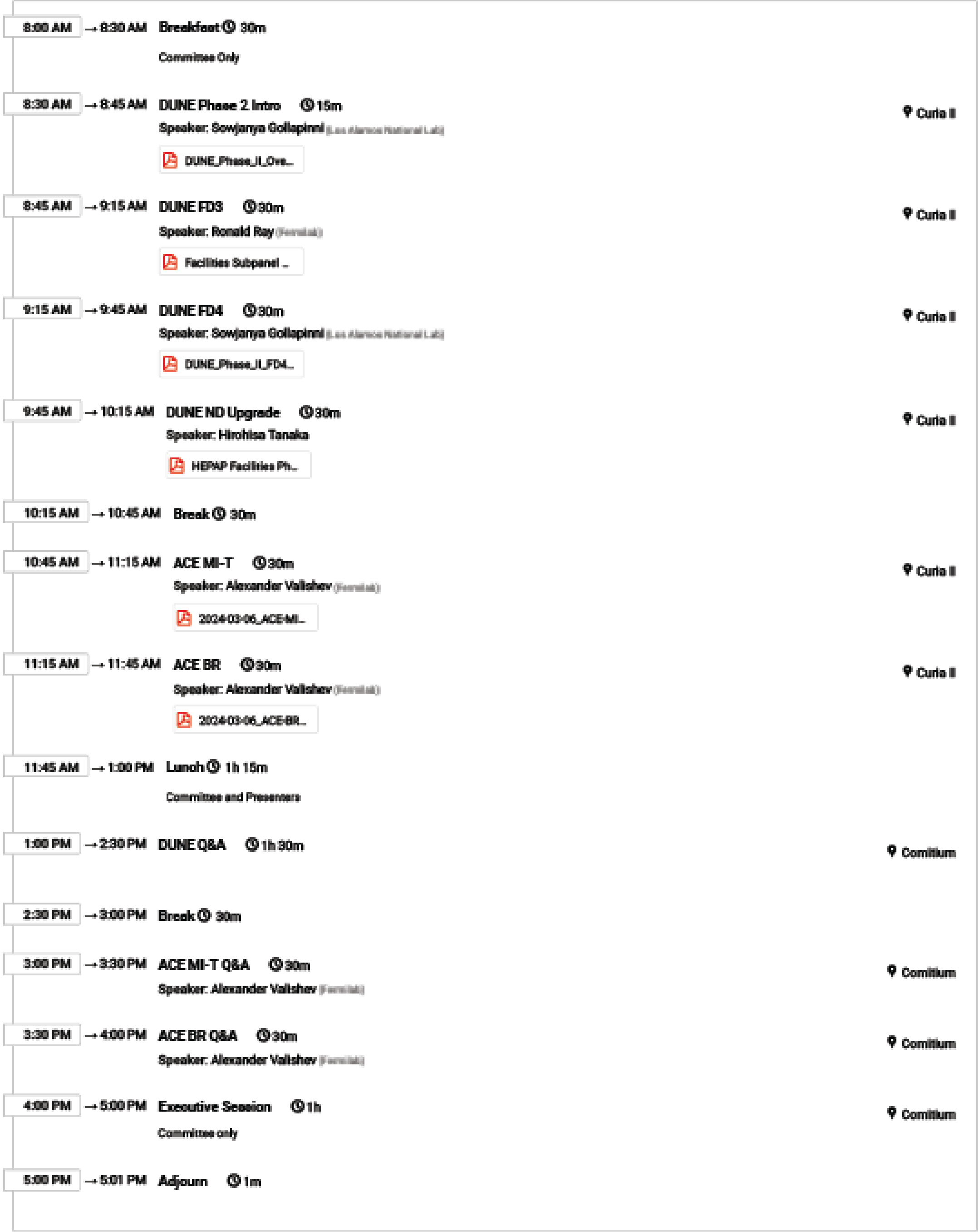
3:30 PM → 4:00 PM **AATF - kBELLA Q&A** ⏱30m 📍 Comitium
Speaker: Cameron Geddes (LBNL)

4:00 PM → 5:00 PM **Executive Session** ⏱1h 📍 Comitium
Committee Only

5:00 PM → 6:00 PM **Reception** ⏱ 1h 📍 2nd Floor Crossover (Wilson ...
Committee and Presenters

7:00 PM → 8:30 PM **Working Dinner** ⏱1h 30m 📍 Hotel Restaurant
Committee Only

Wednesday, March 6



8:00 AM → 8:30 AM **Breakfast** 🕓 30m
Commitee Only

8:30 AM → 8:45 AM **DUNE Phase 2 Intro** 🕓 15m 📍 Curia II
Speaker: Sowjanya Gollapinni (Los Alamos National Lab)
DUNE_Phase_II_Ove...

8:45 AM → 9:15 AM **DUNE FD3** 🕓 30m 📍 Curia II
Speaker: Ronald Ray (Fermilab)
Facilities Subpanel ...

9:15 AM → 9:45 AM **DUNE FD4** 🕓 30m 📍 Curia II
Speaker: Sowjanya Gollapinni (Los Alamos National Lab)
DUNE_Phase_II_FD4...

9:45 AM → 10:15 AM **DUNE ND Upgrade** 🕓 30m 📍 Curia II
Speaker: Hirohisa Tanaka
HEPAP Facilities Ph...

10:15 AM → 10:45 AM **Break** 🕓 30m

10:45 AM → 11:15 AM **ACE MI-T** 🕓 30m 📍 Curia II
Speaker: Alexander Valishev (Fermilab)
2024-03-06_ACE-MI...

11:15 AM → 11:45 AM **ACE BR** 🕓 30m 📍 Curia II
Speaker: Alexander Valishev (Fermilab)
2024-03-06_ACE-BR...

11:45 AM → 1:00 PM **Lunch** 🕓 1h 15m
Committee and Presenters

1:00 PM → 2:30 PM **DUNE Q&A** 🕓 1h 30m 📍 Comitium

2:30 PM → 3:00 PM **Break** 🕓 30m

3:00 PM → 3:30 PM **ACE MI-T Q&A** 🕓 30m 📍 Comitium
Speaker: Alexander Valishev (Fermilab)

3:30 PM → 4:00 PM **ACE BR Q&A** 🕓 30m 📍 Comitium
Speaker: Alexander Valishev (Fermilab)

4:00 PM → 5:00 PM **Executive Session** 🕓 1h 📍 Comitium
Committee only

5:00 PM → 5:01 PM **Adjourn** 🕓 1m

Appendix D: Definition of Acronyms

Acronym	Stands For
AATF	Advanced Accelerator Test Facilities
AAC	Advanced Acceleration Concept program
ACE	Accelerator Complex Evolution
ACE-BR	Accelerator Complex Evolution Booster Replacement
ACE-MIRT	Accelerator Complex Evolution Main Injector, Ramp, and Target
ACT	Atacama Cosmology Telescope
AI/ML	Artificial Intelligence/Machine Learning
ARGO	Astrophysical Radiation Ground-based Observatory
AWA	Argonne Wakefield Accelerator
BELLA	Berkeley Lab Laser Accelerator
BICEP	Background Imaging of Cosmic Extragalactic Polarization
BSM	Beyond Standard Model
CCD	Charge Coupled Device
CMB	Cosmic Microwave Background
CMB-S4	Cosmic Microwave Background Stage 4
CP	Charge Parity
CTIO	Cerro Tololo Inter-American Observatory
DARWIN	DARk matter WImp search with liquid XenoN
DEAP	Dark matter Experiment using Argon Pulse shape discrimination
DECam	Dark Energy Camera
DESI	Dark Energy Spectroscopic Instrument
DUNE	Deep Underground Neutrino Experiment
FACET	Facility for Advanced Accelerator Experimental Tests
FCC	Future Circular Collider
FCC-ee	Future Circular Collider - electron(e^-)-positron(e^+)
FCC-hh	Future Circular Collider - proton-proton
FD3	Far Detector 3
FD4	Far Detector 4
GARD	Generic Accelerator R&D program
G3DM	Generation 3 Dark Matter
HEP	High Energy Physics
HEPAP	High Energy Physics Advisory Panel
HL-LHC	High Luminosity Large Hadron Collider
HPDF	High-Performance Data Facility
HTS	High Temperature Superconductors
ICFA	International Committee for Future Colliders
IDT	ILC International Development Team
ILC	International Linear Collider
ITN	ILC Technology Network
kBELLA	kHz Berkeley Lab Laser Accelerator

KPNO	Kitt Peak National Observatory
LAr	Liquid Argon
LAr TPC	Liquid Argon Time Projection Chamber
LBNF	Long-Baseline Neutrino Facility
LHC	Large Hadron Collider
LiteBIRD	Lite satellite for study of B-mode polarization & Inflation from cosmic background Radiation Detection
LNGS	Laboratori Nazaionali del Gran Sasso
LPA	Laser Plasma wakefield Acceleration
LSST	Large Synoptic Survey Telescope
LZ	LUX-ZEPLIN
MCND	More Capable Near Detector
MI	Main Injector
nEXO	next generation Enriched Xenon Observatory
NOIRLab	National Optical-Infrared Astronomy Research Laboratory
P5	Particle Physics Project Prioritization Panel
pCM	parton Center of Mass
PIP-II	Proton Improvement Plan II
QCD	Quantum Chromo Dynamics
RF	Radio Frequency
SNOLAB	A deep underground research laboratory located in Sudbury, Ontario, Canda
SO	Simons Observatory
Spec-S5	Spectroscopic Survey Stage 5
SPT	South Pole Telescope
SuperCDMS	Super Cryogenic Dark Matter Search
SURF	Sanford Underground Research Facility
TPC	refers to Time Projection Chamber or Total Project Cost depending on the use case
WIMP	Weakly Interacting Massive Particle
XENONnT	n Ton XENON experiment
XFEL	X-ray Free Electron Laser
XLZD	consortium of three collaborations: XENON, LZ, and DARWIN

Important References:

- 2023 Particle Physics Project Prioritization Panel (P5) Report, Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics, https://www.usparticlephysics.org/2023-p5-report/

- Summary report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021), https://arxiv.org/abs/2301.06581

- HEP International Benchmarking Study, https://science.osti.gov/-/media/hep/hepap/pdf/202203/International_Benchmarking_HEPAP_2023112.pdf

- 2014 Particle Physics Project Prioritization Panel (P5) Report, Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context, https://www.usparticlephysics.org/wp-content/uploads/2018/03/FINAL_P5_Report_053014.pdf