

Science and Technology Strategy for the Future

Fermilab's Strategic Plan (Updated May 2017)

This document is adapted from the Fermi National Accelerator Laboratory FY 2017 Annual Lab Plan, submitted to the U.S. Department of Energy Office of Science in April 2017. The Annual Lab Plan format is prescribed by DOE and the ALP document is written for DOE staff members, whereas this document has been edited to provide an overall summary of Fermilab's strategic plan to lab employees and users.

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Our Mission

Fermi National Accelerator Laboratory is an international hub for particle physics located 40 miles west of Chicago, Illinois. Fermilab's 1,800 employees and more than 2,600 users drive discovery in particle physics by building and operating world-leading accelerator and detector facilities, performing pioneering research with national and global partners, and developing new technologies for science that support U.S. industrial competitiveness.

Fermilab's science strategy for the future delivers on the U.S. particle physics community's goals as outlined in the Particle Physics Project Prioritization Panel's 2014 report (P5 report)¹. The strategy's primary ten-year goal is to establish a world-leading neutrino science program anchored by the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). The flagship facility comprised of LBNF and DUNE will be the first international mega-science project based at a Department of Energy (DOE) national laboratory and is the largest new particle physics project being undertaken anywhere in the world since the Large Hadron Collider at CERN.

Fermilab's particle accelerator complex is the only one in the world to produce both low- and high-energy neutrino beams for study. Fermilab integrates U.S. universities and national laboratories into the global particle physics enterprise through its Large Hadron Collider (LHC) programs; accelerator science, neutrino science and precision science programs; and dark-energy and dark-matter experiments. Large-scale computing facilities drive research in particle physics and other fields of science. The laboratory's R&D infrastructure as well as its engineering and technical expertise advance particle accelerator and detector technology for use in science and society. Fermilab's partnerships and technology transitions programs, including the Illinois Accelerator Research Center, leverage this expertise to apply particle physics technologies to problems of national importance in energy and the environment, national security, and industry.

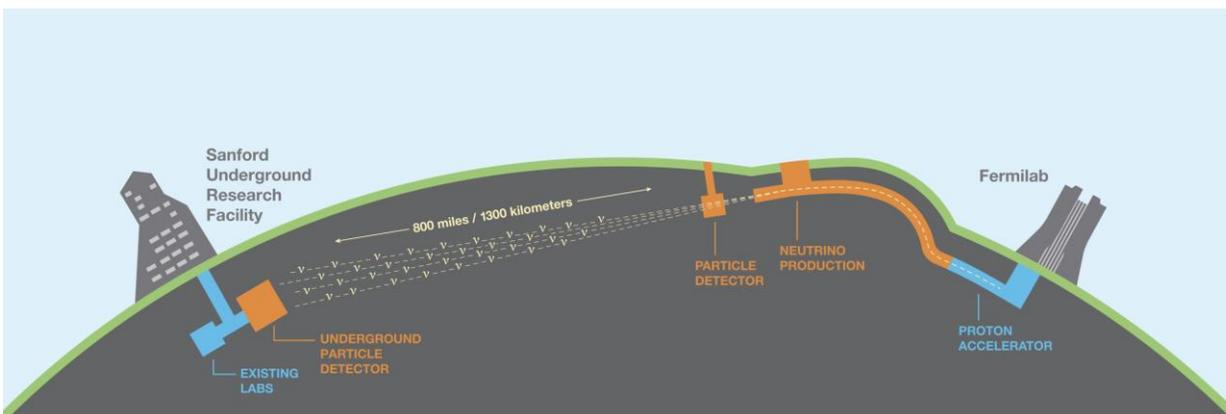
Our Science and Technology Strategy for the Future

Fermilab's primary ten-year goal is to establish a world-leading neutrino science program led by LBNF and DUNE and powered by megawatt beams from an upgraded and modernized accelerator complex. This national flagship particle physics initiative will be the first-ever large-scale international science facility hosted at a U.S. DOE laboratory. Identified by the U.S. particle physics community in its consensus P5 report as the highest-priority domestic construction project in its timeframe, LBNF/DUNE is

¹ <http://www.usparticlephysics.org/strategy.html>

attracting global partners willing to invest significant financial, technical, and scientific resources. A five-year program that includes current and near-term neutrino experiments and an R&D platform that serves the wider neutrino physics community is driving the development of capabilities and bringing together the international community needed for LBNF/DUNE.

Fermilab's success in operating both low- and high-energy neutrino beams, its core scientific and technical capabilities, its project management expertise, and its international reputation as an excellent scientific partner are making it the destination of choice for the world's neutrino researchers.



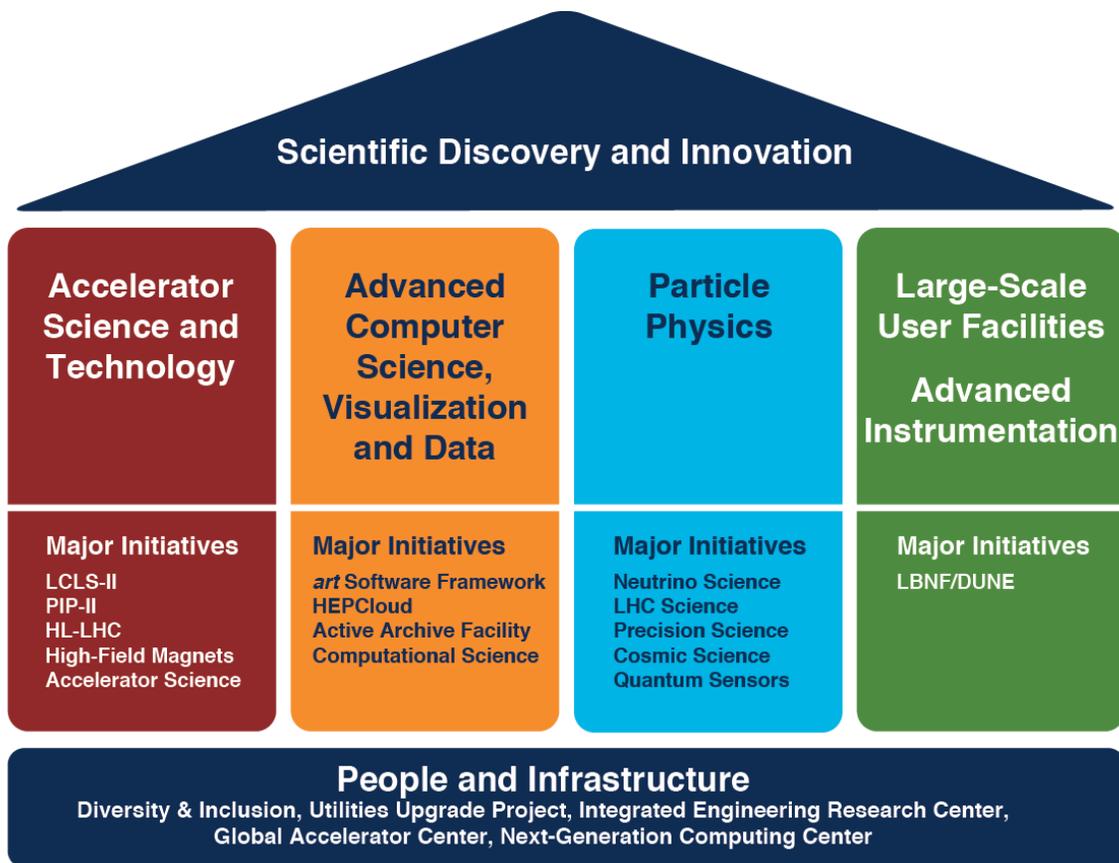
Artist's rendering of the Long-Baseline Neutrino Facility (LBNF) that will send a very intense beam of neutrinos 1300 km (800 miles) to a massive liquid-argon detector located deep underground in the Sanford Underground Research Facility in South Dakota.

As the country's particle physics and accelerator laboratory, Fermilab is moving forward with new experiments, new international and national partnerships, and R&D programs that support all of the science drivers identified in the P5 report:

- Over the next decade Fermilab will continue to be the leading U.S. center – and the second leading center in the world – for Large Hadron Collider science, enabling leading roles for U.S. scientists in future LHC discoveries and driving key contributions to upgrades of the LHC accelerator and the Compact Muon Solenoid (CMS) detector.
- The start of the Muon g-2 and Mu2e experiments will turn Fermilab into the world center for the study of muons, particles whose properties may open a window onto new physics.
- Fermilab will support the community-endorsed diversified approach to dark matter detection, including key roles in the Generation 2 dark matter projects.
- The laboratory's leading role in the Dark Energy Survey, supporting roles in its successor experiments and involvement with the South Pole Telescope will ensure continued U.S. leadership in the study of cosmic acceleration.
- In partnership with academics from nearby universities and colleagues at Argonne National Laboratory, Fermilab will establish Illinois as a world center for advanced accelerator research with a suite of unique test facilities and R&D programs that will drive major advances in accelerator science and technology.

- Fermilab will collaborate with university, lab, and industry partners in the fast-moving area of quantum information science, developing new quantum sensors for particle physics experiments while advancing quantum computing and quantum networks for HEP applications.

Fermilab’s four core capabilities define the scope of the laboratory’s science and technology strategy. Major initiatives identified within each of the four core capabilities represent the focus areas for the majority of the laboratory’s time and effort over the next 10 years. A “Building for Science” theme focuses on major initiatives related to people, infrastructure, and R&D to support the strategy. The graphic below illustrates how the lab’s core capabilities and major initiatives comprise the strategy focused on scientific discovery and innovation.



Our Core Capabilities

As defined by criteria established by the U.S. Department of Energy Office of Science (DOE/SC), Fermilab has four core capabilities that support the DOE/SC Scientific Discovery and Innovation mission:

1. Particle physics
2. Large-scale user facilities and advanced instrumentation
3. Accelerator science and technology
4. Advanced computer science, visualization, and data

The laboratory's four core capabilities are leveraged to deliver on DOE science priorities. High-intensity particle beams are used to answer compelling questions in neutrino science and reveal new physics phenomena through high-precision tests of the Standard Model of particle physics. High-energy particle beams are used to discover new particles and probe the architecture of the fundamental forces of nature. Underground experiments as well as telescopes are used to uncover the natures of dark matter and dark energy and probe the cosmic microwave background. The 2014 report of the Particle Physics Project Prioritization Panel (P5) identified the long-term science priorities for the U.S. particle physics community, and the laboratory is executing its strategic plan in alignment with P5, DOE, and the science community.

Particle Physics

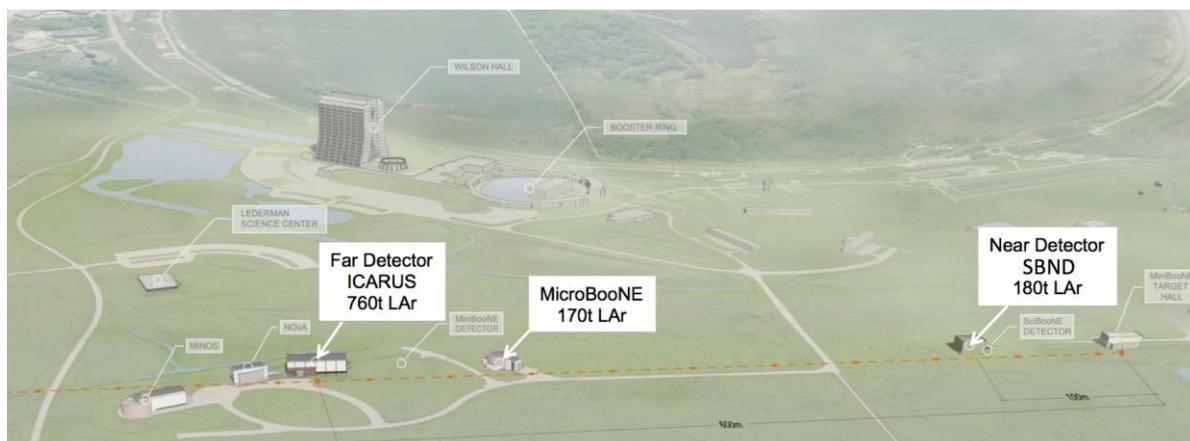
Fermilab's science strategy enables a diverse science program with major discovery potential, from the science of neutrinos and the Large Hadron Collider, to the search for dark matter and anomalies in precision science, to the study of dark energy. To realize this strategy, the laboratory is advancing major initiatives in neutrino science, LHC science, precision science, cosmic science, and quantum sensors. The overarching goal is to maintain and enhance a world-leading program that serves the needs and scientific goals of the U.S. and international particle physics community.

Neutrino science

The revolutionary discovery that neutrinos can change from one type to another—and hence have mass—sparked a global initiative to investigate the phenomenon known as neutrino oscillations. The scientific community's vision for the future of U.S. particle physics is laid out in the P5 report and envisions Fermilab as the most advanced and diverse accelerator-based neutrino facility in the world. The community will achieve this ambitious goal by completing major upgrades to Fermilab's accelerator complex to deliver megawatt particle beams, building a new suite of three on-site neutrino experiments that will also serve as a test bed for advanced neutrino detectors, and leveraging international

partnerships to construct the flagship international LBNF/DUNE facility. In 2015, Fermilab identified the need to establish a neutrino user community with more than 1,000 members as a 10-year goal. This goal will be achieved 7 years ahead of schedule, with the DUNE collaboration alone now numbering 950 scientists from 30 countries and expected to pass 1,000 members within the next year.

Fermilab is the one facility in the world that simultaneously operates two accelerator-based neutrino beams. These two intense beams drive an ensemble of experiments that are studying the detailed properties of neutrinos at both low and high energies and over both short and long distances. Updated results from the long-baseline NOvA experiment, based on 16% of its initial planned data set, disfavor at more than 2.5 sigma a muon-tau flavor symmetry in neutrino mixing. NOvA results also disfavor combinations of an inverted neutrino mass hierarchy, lower values of the so-called atmospheric mixing angle, and CP violation effects that would suppress the appearance probability for electron neutrinos. The success of current and future neutrino experiments depends critically on beam delivery. Accelerator improvements underway now, and even more ambitious upgrades planned for the next decade, will guarantee Fermilab's pre-eminence as the world's source of accelerator-driven neutrino beams for the next 20 years. The first of these upgrades, the Proton Improvement Plan (PIP), has doubled the number of protons used to make low-energy neutrino beams and increased proton beam power for high-energy neutrino experiments to 700 kW. The next accelerator upgrade (PIP-II) will replace the lab's existing 40-year-old linear accelerator with a new one based on superconducting RF cavities. PIP-II will increase the proton beam intensity for high-energy neutrino experiments to 1.2 MW by 2025, and will provide a platform for a future increase of the proton beam intensity to 2 MW for experiments envisioned beyond 2025. Fermilab is also proposing a series of upgrades, PIP-I+, to achieve up to 1 MW by upgrading the existing accelerator complex prior to PIP-II.



The new international short-baseline neutrino program at Fermilab that will include three liquid-argon (LAR) detectors on the Booster neutrino beam line: SBND at 110m, MicroBooNE at 470m, and the ICARUS T600 detector at 600m from the Booster neutrino source.

For the short-baseline neutrino program, a three-detector suite of experiments being built on the Fermilab site has the potential to make a groundbreaking discovery: the discovery of a fourth type of neutrino, the so-called sterile neutrino. An international team is preparing three detectors based on liquid-argon time-projection-chamber (TPC) technology with the goal of bringing all three online by 2019. Besides definitively addressing time-critical physics, this program will also provide an important platform for detector development and international coordination towards LBNF/DUNE. The first in this succession is the MicroBooNE experiment, using a 170-ton detector that began taking data in 2015. While pushing towards significant advances in the liquid-argon TPC technology, MicroBooNE will also produce the first measurements of low-energy neutrino interactions in argon. By 2019, two additional detectors will have come online: the Short-Baseline Neutrino Detector (SBND) that will be closest to the neutrino source; and the ICARUS T600—the largest liquid-argon TPC in the world—that has been refurbished at CERN and will be transported to Fermilab in 2017.

Although the future short- and long-baseline neutrino programs involve multiple scientific collaborations that have distinct scientific goals, synergies in liquid-argon TPC technology and personnel provide coherence. The two programs together provide a coordinated approach to addressing some of the most fundamental questions about neutrinos, but also provide a means to grow the technical expertise necessary to achieve success. The integrated program managed and enabled by facilities and staff at Fermilab will provide groundbreaking opportunities in research while also developing the expertise, technology, and computing required for the long-term program.

The ultimate goal of Fermilab's neutrino science strategy is the operation of the LBNF/DUNE program. This new large-scale user facility is a major initiative for the laboratory and is discussed in more detail starting on page 13.

LHC science

The Large Hadron Collider (LHC) at CERN is currently the only machine that allows the study of the Higgs boson, and is a critical component of multifaceted explorations of dark matter and the unknown—three of the key science drivers identified in the P5 report. Fermilab's four core capabilities allow the laboratory to play a significant role in driving LHC science over the next ten years through leadership roles in the CMS collaboration and technological contributions to the LHC accelerator and CMS detector upgrades. Two phases of upgrades, including the ongoing LHC CMS detector upgrade and the upcoming detector and accelerator upgrades for High Luminosity LHC (HL-LHC) operation, were identified in the P5 report as the U.S. community's highest-priority near-term large project. Looking farther ahead, Fermilab plays critical roles in carrying out long-term R&D for accelerator technology and the physics program of future colliders.

Fermilab's continued participation in the international CMS experiment will ensure the collaboration's scientific success throughout LHC Run 2 (2015-2018), Run 3 (2021-2023), and into the HL-LHC era (beginning in 2026). Scientific leadership for the CMS experiment is currently being provided by Joel Butler, a Fermilab scientist elected as spokesperson for the 3,000-member CMS collaboration in 2016. The laboratory also provides scientific leadership through contributions of its approximately 60 scientists to publication of innovative analyses of CMS data, technical and managerial contributions to detector upgrades and operations, and maintenance and continuing development of computing facilities and software infrastructure.

Fermilab has proposed making the CMS Center a DOE/SC national user facility that promotes U.S. scientific leadership at the LHC by supporting over 1,000 users through its LHC Physics Center (LPC), LHC Remote Operations Center, and dedicated computing facilities. In this context, the LPC already provides a vibrant on-shore academic environment focused around the LHC that includes tutorials, seminars, colloquia, visiting theorists, and organized and informal discussions. The annual LPC-hosted CMS Data Analysis School is crucial for training the newest members of the U.S. particle physics community, and the LPC Distinguished Researcher program is critical for maintaining a core group of physicists with diverse expertise at the LPC. The proposal to make the CMS Center a national user facility is currently under review by DOE/SC.

Precision science

Experiments that study the properties of muons with high precision have the potential to elucidate the physics that leads to a low-mass Higgs boson, indicate the existence of new dark sectors responsible for dark matter, shed light on non-standard neutrino interactions, and indirectly probe energy scales as high as 104 TeV. Muon physics was identified by the P5 report as a critical component of the science driver to "explore the unknown" and the strategy correspondingly endorsed the construction of a Muon Campus at Fermilab that includes a new muon beam and two forefront experiments. This year the Muon g-2 experiment will begin using the new muon beam to carry out the highest-precision measurement of the anomalous magnetic moment of the muon and by 2021, the Mu2e experiment will be searching for charged-lepton-flavor violation using muons. The growing precision science program currently hosts 385 users from 57 U.S. and international institutions.

To realize the vision of a Muon Campus, Fermilab has constructed the world's brightest muon source, has refurbished the Muon g-2 storage ring into a first-in-class technical instrument, and is building the Mu2e project. The new muon source, to be commissioned this year, will eventually deliver a muon flux to the Muon g-2 experiment that is 20 times greater than that achieved for the previous experiment at Brookhaven National Laboratory. The refurbished Muon g-2 storage ring will allow for a measurement of the muon's magnetic moment that is a factor of four more precise than previously achieved. The Mu2e

apparatus will allow for a factor of 10,000 improvement in the search for charged-lepton-flavor violation. Building and operating these facilities brings together expertise from particle, nuclear, and atomic physics. Fermilab staff designed most aspects of the technical instrumentation for Muon g-2 and Mu2e, and through their leading roles in the two experiments' scientific collaborations defined the physics program of the Muon Campus. The laboratory's strong lattice gauge theory group is deeply embedded in improving the Standard Model calculation of Muon g-2 so that the precision in the expected value will shrink in relation to the expected improved precision in the experimental value.

Fermilab's accelerator science and technology core capability includes the ability to develop technologies to accelerate, characterize, and manipulate the particle beams that are required for precision science. For example, experimental, computational, and theoretical research on the physics of particle beams has been important in designing beam delivery systems for Muon g-2 and Mu2e. The configuration of the Fermilab Accelerator Complex is unique in its ability to simultaneously deliver beam to the muon and neutrino programs, and the PIP-II upgrade will support a factor of ten enhancement in beams delivered to a possible second generation Mu2e experiment. Fermilab's core capability in advanced computer science, visualization, and data is critical to the success of this program since the multi-petabyte data sets are orders of magnitude larger than those generated by the previous iterations of these experiments.

The Muon Campus is a significant addition to Fermilab's scientific user facility and is in close proximity to the Central Campus. The Muon Campus program advances the mission of the DOE Office of High Energy Physics with the ability to deliver significant and potentially revolutionary results. The program has helped foster integration by driving closer collaboration with Brookhaven, Argonne and Lawrence Berkeley national laboratories, with the NSF through a Major Research Instrumentation grant to provide the detector package for Muon g-2, and with seven other nations to optimize the use of the resources available in achieving our scientific goals.

Cosmic science

The P5 report identified the new physics of dark matter, understanding cosmic acceleration, and pursuing the physics of neutrinos as three of the primary science drivers in particle physics, each of which is addressed by the study of cosmic science. With its strong particle astrophysics program and advanced infrastructure, Fermilab is a leader in all of these areas and an active participant in the DOE Cosmic Visions planning process. Over the next decade, the laboratory will continue to explore cosmic acceleration through large-scale surveys, build the next generation of detectors for the cosmic microwave background, and advance the search for dark matter using select technologies.

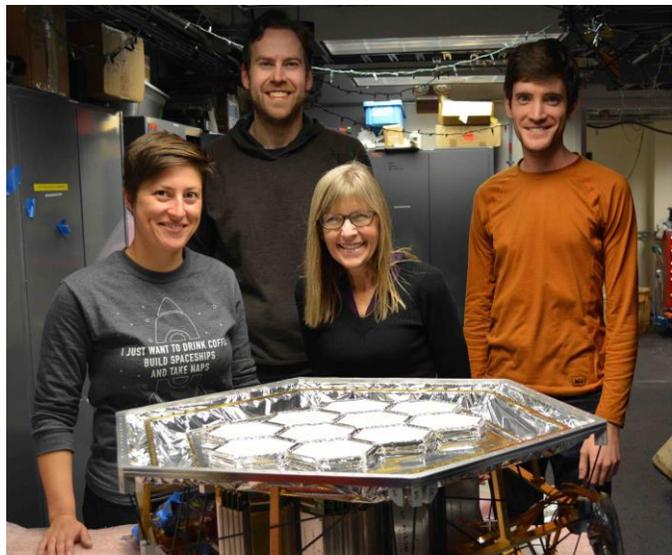
The Dark Energy Survey (DES), which recently finished its fourth year of data taking, is the world leader in exploring the mysterious phenomenon of dark energy. Fermilab both manages operations and leads

analysis of data from this forefront survey. Over 100 scientific papers have been submitted and 83 published so far. Many of these papers covered the groundwork needed to extract the full potential of the DES data; new cosmology results are expected in 2017. Fermilab scientists led the analysis that placed tight constraints on intermediate mass primordial black holes as a dark matter candidate and have built frameworks that enable the collaboration to go from catalogs to cosmological constraints. These frameworks are being used in the analysis that will be released in Spring 2017. The first cosmological results from DES supernovae are also expected in 2017. These results will use several new techniques, including a deep learning technique invented at Fermilab.

Over the next ten years, Fermilab will play important roles in two cosmic surveys strongly endorsed by P5, the Dark Energy Spectroscopic Instrument (DESI) and the Large Synoptic Survey Telescope (LSST). For DESI, Fermilab will provide scientific management, a massive image corrector system, the online database, software to ensure that DESI observes the correct targets, and detector packaging and testing. Because of its experience leading the Sloan Digital Sky Survey and DES, Fermilab has a unique understanding of the challenges facing LSST and will be an active participant in the LSST Dark Energy Science Collaboration. The laboratory is currently developing a software framework for dark energy science at LSST based on the one used by DES, leveraging Fermilab's core capability in advanced computer science.

Motivated in part by ideas generated by the Fermilab Astro Theory Group, the Cosmic Microwave Background (CMB) has become the most precise tool for understanding cosmology, with significant implications for particle physics. The P5 report endorsed DOE participation in CMB-S4, a U.S.-led program to build a next-generation CMB experiment and enable new constraints on the physics of inflation, neutrinos, and dark energy. Fermilab plans to become a leader in CMB studies over the next ten years.

Building off expertise developed for DES, Fermilab led the design, fabrication, and integration of the new SPT-3G camera for the South Pole Telescope (SPT). This fall, the SPT-3G camera was completed on schedule and shipped to the South Pole. The Fermilab team spent months at the South Pole installing and commissioning the SPT-3G camera, which will improve the mapping speed of the SPT by



The Fermilab CMB team in front of the fully assembled SPT-3G focal plane at the South Pole, Antarctica. Pictured from left to right: Alexandra Rahlin (postdoc), Bradford Benson (scientist), Donna Kubik (physicist), and Adam Anderson (postdoc).

more than a factor of ten. A recent Laboratory Directed Research and Development (LDRD) award has allowed Fermilab scientists to begin developing next generation CMB detectors and instrumentation, positioning the laboratory for a leading role on CMB-S4.

Fermilab is committed to understanding the nature of dark matter and plays a key role in the second-generation (G2) dark matter projects now underway. Over the next several years, Fermilab will co-lead the SuperCDMS-SNOLAB project with SLAC National Accelerator Laboratory, building on world-leading limits on low-mass dark matter released in the past year. Fermilab is also a strong contributor to the LUX-Zeplin (LZ) experiment at the Sanford Underground Research Facility, providing cryogenic and process control engineering to safely manage the 10 tons of liquid xenon required by the detector. The LZ experiment will improve on the current best sensitivity for high-mass dark matter by a factor of a hundred. Rounding out the G2 program, Fermilab is the DOE lead lab for the operations phase of the Axion Dark Matter Experiment (ADMX) that searches for axions that scatter in a strong magnetic field and convert into microwave photons. Also, supported in part by LDRD funding, Fermilab's core capability in accelerator science and technology will be used to study high-quality-factor resonant cavities and single microwave photon detectors, enabling future high-mass axion searches.

Fermilab's detector R&D program has supported many efforts in cosmic science. Fermilab led the development of the COUPP/PICO bubble-chamber dark-matter detectors and leveraged its DES experience to pioneer the use of Charge Coupled Devices (CCDs) as low-threshold detectors in the Dark Matter in CCDs (DAMIC) experiment, with both efforts leading to recent world-leading results. The DAMIC effort, which was supported by a Presidential Early Career Award for Scientists and Engineers, and the PICO effort grew into international collaborations. Leadership of the DAMIC collaboration was recently transferred from Fermilab to the University of Chicago to focus Fermilab's efforts on the G2 dark matter program. Similarly, leadership of the PICO collaboration was recently moved from Fermilab to Canada and Pacific Northwest National Laboratory. Fermilab researchers supported by a 2016 LDRD award developed even lower-noise CCD readout, enabling the detection of single electrons and opening a potential new window for testing dark photon models of dark matter. Fermilab will continue R&D towards next-generation detectors for cosmic science, for example developing cryogenic systems for superconducting detectors with sub-Kelvin capabilities.

Cosmic science provides a showcase for the benefits of broad collaboration among DOE laboratories and universities. As noted in the P5 report, particle physics drivers are intertwined, and cross-project expertise is required to extract the most science from the data. Fermilab scientists are leading these efforts. For example, the dwarf galaxies discovered by DES have led to dark matter constraints, and joint analyses of the DES and SPT data sets have placed new constraints on dark energy and gravity at large

scales. Over the next decades, Fermilab will act as a central platform and host for understanding cosmic science data, maximizing the scientific output of experiments across the field.

Quantum sensors

Research into quantum sensors provides an opportunity for cross-fertilization and technology transfer between the field of particle physics and the field of quantum computing. Quantum computing relies on the accurate manipulation of qubits of information encoded using single microwave photons. The high fidelity required for quantum computing translates into high quantum efficiency and low dark rates when these qubit devices are repurposed as single-photon detectors for HEP. The dark noise levels of these quantum non-demolition photon detectors can be orders of magnitude below those of detectors based on even quantum-limited linear amplifiers. An application is already envisioned in which qubit-based photon detectors may enable the next generation of dark matter axion experiments that would search for higher-mass axions. Moreover, the several-gigahertz operating frequency of superconducting qubit devices coincides with the frequencies of superconducting radio frequency (SRF) cavities used in HEP. Thus, the large investment by HEP in SRF cavity materials processing and fabrication technologies can potentially be applied to improve the performance of qubit devices by orders of magnitude, possibly providing significant improvements in quantum computing.

Fermilab has engaged local experimental quantum computing and superconducting materials experts and is constructing two milli-Kelvin test stands to enable this technology transfer. One test stand will incorporate a high-field magnet to explore the axion detector option, and the other will be dedicated to studies of superconducting materials at ultralow temperatures where thermal noise can be exponentially suppressed. Both efforts have received LDRD seed funding and will proceed over the next 2-3 years.

Large-Scale User Facilities

LBNF and DUNE

Fermilab's science strategy sets the trajectory for the United States to lead the world in accelerator-based neutrino science, anchored by LBNF/DUNE. The laboratory has demonstrated excellence in building and operating long-baseline neutrino experiments starting with the MINOS experiment and continuing with NOvA. These projects, together with Fermilab accelerator upgrades, detector R&D to advance liquid-argon time projection chamber (TPC) technology, and the short-baseline neutrino program, set the stage for a flagship international neutrino program based on LBNF and DUNE.

Coupling a massive 70-kiloton underground liquid-argon TPC detector with the world's most intense neutrino beam, LBNF/DUNE offers unparalleled opportunities for discovering CP violation in the

neutrino sector and excellent sensitivity to proton decay, supernova neutrinos, and atmospheric neutrinos. Fermilab, working with international and national laboratory and university partners, plans to host this new long-baseline program that will include intense neutrino and antineutrino beams, conventional facilities at both Fermilab and the Sanford Underground Research Facility (SURF) in South Dakota, an advanced (near) detector on the Fermilab site, and a massive liquid-argon TPC (far) detector and associated cryogenics at SURF. A neutrino experiment of this scale and capability has never been realized. LBNF/DUNE advances the P5 plan by establishing the first phase of this facility with a new beamline and infrastructure for a far detector sited deep underground in the 2020s.

To advance LBNF/DUNE, the U.S. and CERN signed a bilateral international cooperation agreement and approved the subsequent neutrino protocol. In this context, CERN committed to build the first cryostat for LBNF. To support the DUNE prototyping effort, CERN is currently constructing cryogenics, cryostat, beamline, and conventional facility infrastructure for two protoDUNE detectors that are anticipated to be operational before the end of 2018. To deliver the international protoDUNE effort within this timeframe, Fermilab is working with Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, and Argonne National Laboratory as well as the 950-member DUNE collaboration, which includes members from 162 institutions in 30 countries. U.S. membership in DUNE includes both DOE- and NSF-funded institutions.

CMS upgrade projects

The CMS and ATLAS experiments at the LHC made the historic discovery of a Higgs boson in 2012, and future research promises to further revolutionize our understanding of the universe. Initiated in 2012 and targeting completion in 2018 for the start of LHC Run 3, the first significant upgrade of the CMS detector will allow collection of high-quality data at event rates and radiation levels three times higher than those recorded in the LHC's first run. Fermilab is responsible for project management of the U.S. contribution to this upgrade project, which is jointly funded by DOE and NSF and includes upgrades of the forward pixel detector, the hadron calorimeter, and the trigger system. The project includes 30 university partner institutes (all part of the CMS collaboration) that account for 80% of labor and M&S expenditures on the project and contribute to the success of the project by providing expertise available at the universities.

A second and significantly more extensive upgrade of the CMS detector is required to handle the extreme data rates and associated radiation damage that the detector will face during the HL-LHC running period. The CMS collaboration is engaged in detailed planning and R&D activities for the second upgrade. The U.S. CMS collaboration and Fermilab will play a major role in several aspects of this upgrade, including construction of a new forward pixel detector, silicon strip tracker, endcap calorimeter, and trigger. An aggressive, but achievable, upgrade timeline has been developed to meet CERN's HL-

LHC timeline: design and prototyping through 2018; pre-production in 2018-2019; construction in 2019-2024; and installation and commissioning in 2024-2025.

Over the next several years the laboratory will work in conjunction with CMS, DOE, NSF, and university partners to define the role of Fermilab in the second upgrade. DOE CD-0 for the upgrade project was approved on March 7, 2016. The project is targeting CD-1 in FY17, and CD-2/3 in FY19 with a potential CD-3a in the middle of FY18 so that engineering and construction of large prototypes can proceed according to plan.

Accelerator Science and Technology

Fermilab's core capability in accelerator science and technology powers particle physics discoveries and makes significant contributions to research in other scientific disciplines. The laboratory's accelerator science and technology strategy is motivated by the P5 report, which identified the need for accelerated beams to investigate four of its five science drivers. Recommendations from the HEPAP accelerator R&D subpanel strongly endorse Fermilab's plans to pursue an aggressive research program funded by DOE's General Accelerator R&D (GARD) program. The program includes superconducting radio-frequency (SRF) acceleration technology, high-field superconducting magnets, beam physics, and high-power targets. Over the next 10 years, Fermilab will make significant contributions to CERN's HL-LHC accelerator upgrade, the PIP-II project that upgrades Fermilab's accelerator complex for LBNF/DUNE, and SLAC's LCLS-II project. The following five major initiatives comprise the laboratory's strategy for accelerator science and technology.

LARP and the HL-LHC upgrade

CERN is planning a major upgrade of the Large Hadron Collider that will increase instantaneous luminosity by ten times compared to the LHC's luminosity in 2012. The High-Luminosity LHC (HL-LHC) accelerator upgrade, scheduled for 2024-2025, is a major initiative for Fermilab that requires significant advances in accelerator science and technology. Fermilab is leading the U.S. contribution to HL-LHC R&D through the ongoing LHC Accelerator Research Program (LARP), which is the U.S. national program that funds accelerator research in support of the LHC. LARP is expected to complete its HL-LHC R&D effort in FY 2018 following the delivery of two prototypes for the HL-LHC upgrade. A pre-series magnet and a cold-mass prototype will be developed and tested by the U.S. HL-LHC Accelerator Upgrade Project (HL-LHC AUP). This project will deliver the components to CERN that will encompass the U.S. contribution to the HL-LHC upgrade. Fermilab will lead this project, working in conjunction with DOE and CERN to define deliverables. The project is expected to achieve CD-1 in FY 2017, and a consolidated CD-2/CD-3 in FY 2018. Achieving CD-3a in advance of FY 2018 for long-lead time

procurements such as superconductor, assembly tooling, and magnet parts is under consideration to meet the delivery schedule requested by CERN.

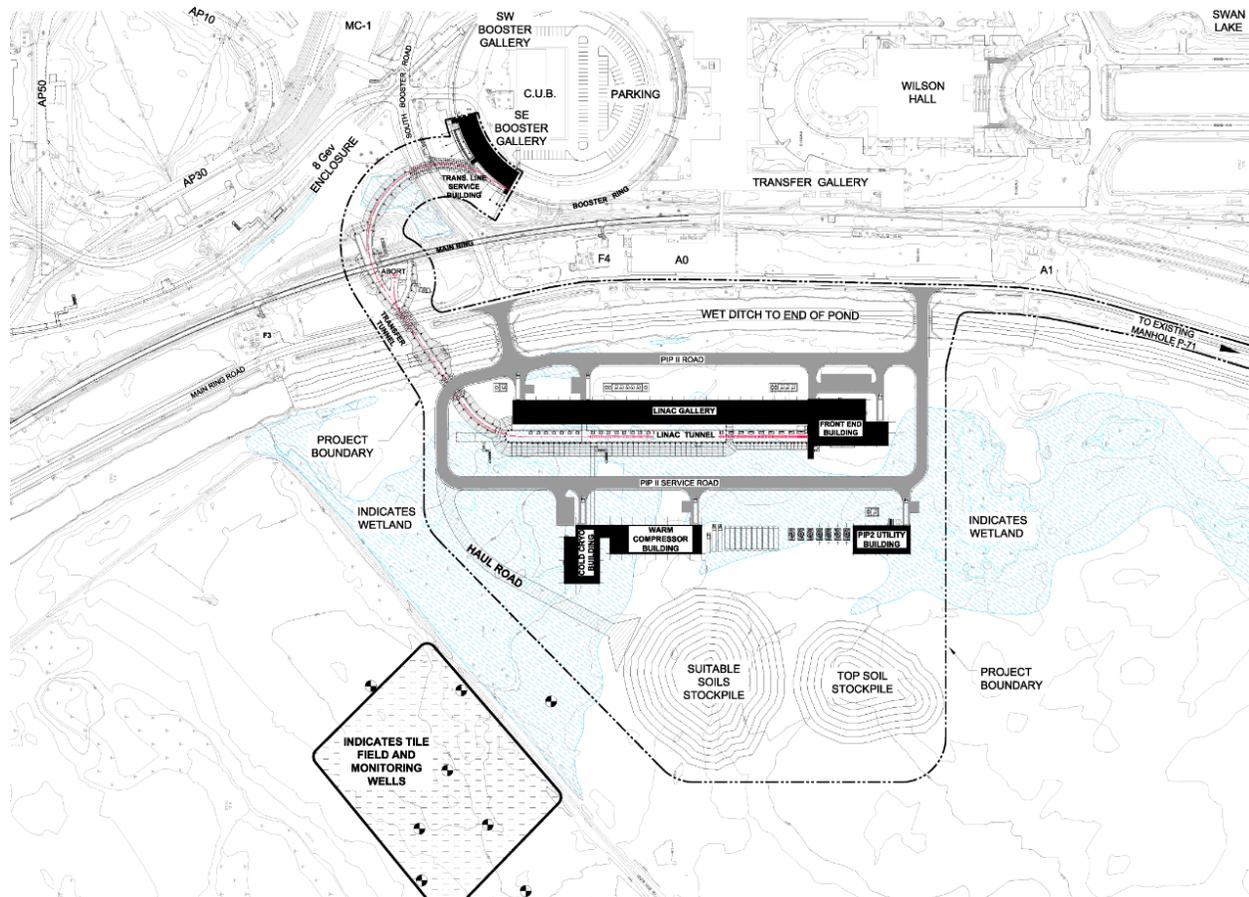
The LARP program will be recast after the spin-off of the HL-LHC AUP project in FY 2019. The continuation of a Fermilab fellowship program (Toohig Fellowship) for postdoctoral researchers interested in pursuing studies in accelerator science is expected to take place under a new program, with goals established by DOE/HEP in the coming year. The new goals are not expected to include superconducting magnet development activities, but may include accelerator studies and R&D at the HL-LHC.

PIP-II upgrade to the Fermilab accelerator complex

Over the next ten years a two-stage upgrade will increase the power of Fermilab's proton beams, enabling the laboratory's flagship neutrino and precision science programs. Beam power delivered to the NuMI facility has been increased to 700 kW by the Proton Improvement Plan (PIP) and by upgrades to the Recycler. Recent improvements include beam loss reduction and capture, new transverse dampers for slipstacking, and reliability improvements that resulted in record beam delivery to both the Booster and NuMI neutrino beams. Following the completion of PIP, the Fermilab Accelerator Complex will be unique in the world in its ability to deliver beams simultaneously to both neutrino and precision science programs. The PIP-II project, a major initiative for Fermilab, will further increase the power to 1.2 MW as required for LBNF/DUNE while enabling further performance enhancements to the precision science program. SRF, the technology chosen for PIP-II, is the only modern technology suitable for continuous-wave accelerators, as would be required for a second-generation Mu2e experiment. The siting of PIP-II (see figure on following page) was chosen to be consistent with providing a platform for long-term development of the Fermilab Accelerator Complex.

The PIP-II project received CD-0 in the fall of 2015 and is now working toward a goal of CD-1 approval in late 2017. In addition to project-definition activities, PIP-II is supported by a comprehensive R&D program pursued as a collaboration of the DOE, the Indian Department of Atomic Energy (DAE), and the Italian Istituto Nazionale di Fisica Nucleare (INFN). Over the next five years this program incorporates R&D aimed at demonstrating state-of-the-art performance in the PIP-II low-energy front end and development of SRF systems required for acceleration of proton beams. Fermilab is working with Argonne National Laboratory (ANL) to develop and build a low-frequency half-wave resonator SRF cryomodule for PIP-II. ANL's expertise in this area is complementary to Fermilab's SRF capabilities. These major elements of the program are accompanied by comprehensive theoretical and experimental investigations of major loss mechanisms and beam instabilities in the laboratory's existing Booster, Main Injector, and Recycler proton accelerator complex. High-intensity targets and focusing systems are crucial, and R&D to improve them will be actively pursued. Advanced computer modeling and

simulation of beams with space charge in realistic ring environments will benefit both the Fermilab Accelerator Complex upgrades as well as other existing accelerators.



Conceptual design of the PIP-II upgrade, showing the location of the linear accelerator, transfer line, and service buildings.

LCLS-II and future SRF accelerators

At the center of Fermilab's accelerator technology activities is the superconducting radio-frequency program. SRF is the enabling technology for future-generation high-intensity accelerators that are at the core of the missions of DOE/HEP and the Office of Science. Fermilab's world-leading SRF capabilities and infrastructure were enabled by an approximately \$200M investment by DOE/HEP over the last decade. Currently, Fermilab's SRF program focuses on three major areas: production of LCLS-II cryomodules in close partnership with SLAC National Accelerator Laboratory and Thomas Jefferson National Accelerator Laboratory, directed R&D for PIP-II, and advanced accelerator R&D on basic SRF science and cavity development for future accelerators. The laboratory's SRF expertise is a key enabler of SLAC's LCLS-II accelerator project. Experience, knowledge, and infrastructure developed through the LCLS-II project will subsequently be applied to the lab's PIP-II project.

The DOE/HEP investment in the Fermilab SRF R&D program has led to major breakthroughs – such as nitrogen doping and infusion and magnetic flux expulsion – that dramatically increase the SRF cavity quality factor (Q_0) and hence reduce operating costs. LCLS-II is the first benefactor of this success, and the current LCLS-II design depends on transitioning these results from R&D to production and operations. Fermilab plays a key role in this endeavor by providing overall technical leadership. A thorough understanding of the underlying physics is crucial to realize the full potential of these breakthroughs and to transfer benefits to all future SRF accelerators. Over the next few years, fundamental investigations into the physics of quality factor limitations at low and high fields will be actively pursued in collaboration with laboratories (CERN, KEK, TJNAF) and international and U.S. universities (for example, Cornell University, Illinois Institute of Technology, Northern Illinois University, Northwestern University, and the University of Chicago). A Fermilab-Northwestern Center for Applied Physics and Superconducting Technologies (CAPST) has been established to facilitate long-term collaboration in the fields of mutual interest and to leverage strengths of the two institutions. A primary goal is to decrease capital costs and operational cryogenic costs of future continuous-wave accelerators by a factor of two or more.

Fermilab has a nascent effort to develop detector technology for LCLS-II. The laboratory's Application Specific Integrated Circuit (ASIC) design group collaborates with SLAC's detector development group to develop a next-generation, very-high-readout-speed X-ray detector for use at the LCLS-II facility. This effort will leverage experience gained by the Fermilab ASIC group in the development of high-speed readout chips for HEP silicon vertex detectors and in collaborative efforts with Argonne National Laboratory and Brookhaven National Laboratory in the development of X-ray detector systems for use at the Argonne Advanced Photon Source and at the National Synchrotron Light Source II (NSLS-II) at Brookhaven.

High-field superconducting magnets

Fermilab is home to world-class R&D facilities and is a world leader in high-field superconducting accelerator magnets, materials, and technology R&D. Cost-effective superconducting accelerator magnets with operating fields up to 16 Tesla are being considered for the LHC energy upgrade (HE-LHC) and a future proton-proton circular collider (FCC) under study at CERN and in China. To demonstrate the feasibility of such magnets, Fermilab, as a key partner in the recently established U.S. Magnet Development Program (MDP) together with Lawrence Berkeley National Laboratory and the National High Magnetic Field Laboratory (Florida State University), has initiated and is leading the development of a 15 Tesla dipole demonstrator based on Nb_3Sn superconductor. Fermilab researchers perform extensive magnet design studies to explore the limit of the Nb_3Sn accelerator magnet technology, optimize magnet design and performance parameters, and reduce magnet cost. Fermilab will contribute

to the MDP effort to develop and evaluate generic technology of high-temperature superconductor inserts with the possibility of producing fields up to 20 Tesla.

Fermilab is conducting extensive superconducting wire and cable R&D with the goals of improving key properties and providing conductor specifications for the design and construction of superconducting accelerator magnets. Superconducting wire R&D is focused on 1) optimizing state-of-the-art Nb₃Sn composite wires, 2) developing Nb₃Sn wires with substantially higher critical current density in high fields by introducing artificial pinning centers, and 3) developing Nb₃Sn wires with increased specific heat to improve conductor stability and reduce sensitivity to external perturbations. Rutherford cable R&D includes heat treatment studies to boost the performance of present cables and innovative design ideas for the larger cables that are preferred for high-field accelerator magnets.

Accelerator science

Over the next five years Fermilab will establish a fully operational test facility to address key questions related to intense beams for future, cost-effective accelerators. The facility will enable transformative accelerator science. The central component of the test facility is the Integrable Optics Test Accelerator (IOTA), an innovative nonlinear storage ring that will include a proton and ion injector as well as a world-class high-brightness electron injector. Fermilab will complete construction and begin commissioning IOTA in 2017 by leveraging GARD funding together with LDRD funds. The laboratory will build community interest through university-lab partnerships, develop a focused science program via directed workshops, and produce a schedule for implementing the IOTA science program collaboratively with partners. IOTA scientific output will be critical to define the next steps in high-intensity particle beam development beyond PIP-II, and to establish novel approaches to advanced beam physics research.

Advanced Computer Science, Visualization and Data

Fermilab is continually expanding its capabilities for handling, storing, processing, and analyzing scientific data to meet the needs of the U.S. community's exciting and ambitious particle physics research program. To keep the community at the forefront of discovery and enable new directions in physics research, Fermilab pursues an advanced R&D program for software and computing solutions, specifically targeting the application of industry standards and emerging technologies. This strategy is based on a close partnership with the DOE Advanced Scientific Computing Research (ASCR) program to enable the particle physics community to take advantage of the latest developments in High-Performance Computing (HPC) and to contribute to the evolution of the National Strategic Computing Initiative

towards exascale computing. The following four major initiatives comprise the lab's strategy for Advanced Computer Science, Visualization, and Data.

Common solutions for the community: The scientific workflow framework *art*

Software is an integral part of the scientific process and is at the heart of every experiment. From recording, storing, and retrieving detector data to performing physics reconstruction and analysis, software needs to be efficient and user-friendly to enable experiments to extract physics results. The scientific workflow framework *art* provides the community with a common software layer to store and access scientific data and to schedule algorithms in an efficient and convenient way. The system grows to meet the needs of individual experiments through minimal experiment-specific customizations that don't require expert knowledge. All of Fermilab's operating neutrino and muon experiments now use the *art* framework for their experiment's software. NOvA has been using *art* for offline data handling and data analysis. MicroBooNE uses the framework extensively for their online and offline data handling and processing. Fermilab will continue to evolve *art* to keep pace with major software and computing hardware developments like the increased diversity of grid, cloud, and supercomputer resources. These will require changes in the underlying framework but will benefit many experiments simultaneously, thus minimizing the effort required from each individual project. Furthermore, the community has started to benefit from derived products that are based on *art*, such as *artdaq*, a common data acquisition system, and LArSoft, a common reconstruction algorithm for liquid-argon neutrino detectors. The evolution of *art* and its software ecosystem is a significant cornerstone of Fermilab's strategy to enable future scientific workflows. Fermilab's approach of common solutions for the community is successful and spans a wide range of scientific software. In addition to *art*, Fermilab is providing common solutions for workload management and data management for many experiments. Together with HTCondor and the Open Science Grid, Fermilab is also providing a common solution for resource provisioning (*glideinWMS*).

HEPCloud: A new paradigm for particle physics computing

Particle physics requires copious computing resources to extract physics results. Such resources are delivered by various systems: local batch farms, grid sites, private and commercial clouds, and supercomputing centers. Grid resources will continue to play a central role in Fermilab's strategy to provide access to computing resources for experiments. Elasticity and temporary significant increases of resources needed for individual experiments is becoming more and more important. Sharing unused grid resources opportunistically is vital to allow for more elasticity. In the future, this will not be sufficient and new forms of computing resources like clouds and HPC centers will need to be integrated. Fermilab's strategy is to provide easy access to all these resources. Historically, expert knowledge was required to access and concurrently use all these resources efficiently. Fermilab is pursuing a new paradigm in

particle physics computing through a single managed portal (HEPCloud) that will allow more scientists, experiments, and projects to use more resources to extract more science, without the need for expert knowledge. HEPCloud will provide cost-effective access by optimizing usage across all available types of computing resources and will elastically expand the resource pool on short notice (e.g. by renting temporary resources on commercial clouds). This new elasticity, together with the transparent accessibility of resources, will change the way experiments use computing resources to produce physics results. The CMS collaboration was amongst the first users of HEPCloud, which is now also used by Mu2e and NOvA. CMS was able to exploit elasticity at high scales in a SuperComputing 2016 demonstration in partnership with Google. Using the Google cloud, CMS doubled its computing resources to over 300,000 cores in peaks of 8 hours. The samples produced were used to generate scientific results presented at 2017 winter conferences. The partnership with ASCR HPC facilities is becoming a cornerstone of the HEPCloud resource portfolio. Experiments gain access through HEPCloud to HPC resources and are using them successfully for a variety of processing tasks. CMS and Mu2e were amongst the first to exploit these capabilities through HEPCloud. Both the U.S. neutrino and muon physics programs and the U.S. CMS program received allocations on ASCR HPC facilities during 2017, which they plan to use through HEPCloud. It is Fermilab's continuing goal to engage ASCR researchers and facilities experts to deepen the necessary partnerships both for porting HEP applications to these resources and for developing software and security infrastructure to access them.

Active Archive Facility: Sharing Fermilab's data handling leadership with other communities

Fermilab is a world leader in the handling of many petabytes of scientific data for the national and international particle physics community. This includes transferring large amounts of data into the Fermilab facility, archiving the data on Fermilab's exabyte-scale tape system, and using high-performance disk caches to provide efficient and secure access to the data, either locally or from off-site. A similar need for large-scale data handling has also recently arisen in other scientific disciplines. Fermilab's Active Archive Facility (AAF) will be developed to enable non-particle physics experiments and collaborations to benefit from Fermilab's leadership, expertise, and facilities. AAF will open Fermilab's storage, archiving, and data access capabilities to other research communities, with methods implemented to recover costs. The Simons Foundation continues to be one of the first non-particle physics science organizations benefiting from AAF capabilities. Additional genomics research data have been stored on tape media at the AAF and are regularly and securely accessed from around the world.

Computational science

New computing architectures are emerging because of advancements in computing hardware. The exascale era of computing will drive these innovative hardware and software technologies. Particle physics will need to adapt so that researchers can benefit from the increased performance of these

architectures. Synergies between the DOE/HEP program and the DOE/ASCR program will be essential to allow the U.S. particle physics community to take advantage of this new computing era. Fermilab will seed, cultivate, and coordinate cross-cutting development efforts between DOE/HEP experimental programs and DOE/ASCR institutions to maximize the benefit from exascale computing. With a recently funded LDRD effort on “Exascale-era computing and HEP”, Fermilab is starting on the path to evolve particle physics software and computing to be part of the exascale future.

Building for Science: People, Infrastructure, Innovation

Fermilab’s strategy for supporting its four core capabilities is known as “Building for Science” and incorporates building a diverse and inclusive workforce, modernizing infrastructure at all levels, and investing in the Laboratory Directed Research and Development (LDRD) program. In the area of infrastructure, the Utilities Upgrade Project (UUP), which is 90% complete, includes replacement of the master substation and industrial cooling water piping backbone by FY 2019. This project addresses infrastructure needs for Fermilab as a large-scale user facility. The Integrated Engineering Research Center (IERC) is a major initiative that will transform the laboratory’s core capability in particle physics. Two other major initiatives, the Global Accelerator Center (GAC) and the Next Generation Computing Center (NGCC), will transform the laboratory’s core capabilities in accelerator science and technology and advanced computer science, visualization and data, respectively.

Infrastructure upgrades driven by the Fermilab Campus Master Plan

The Campus Master Plan, which presents a comprehensive approach to Fermilab’s future infrastructure, has four primary objectives:

1. Construct sustainable infrastructure that will attract international investment and the brightest minds to the world’s leading laboratory for accelerator-based neutrino science
2. Maximize productivity by establishing an atmosphere of *“eat-sleep-work to drive discovery”* that efficiently meets the needs of the scientific community
3. Integrate into one geographic area the entire life cycle of research, engineering, fabrication, and operations expertise for accelerators and detectors
4. Consolidate, centralize, and modernize to optimize operational resources, maximize efficiency, enhance communication, and foster succession planning

These objectives address the needs of the laboratory’s core capabilities by providing facilities and infrastructure to close identified infrastructure gaps that include:

- Sufficient space for project teams and international users for the first-ever large-scale international science facility hosted by a U.S. DOE laboratory
- Buildings located closer to where the work is performed to improve efficiencies for matrixed resources supporting projects and operations

- Increased high-bay space for production facilities
- Modernized facilities with modular walls and furniture for efficient reconfiguration
- Short-term accommodations for a growing number of collaborating visitors and users
- State-of-the-art computing facilities

Integrated Engineering Research Center

A world-leading science laboratory needs world-class facilities and infrastructure to support its program. Fermilab's campus master plan portrays a future envisioned as "a state-of-the-art particle physics laboratory that will host a vibrant, international community of employees and users on a safe, accessible site that celebrates and protects the natural environment." The Integrated Engineering Research Center (IERC) anchors the development of the laboratory's central campus. The IERC provides interdisciplinary laboratory, technical, office, and collaboration spaces necessary for a world-class international neutrino science program by co-locating engineering and technical staff immediately adjacent to the main administrative building, where scientific staff and project teams reside. The IERC project received CD-1 Energy Systems Acquisition Advisory Board (ESAAB) approval in April 2017 and is a new start with project engineering and design funding anticipated in FY 2017. IERC construction is expected



Artist rendering of a conceptual design concept for the Integrated Engineering Research Center.

to begin in FY 2019. The project will transform the laboratory's core capability in particle physics by providing modernized infrastructure as well as a collaborative environment with laboratory and technical team spaces.

Global Accelerator Center

The Global Accelerator Center is envisioned as a mission-driven infrastructure improvement that will transform the laboratory's core capability in accelerator science and technology, thus sustaining the national and international accelerator science community for many years to come. At the same time as Fermilab's accelerator complex has transitioned from high-energy colliding beams to high-intensity proton beams for neutrino and precision science, the laboratory's accelerator scientists and technical teams have focused more on developing transformational accelerator technologies for use across the DOE/SC complex and around the globe. These transitions, combined with the condition and age of Fermilab's accelerator facilities, drive the need to consolidate core research functions and modernize key support facilities. The current lack of a modern, efficient, centralized space for accelerator scientists and key mission support staff reflects an infrastructure gap. A new building can bridge this gap by upgrading

working conditions for more than 25% of the laboratory staff and by providing a modern work space for visiting and collaborating national and international accelerator scientists. Co-locating accelerator scientists and their technical teams will allow better integration of the accelerator science, operations, and technology functions of the laboratory and will drive future national and international advances in accelerator science and technology.

Next-Generation Computing Center

The Next-Generation Computing Center (NGCC) will transform the laboratory's core capability in advanced computer science, visualization, and data, allowing Fermilab to keep pace with rapidly developing technologies and changing scientific demands. The NGCC will support the major initiatives that have been identified for this core capability, including HEPCloud and the Active Archive Facility. Three critical components have been identified for the NGCC. The first is big data storage. This component will provide large disk storage, tape storage, and networking and will be located underground to protect systems and data from natural disasters. The second component will provide space needed for computing systems. This will include space for scientific computing and business computing systems that will be deployed using open-air, state-of-the-art, and green cooling systems. The third component of the NGCC will provide collaboration and meeting space that is currently unavailable at Fermilab's Feynman Computing Center. Computer scientists and their technical teams as well as collaborating scientists from around the world will benefit from the availability of small-group workspaces for collaboration, medium-sized meeting rooms, and a 300-seat auditorium. The laboratory is seeking non-DOE funding for the NGCC, and as the third major new building on the Fermilab site this building will complete the mission-driven infrastructure modernization needs identified in the Campus Master Plan.

Diversity and inclusion

The international nature of projects that define Fermilab's future elevates the status of the laboratory's core organizational values of diversity and inclusion. Fermilab is committed to attracting, developing, and retaining diverse talent and cultivating an inclusive and productive work environment to support scientific, technological, and operational excellence on the part of its own staff and visiting collaborators from around the world.

To be successful, the laboratory's culture must be conducive to continual learning, dialogue, and feedback on diversity and inclusion issues. In conjunction with the laboratory's Diversity and Inclusion Office, the Employee Advisory Group (EAG) and an increasing number of Laboratory Resource Groups (LRGs) provide forums for dialogue and are key to identifying, prioritizing, and advancing diversity and inclusion initiatives from the ground up. Last year, Fermilab conducted inaugural sessions of implicit bias training to educate employees on the impact that subtle attitudes and behaviors have on decision-making in the workplace.

Consideration for diversity is included in every step of the recruitment process. Selection committees are diverse and members of selection committees receive training on diversity recruitment strategies and awareness of implicit bias in hiring. The recruitment website was recently updated to include an emphasis on diversity and work/life options. A jobs committee was established in FY 2016. The committee reviews all job requisitions, including the diversity recruitment plan for hiring. Quarterly reports are sent to division heads to ensure that they are accountable for increasing diversity in their divisions. In FY 2016, the laboratory launched a mentoring program to afford individuals the opportunities to develop skills and further their careers.

Laboratory Directed Research and Development

Fermilab has a LDRD program that supports discretionary research in science and technical areas that are aligned with the DOE/SC Scientific Discovery and Innovation mission and the laboratory's strategic plan. The program maintains the scientific and technical vitality of the laboratory and supports "high-risk, high-payoff" research involving new ideas, new technical concepts, and new technology. Projects are either initiated as a targeted opportunity by the Laboratory Director or are selected via an open call for proposals. The selection committee evaluates proposals and makes recommendations to the Laboratory Director for approval.

For this fifth year of LDRD, the strategic focus again will be to solicit several small and modest scale proposals. The FY 2018 call for proposals will emphasize and encourage a broad scope of proposals with all laboratory divisions encouraged to participate. The LDRD proposals solicited during this fiscal year will be judged on, in part, the alignment of the proposed project with the laboratory's current strategic plan.