High Energy Physics

Overview

The High Energy Physics (HEP) program's mission is to understand how the universe works at its most fundamental level by discovering the elementary constituents of matter and energy, probing the interactions between them, and exploring the basic nature of space and time.

Our current understanding of the elementary constituents of matter and energy is captured in what is called the Standard Model of particle physics. It describes the elementary particles that comprise ordinary matter and the forces that govern them with very high precision. However, recent observations that are not explained by the Standard Model suggest that it is incomplete and new physics may be discovered by future experiments. Astronomical observations indicate that ordinary matter makes up only about 5% of the universe, the remainder being 70% dark energy and 25% dark matter, both "dark" because they are either nonluminous or unknown. The observation of very small but non-zero masses of the elementary particles known as neutrinos provides further hints of new physics beyond the Standard Model.

An international enterprise of particle physics research is underway to discover what lies beyond the Standard Model. To guide U.S. investments, the U.S. particle physics community developed a long-term strategic plan through a multi-year process that culminated in the May 2014 report of the Particle Physics Project Prioritization Panel (P5), "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context."[a] The report, which was unanimously approved by the High Energy Physics Advisory Panel (HEPAP) to serve the DOE and National Science Foundation (NSF) as the ten-year strategic plan for U.S. high energy physics in the context of a 20-year global vision, identified five intertwined science drivers of particle physics that provide compelling lines of inquiry with great promise for discovery:

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

The HEP program enables scientific discovery through three experimental frontiers of particle physics research aligned with three HEP subprograms:

- Energy Frontier Experimental Physics, where researchers accelerate particles to the highest energies ever made by humanity and collide them to produce and study the fundamental constituents of matter. This requires some of the largest machines ever built. The Large Hadron Collider (LHC) at the European Organization for Nuclear Research, known as CERN, is 17 miles in circumference and accelerates and collides high-energy protons, while sophisticated detectors, some the size of apartment buildings, observe newly produced particles that provide insight into fundamental forces of nature and the conditions of the early universe.
- Intensity Frontier Experimental Physics, where researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, study some of the rarest interactions predicted by the Standard Model, and search for new physics. Measurements of the mass and other properties of neutrinos may have profound consequences for understanding the evolution and ultimate fate of the universe.
- Cosmic Frontier Experimental Physics, where researchers use naturally occurring cosmic particles and phenomena to reveal the nature of dark matter, understand the cosmic acceleration caused by dark energy and inflation, infer certain neutrino properties, and explore the unknown. The highest-energy particles ever observed have come from cosmic sources, and the ancient light from the early universe and distant galaxies allows the distribution of dark matter to be mapped and perhaps the nature of dark energy and inflation to be unraveled. Ultra-sensitive detectors deep underground may glimpse the dark matter passing through Earth. Observations of the cosmic frontier may reveal a universe far stranger than ever thought possible.

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[a] High Energy Physics Advisory Panel, Department of Energy. Report of the Particle Physics Project Prioritization Panel (P5). Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context. May 2014. https://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf

HEP's Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics) and Advanced Technology Research and Development (R&D) subprograms formulate and enable scientific discovery. The Theoretical, Computational, and Interdisciplinary Physics subprogram provides the framework to explain experimental observations and gain a deeper understanding of nature. Theoretical physicists take the lead in the interpretation of a broad range of experimental results and synthesize new ideas as they search for deep connections and develop testable models. Computational Physics provides advanced computing tools and simulations that are necessary for designing, operating, and interpreting experiments across the frontiers and enables discovery research via new techniques in high performance computing and Artificial Intelligence (AI)-Machine Learning (ML). Quantum Information Science (QIS) is a rapidly-developing, inter-disciplinary field, and HEP QIS efforts are aligned with the National Quantum Initiative and DOE priorities in this area. The HEP QIS research program promotes the co-development of quantum information, theory, and technology with the science drivers and opens prospects for new capabilities in sensing, simulation, and computing. In support of the National Quantum Initiative, at least one SC QIS Center will be established through a partnership between the HEP, Advanced Scientific Computing Research (ASCR), and Basic Energy Sciences (BES) programs. This partnership will be coupled with a robust core research portfolio stewarded by the individual SC programs including HEP, and will create the ecosystem across universities, national laboratories, and industry that is needed to developments in QIS and related technology.

The Advanced Technology R&D subprogram fosters fundamental research into particle acceleration and detection techniques and instrumentation. These enabling technologies and new research methods advance scientific knowledge in high energy physics and a broad range of related fields, advancing the DOE's strategic goals for science.

The Accelerator Stewardship subprogram supports R&D efforts that are synergistic with the HEP mission but also impacts activities outside the traditional HEP boundaries. The activities of the Accelerator Stewardship subprogram include: improving access to Office of Science (SC) accelerator R&D infrastructure for the private sector and other users; near-term translational R&D to adapt HEP accelerator technology for potential uses in medical, industrial, security, and defense applications; and long-term R&D for science and technology needed to build future generations of accelerators, with a focus on transformational opportunities.

HEP supports individual investigators and small-scale collaborations, as well as very large international collaborations, chosen for their scientific merit and potential for significant impact. More than 20 HEP-supported physicists have received the Nobel Prize in physics. Moreover, many of the advanced technologies, research tools, and analysis techniques originally developed for high energy physics have proved widely applicable to other scientific disciplines as well as for health services, national security, and the private sector.

Highlights of the FY 2020 Request

The HEP FY 2020 Request for $768,038,000 focuses resources toward the highest priorities in fundamental research, operation and maintenance of scientific user facilities, facility upgrades, and projects identified in the P5 report.

Key elements in the FY 2020 Request include:

Research supports university and laboratory researchers to preserve critical core competencies, enable high priority theoretical and experimental activities in pursuit of discovery science, explore the potential of QIS and AI-ML, and invest in high-performance computing and preparing for exascale, and world-leading R&D that requires long-term investments. These include:

- U.S. responsibilities and leadership roles in the A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) experiments at the LHC. To prepare for a ramp up to higher particle collision energy, the installation and commissioning of the upgrades to the ATLAS and CMS detectors will continue during the scheduled two-year long LHC technical stop from January 2019 to December 2020;
- U.S.-hosted, world-leading neutrino and muon physics experiments at Fermi National Acceleratory Laboratory (Fermilab), consisting of the Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE), the related Short-Baseline Neutrino (SBN) program, Muon g-2, and the Muon to Electron Conversion Experiment (Mu2e);

- U.S. responsibilities and leadership roles in world-leading, next-generation experiments to advance our understanding of the nature of dark energy and cosmic acceleration during inflation in the early universe, and the search for dark matter particles;
- Theoretical research, intertwining the physics of the Higgs boson, neutrino masses, the dark universe, and exploring the unknown;
- QIS R&D to accelerate discovery in particle physics while advancing the national effort;
- HEP, in partnership with SC's ASCR and BES programs, will establish at least one multi-disciplinary QIS center to accelerate the advancement of QIS through vertical integration between systems and theory, and hardware and software. The scope of the QIS Center will include work on sensors, quantum emulators/simulators, and enabling technologies that will pave the path to exploit quantum computing and qubit technology in the longer term;
- Artificial Intelligence (AI)-Machine Learning (ML) research to tackle the challenges of managing increasingly high volumes and complexity of experimental and simulated data across the HEP experimental frontiers, theory, and technology thrusts, and to address cross-cutting challenges across the HEP program in coordination with DOE investments in exascale computing and associated AI efforts;
- World-leading Advanced Technology R&D that will enable transformative technology for the next-generation of accelerators and particle detectors and the training of experts who build them. The HEP General Accelerator R&D (GARD) activity will increase support for the Traineeship Program for Accelerator Science and Technology to revitalize graduate level training and innovation in the physics of particle accelerators for the benefit of HEP and other SC programs that rely on these enabling technologies; and,
- Accelerator Stewardship to develop the fundamental building blocks of new technological advances in accelerator technology, to empower the private sector to accelerate research discoveries from the laboratory to the marketplace, and to support the mission of other federal agencies.

Facility Operations includes funding for the operations of the HEP scientific user facilities and other facility operation costs. Requested funding directs efforts to enable world-class science and the optimization of existing capabilities. This includes:

- Operation of the Fermilab Accelerator Complex for 4,200 hours (88% of optimal);
- Operation of the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) for 1,845 hours (74% of optimal);
- Commissioning, installation, and 1,500 hours of initial operation (50% of optimal) for Facility for Advanced Accelerator Experimental Tests II (FACET-II);
- New Fermilab Kautz Road Sub-Station General Plant Project (GPP), which will replace or upgrade existing electrical feeders that serve the Main Ring area of the site;
- Sanford Underground Research Facility (SURF) services to enable commissioning of the Large Underground Xenon (LUX)-ZonED Proportional Scintillation in Liquid Noble gases (Zeplin) (LUX-ZEPLIN) (LZ) dark matter experiment, to continue operations of the neutrino-less double beta decay Majorana Demonstrator, and to make investments to enhance SURF infrastructure;
- Refresh of computing resources at the U.S. Tier 1 centers at Fermilab and BNL; and,
- Commissioning, facilities, and pre-operations activities at the Large Synoptic Survey Telescope (LSST) telescope facility in Chile, and science operations of Dark Energy Spectroscopic Instrument (DESI), installed on the Mayall telescope in Arizona.

Construction, Major Items of Equipment (MIEs), and Future Project R&D includes:

- Continued investments in the LHC by contributing to the U.S. share of the High-Luminosity (HL-LHC) Accelerator Upgrade Project and the HL-LHC ATLAS and CMS Detector Upgrade Projects to increase the particle collision rate by a factor of three times to explore new physics beyond its current reach;
- Support for LBNF/DUNE, which will enable the Critical Decision (CD)-3A approved scope for the pre-construction activities: the Far Site excavation of the underground equipment caverns and connecting drifts (tunnels); design and procurement activities for the Far Site cryogenics systems; LBNF Near Site (Fermilab) beamline and conventional facilities design; and a site-preparation construction subcontract at the Near Site for relocation of existing service roads and utilities, including communications, power and water systems;
- Support for Proton Improvement Plan II (PIP-II), which will enable engineering design work for conventional facilities and technical systems, continuation of site-preparation activities, and initiation of construction for cryogenic plant support systems, and continued fabrication of prototype accelerator system components; and

- Technology R&D and pre-conceptual design studies for the next generation Cosmic Microwave Background (CMB S4) experiment

High Energy Physics supports the following FY 2020 Administration Priorities.

FY 2020 Administration Priorities

	(dollars in thousands)	
	Artificial Intelligence (AI)	**Quantum Information Science (QIS)**
High Energy Physics	15,000	38,308

High Energy Physics
Funding

(dollars in thousands)

	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Energy Frontier Experimental Physics				
Research	79,530	76,530	52,510	-24,020
Facility Operations and Experimental Support	54,340	52,000	44,480	-7,520
Projects	51,000	105,000	96,935	-8,065
SBIR/STTR	6,068	5,390	3,674	-1,716
Total, Energy Frontier Experimental Physics	**190,938**	**238,920**	**197,599**	**-41,321**
Intensity Frontier Experimental Physics				
Research	60,700	61,646	41,370	-20,276
Facility Operations and Experimental Support	153,385	155,035	136,681	-18,354
Projects	24,100	16,000	9,000	-7,000
SBIR/STTR	8,583	8,299	6,631	-1,668
Total, Intensity Frontier Experimental Physics	**246,768**	**240,980**	**193,682**	**-47,298**
Cosmic Frontier Experimental Physics				
Research	49,892	50,741	31,140	-19,601
Facility Operations and Experimental Support	16,310	20,076	23,230	+3,154
Projects	52,400	27,350	1,000	-26,350
SBIR/STTR	2,644	2,869	2,098	-771
Total, Cosmic Frontier Experimental Physics	**121,246**	**101,036**	**57,468**	**-43,568**
Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics)				
Research				
Theory	47,803	45,760	32,650	-13,110
Computational HEP	9,500	13,351	20,290	+6,939
Quantum Information Science	18,000	27,500	38,308	+10,808
Total, Research	75,303	86,611	91,248	+4,637
SBIR/STTR	2,853	3,223	3,457	+234
Total, Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics)	**78,156**	**89,834**	**94,705**	**+4,871**

	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
	(dollars in thousands)			
Advanced Technology R&D				
Research				
HEP General Accelerator R&D	46,500	48,447	40,873	-7,574
HEP Directed Accelerator R&D	5,000	—	—	—
Detector R&D	19,257	23,694	16,700	-6,994
Total, Research	70,757	72,141	57,573	-14,568
Facility Operations and Experimental Support	30,500	27,625	30,878	+3,253
Projects	10,000	10,000	—	-10,000
SBIR/STTR	3,705	3,740	3,256	-484
Total, Advanced Technology R&D	**114,962**	**113,506**	**91,707**	**-21,799**
Accelerator Stewardship				
Research	9,000	9,083	7,930	-1,153
Facility Operations and Experimental Support	6,000	6,067	4,477	-1,590
SBIR/STTR	530	574	470	-104
Total, Accelerator Stewardship	**15,530**	**15,724**	**12,877**	**-2,847**
Subtotal, High Energy Physics	**767,600**	**800,000**	**648,038**	**-151,962**
Construction				
18-SC-42 Proton Improvement Plan II, FNAL	1,000	20,000	20,000	—
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL	95,000	130,000	100,000	-30,000
11-SC-41, Muon to Electron Conversion Experiment, FNAL	44,400	30,000	—	-30,000
Total, Construction	**140,400**	**180,000**	**120,000**	**-60,000**
Total, High Energy Physics	**908,000**	**980,000**	**768,038**	**-211,962**

SBIR/STTR Funding:

- FY 2018 Enacted: SBIR $21,377,000 and STTR $3,006,000
- FY 2019 Enacted: SBIR $21,124,000 and STTR $2,971,000
- FY 2020 Request: SBIR $17,171,000 and STTR $2,415,000

High Energy Physics
Explanation of Major Changes

	(dollars in thousands) FY 2020 Request vs FY 2019 Enacted
Energy Frontier Experimental Physics The Request will continue support for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade Projects and will continue preparing for project baseline approval, and the HL-LHC Accelerator Upgrade Project will continue magnet fabrication and production of radio-frequency cavities. The Request will prioritize support to Research activities that address the Higgs boson, new directions in dark matter, and will continue the participation of U.S. research contributions to the HL-LHC ATLAS and HL-LHC CMS Detector upgrades. The Request will support completing the commissioning of the LHC ATLAS and CMS Detector Upgrade projects in FY 2020.	**-41,321**
Intensity Frontier Experimental Physics The Request will support the Fermilab Accelerator Complex (88% of optimal) to deliver particle beams and provide experimental operations. The FY 2019 Appropriation provided sufficient funding to complete the Fermilab NuMI Target Systems AIP and Utility Corridor GPP, which results in a decrease in the request for FY 2020. This will be partially offset by support for the Kautz Road Sub-Station GPP starting in FY 2020, and the conclusion of operations of mature experiments that have achieved their science goals. The Request will support work with international partners to reduce technical risks for the PIP-II project and funding for SURF that will support LBNF/DUNE construction. Other Project Costs (OPC) for PIP-II will decrease in FY 2020 since CD-1 was approved in FY 2018 and funding shifts to preliminary design accounted as Total Estimated Costs. The Request will prioritize support for postdoctoral researchers and graduate students engaged in research at the national laboratories and universities with a focus on delivering the final results of completed experiments, and preparing for physics on new experiments.	**-47,298**
Cosmic Frontier Experimental Physics The Request will support an increase for the installation, commissioning, and pre-operations activities for LSSTcam, DESI, LZ, and SuperCDMS-SNOLAB, offset by a decrease in major item of equipment (MIE) projects as the FY 2019 Appropriation provided sufficient funds to complete all remaining deliverables for DESI, LZ, and the Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB) MIEs. The Request will provide a small increase for new support of technology R&D and planning for a future CMB-S4 project. The Request will prioritize research support for postdoctoral researchers and graduate students at the national laboratories and universities with a focus on delivering the final results of completed experiments and preparing for physics on new experiments.	**-43,568**

	(dollars in thousands) FY 2020 Request vs FY 2019 Enacted
Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics) The Request will prioritize support to postdoctoral researchers and graduate students who are engaged in theoretical physics research at the national laboratories and universities with a focus on understanding the results of current experiments, supporting new initiatives in neutrino and dark matter physics, and connecting fundamental theory to the development of quantum information science. Computational physics research will increase with a focus on advancing techniques in AI-ML across the HEP experimental frontiers, theory, and technology thrusts, and accelerating HEP access to high performance computing and future exascale computer systems. In the Request, foundational HEP QIS research, quantum simulation experiments, and quantum computing, controls, and sensors will receive increased support. In addition, the FY 2020 Request will enable the establishment of at least one Quantum Information Science Center in partnership with the ASCR and BES programs. This new center's mission will be to apply concepts and technology from relevant foundational core research in each program and foster broader partnerships in support of the SC mission related to QIS.	**+4,871**
Advanced Technology R&D The Request will prioritize support for research activities in superconducting magnet development and ultrafast lasers. The Request also will prioritize support of cross-cutting Accelerator R&D, which leverages synergistic efforts at the national laboratories and Detector R&D which exploits collaborative opportunities between the national laboratories and the universities. The FY 2019 Appropriation provided final funding for the FACET-II MIE. The decrease in project support in FY 2020 will be slightly offset by an increase to support the commissioning and installation of the electron beam systems, 1,500 hours of FACET-II operations, and to improve superconducting radio-frequency (SRF) facilities and capabilities. The Request also includes an increase for the HEP Graduate Traineeship Program for Accelerator Science and Technology.	**-21,799**
Accelerator Stewardship The Request will prioritize support for transformative R&D for security applications and implementing priority R&D topics identified by a Basic Research Needs workshop planned for the spring of 2019. ATF Operations in FY 2020 will be 88% of optimal.	**-2,847**
Construction The Request will continue support for LBNF/DUNE for completion of the pre-excavation activities such as systems to remove the excavated rock to its nearby disposal site; the start of design and procurement activities for cryogenics systems, Near Site beamline and conventional facilities; and U.S. contributions to design and construction of the DUNE detectors. The Request will continue support for PIP-II engineering design work for conventional facilities and technical systems, continuation of site-preparation activities and initiation of construction for cryogenic plant support systems, as well as continued fabrication of prototype accelerator system components. These increases are offset by the conclusion of construction funding for the Muon to Electron Conversion Experiment (Mu2e); the FY 2019 Appropriation provided final funding for this project.	**-60,000**
Total, High Energy Physics	**-211,962**

Basic and Applied R&D Coordination
Accelerator Stewardship provides the fundamental building blocks of new technological advances in accelerator applications, including advanced proton and ion beams for the treatment of cancer, in coordination with the National Institutes of Health (NIH). HEP developed the Accelerator Stewardship subprogram based on input from accelerator R&D experts drawn from other federal agencies, universities, national laboratories, and the private sector to help identify specific research areas and infrastructure gaps where HEP investments would have sizable impacts beyond the SC research mission. This subprogram is closely coordinated with the SC's Basic Energy Sciences (BES) and Nuclear Physics (NP) programs and partner agencies to ensure federal stakeholders have input in crafting funding opportunity announcements, reviewing applications, and evaluating the efficacy and impact of funded activities. Use-inspired accelerator R&D for medical applications has been closely coordinated with the NIH/National Cancer Institute (NCI); ultrafast laser technology R&D with the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA); and microwave and high power accelerator R&D coordinated with the DOD, the Department of Homeland Security's Domestic Nuclear Detection Office in the Countering Weapons of Mass Destruction Office (DHS/CWMD), the NSF/Chemical, Bioengineering, Environmental and Transport (CBET) Systems Division, and the DOE's Office of Environmental Management (EM). Discussions with the National Nuclear Security Administration (NNSA) on mission needs and R&D coordination in laser technology, radioactive source replacement, and particle detector technologies have led to a Basic Research Needs Workshop on Compact Accelerators for Security and Medicine, to be held in May 2019 to establish research priorities for accelerator R&D in this critical area.

The Accelerator Stewardship subprogram conducts use-inspired basic R&D to provide the fundamental building blocks of new technological advances. Ensuring that the investments result in high-impact applications requires close coordination with other agencies who will carry on the later-stage development. The implementation strategy is to work with applied R&D agencies to jointly define priority research directions at Basic Research Needs Workshops, and then guide R&D and facility investments through joint participation of applied agencies in merit reviews and in the operations review of the Brookhaven National Laboratory Accelerator Test Facility. Where an eventual marketable use is envisioned, R&D collaborations are expected to involve a U.S. company to guide the early-stage R&D.

Specific funded examples include collaborative R&D on proton therapy delivery systems (joint with Varian Medical Systems), advanced proton sources for therapy (joint with ProNova Solutions), advanced detectors for cancer therapy (joint with Best Medical International) advanced microwave source development (joint with Communications Power Industries and General Atomics), and technical design studies for high power accelerators for wastewater treatment (joint with Metropolitan Water Reclamation District of Greater Chicago and the Air Force Research Laboratory). Funded R&D awards have drawn an average of 20% of voluntary cost sharing over the first three years of the subprogram, providing evidence of the potential impact.

The HEP QIS research program has coordinated partnerships with the Department of Defense's Office of Basic Research (DOD/OBR), as well as the Air Force's Office of Scientific Research (AFOSR) on synergistic research connecting cosmic black holes with quantum error correction in qubit devices and a partnership with the Department of Commerce's National Institute of Standards and Technology (NIST) on quantum metrology and quantum sensor development for experimental discovery along HEP science drivers and better understanding fundamental constants. These interdisciplinary QIS activities are aligned with the National Quantum Initiative and Office of Science QIS priorities.

Program Accomplishments
Continued record-breaking LHC performance enables first observation of the Higgs boson decaying to quarks (Energy Frontier Experimental Physics). The LHC continued to improve in its delivery of the highest energy particle collisions in the world, again setting new performance records and exceeding its annual goals. Using the LHC, scientists from the ATLAS and CMS collaborations have observed Higgs bosons interacting with the heaviest quarks for the first time. Using AI-ML techniques to enhance their sensitivity, each collaboration observed the Higgs boson decaying to pairs of top quarks and to pairs of bottom quarks. So far, all Higgs boson production and decay mechanisms measured by LHC experiments are in agreement with predictions from the Standard Model. These measurements support the idea that particle interactions with the Higgs boson generate the mass of elementary particles and that the Higgs boson plays a fundamental role in our universe. During the scheduled two-year long LHC technical stop from January 2019 to December 2020, accelerator and detector upgrades will be installed to enable more detailed measurements of the Higgs boson and more sensitive searches for new physics.

First apparatus provided by international partners for the U.S.-hosted international neutrino program is installed at Fermilab (Intensity Frontier Experimental Physics). The largest liquid-argon based neutrino detector in the world, ICARUS, was successfully transported from Europe to Fermilab, where it was installed as the Far Detector for the Short-Baseline Neutrino (SBN) program. The 65 foot long, 760 ton detector was originally installed in the Gran Sasso National Laboratory in Italy then refurbished at CERN, in Switzerland, before beginning a journey by barge, ship, and truck to Fermilab, in Illinois. As part of SBN, scientists will use it in an effort to definitively resolve experimental anomalies in the measured neutrino energy spectrum and search for “sterile” neutrinos that do not directly interact with other forms of matter. SBN also serves to develop and demonstrate the liquid-argon based neutrino detector technology that serves as the basis for the international Deep Underground Neutrino Experiment at the U.S.-hosted Long-Baseline Neutrino Facility now under construction.

Theorists make most precise prediction of how muons wobble as they travel in a powerful magnetic field (Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics)). Like their lighter cousin the electron, muons have an intrinsic spin, somewhat analogous to a spinning top. The magnetic moment of a muon determines the amount its spin will wobble as it circulates in a magnetic field. A precise comparison between the prediction and the measurement of this wobble provides a stringent test of the Standard Model where a discrepancy may point to the existence of new particles. A team of physicists has improved this prediction using Lattice Quantum Chromodynamics (QCD), modeling all the possible particle interactions on supercomputers at the Leadership Computing Facility at Argonne National Laboratory and Brookhaven’s Computational Sciences Initiative. They combined the simulations with related experimental measurements to produce the highest overall precision prediction to date. To test the Standard Model and search for new physics, the new high-precision prediction will be compared to the results of the ongoing Fermilab Muon g-2 experiment.

Belle II experiment receives first particle collisions from the SuperKEKB accelerator in Japan (Intensity Frontier Experimental Physics). The Belle II experiment will explore the unknown by precisely measuring the properties of particles called B-mesons, which contain bottom quarks. The B-mesons are created by colliding intense beams of electrons and positrons at the SuperKEKB accelerator at the High Energy Accelerator Research Organization (KEK) laboratory in Japan. While the Belle II detector was under fabrication, upgrades transformed the previous KEKB accelerator into SuperKEKB, which will provide 40 times more collisions per second. Belle II recorded the first collisions of the new SuperKEKB collider in April 2018. Scientists will use data from Belle II to study rare B-meson decays, search for new particles, and look for potential differences between matter and antimatter that may explain how the hot, early universe turned into the matter-dominated universe we live in today.

International partnerships continue to grow for LBNF/DUNE (Intensity Frontier Experimental Physics). The U.S.-hosted international LBNF will host massive experiments that may change our understanding of the universe. The international partnerships that support LBNF/DUNE and enable its science continue to grow. The first major project under the United Kingdom (UK)-U.S. Science and Technology Agreement, signed in September 2017, is a UK investment in LBNF/DUNE and the PIP-II accelerator at Fermilab that will enhance the intensity of the LBNF neutrino beam. Project Annex II on Neutrino Research, the signed agreement by DOE and India’s Department of Atomic Energy in April 2018, expands previous collaboration on accelerator science to include science for neutrinos. When complete, LBNF/DUNE will be the largest experiment ever built in the U.S. to study the properties of neutrinos and will enable transformative discoveries about their role in the universe.

Description

The Energy Frontier Experimental Physics subprogram's focus is on the Large Hadron Collider (LHC). The LHC hosts two large multi-purpose particle detectors, ATLAS and CMS, which are partially supported by DOE and the NSF and used by large international collaborations of scientists. U.S. researchers account for approximately 20% and 25% of the ATLAS and CMS collaborations respectively, and play critical leadership roles in all aspects of each experiment. Data collected by ATLAS and CMS will be used to address at least three of the five science drivers:

- *Use the Higgs boson as a new tool for discovery*
  In the Standard Model of particle physics, the Higgs boson is responsible for generating the mass for all fundamental particles. Experiments at the LHC continue to actively measure the Higgs's properties to establish its exact character and discover if there are additional effects that are the result of new physics beyond the Standard Model.
- *Explore the unknown: new particles, interactions, and physical principles*
  Researchers at the LHC probe for evidence of what lies beyond the Standard Model or significantly constrain postulated modifications to it, such as supersymmetry, mechanisms for black hole production, extra dimensions, and other exotic phenomena. The LHC detectors will be increasingly more sensitive to potential deviations from the Standard Model that may be exposed by the highest energy collisions in the world.
- *Identify the new physics of dark matter*
  If dark matter particles are light enough, they may be produced in LHC collisions and their general properties may be measured indirectly through the behavior of the accompanying normal matter. This indirect detection of dark matter is complementary to, and a powerful cross-check on, the ultra-sensitive direct detection experiments in the Cosmic Frontier and Intensity Frontier Experimental Physics subprograms.

<u>Research</u>

The Energy Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and physicists from national laboratories. These groups, as part of the ATLAS and CMS collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, and they perform scientific simulations and physics data analyses. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the Energy Frontier laboratory research groups is planned in FY 2019; the next review is planned for FY 2023. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments on the Energy Frontier and assessed the priority of their science output in the context of the science drivers. In early FY 2019, HEP conducted a Basic Research Needs workshop to assess the science landscape and new opportunities for dark matter particle searches and to identify which areas would be suitable for small projects in the HEP program. The findings from these reviews, in combination with input on strategic directions from regular, open community workshops will inform funding decisions in subsequent years.

<u>Facility Operations and Experimental Support</u>

U.S. LHC Detector Operations supports the maintenance of U.S.-supplied detector systems for the ATLAS and CMS detectors at the LHC, and the U.S.-based computer infrastructure used by U.S. physicists to analyze LHC data, including Tier 1 computing centers at BNL and Fermilab. The Tier 1 centers provide around-the-clock support for the LHC Computing Grid; are responsible for storing a portion of raw and processed data; perform large-scale data reprocessing; and store the corresponding output. Long-term development to analyze large datasets anticipated during future LHC operations are supported, including innovative AI-ML computational techniques.

<u>Projects</u>

During the next decade, CERN will undergo a major upgrade to the LHC machine to further increase the particle collision rate by a factor of three times to explore new physics beyond its current reach. Through the HL-LHC Accelerator Upgrade Project, HEP will contribute to this upgrade by constructing and delivering the next-generation of superconducting accelerator components in which U.S. scientists have critical expertise. After the upgrade, the HL-LHC beam will make the conditions in which the ATLAS and CMS detectors must operate very challenging. As a result, the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades are critical investments to enable the experiments to operate for an additional decade and collect more data by a factor of ten.

Activities and Explanation of Changes

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Energy Frontier Experimental Physics $238,920,000	**$197,599,000**	**-$41,321,000**
Research $76,530,000	$52,510,000	-$24,020,000
The FY 2019 Enacted budget supports U.S. leadership roles in all aspects of the ATLAS and CMS experiments.	The Request will support U.S. scientists leading high profile analysis topics using the large datasets collected by the ATLAS and CMS experiments.	The Request prioritizes ATLAS and CMS research efforts with the highest scientific merit and potential impact based on a competitive peer-review process while continuing participation of U.S. contributions to the HL-LHC ATLAS and HL-LHC CMS Detector upgrades.
Facility Operations and Experimental Support $52,000,000	$44,480,000	-$7,520,000
The FY 2019 Enacted budget supports ATLAS and CMS detector maintenance activities, including those related to commissioning of U.S.-built detector components during the two-year long technical stop of the LHC, which begins in 2019.	The Request will support ATLAS and CMS detector maintenance and operations at CERN; the U.S.-based computing infrastructure and resources necessary to store and analyze LHC data; and commissioning activities of U.S.-built detector components.	Support will focus on the completion of the commissioning activities following the installation of the LHC ATLAS and CMS Detector Upgrade projects while demands on the U.S.-based computing infrastructure are reduced during the technical stop as the experiments prepare for the next LHC run that will resume in 2021.
Projects $105,000,000	$96,935,000	-$8,065,000
The FY 2019 Enacted budget supports the procurement of solid-state detecting components for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade Projects (new MIE starts), and the production of focusing magnets for the HL-LHC Accelerator Upgrade Project.	The Request will support baselining the detector upgrades projects, and continue procurement of components for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades, and production of focusing magnets and radio-frequency cavities for the HL-LHC Accelerator Upgrade Project.	The Request supports fabrication and production activities for the HL-LHC Accelerator Upgrade project. Each of the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade projects continue to prepare for project baseline approval.
SBIR/STTR $5,390,000	$3,674,000	-$1,716,000
In FY 2019, SBIR/STTR funding is at 3.65% of non-capital funding.	In FY 2020, SBIR/STTR funding will be at 3.65% of non-capital funding.	A decrease in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Intensity Frontier Experimental Physics

Description

The Intensity Frontier Experimental Physics subprogram investigates some of the rarest processes in nature including unusual interactions of fundamental particles or subtle effects requiring large data sets to observe and measure. This HEP subprogram focuses on using high-power particle beams or other intense particle sources to make precision measurements of fundamental particle properties. These measurements in turn probe for new phenomena that are not directly observable at the Energy Frontier, either because they occur at much higher energies and their effects may only be seen indirectly, or because their interactions are too weak for detection in high-background conditions at the LHC. Data collected from Intensity Frontier experiments during this period will be used to address at least three of the five science drivers:

- *Pursue the physics associated with neutrino mass*
  Of all known particles, neutrinos are perhaps the most enigmatic and certainly the most elusive. HEP researchers working at U.S. facilities discovered all of the three known varieties of neutrinos. HEP supports research into fundamental neutrino properties that may reveal important clues about the unification of forces and the very early history of the universe. The Intensity Frontier-supported portfolio of neutrino experiments will advance neutrino physics while serving as an international platform for the R&D activities necessary to establish the U.S.-hosted international LBNF/DUNE.
- *Explore the unknown, new particles, interactions, and physical principles*
  A number of observed phenomena are not described by the Standard Model, including the imbalance of matter and antimatter in the universe today. Precision measurements of the properties of known particles may reveal information about what new particles and forces might explain these discrepancies and whether the known forces unify at energies beyond the reach of the LHC.
- *Identify the new physics of dark matter*
  The lack of experimental evidence from current generation dark matter detectors has led to proposed theoretical models with new particles and forces that rarely interact with normal matter. These theoretical particles and forces are effectively invisible to conventional experiments, but may connect to the cosmic dark matter. Experiments use intense accelerator beams at national laboratories outfitted with highly efficient high-rate detectors to explore these theoretical models.

Research

The Intensity Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and national laboratories. These groups, as part of scientific collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, as well as perform scientific simulations and physics data analyses on the experiments. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. An external peer review of the Intensity Frontier laboratory research groups was conducted in FY 2018; the next review is planned for FY 2022. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments on the Intensity Frontier and assessed the priority of their science output in the context of the science drivers. In early FY 2019, HEP conducted a Basic Research Needs workshop to assess the science landscape and new opportunities for dark matter particle searches and to identify which areas would be suitable for small projects in the HEP program. The findings from these reviews, in combination with input on strategic directions from regular, open community workshops will inform funding decisions in subsequent years.

The largest component of the Intensity Frontier subprogram is the support for research in accelerator-based neutrino physics centered at Fermilab with multiple experiments running concurrently in two separate neutrino beams with different beam energies. The flagship NuMI Off-Axis ν_e Appearance (NOvA) experiment uses the Neutrinos at the Main Injector (NuMI) beam. The Booster Neutrino Beam (BNB) is used to study different aspects of neutrino physics. The SBN program, which includes a Near Detector (SBN-ND) and a Far Detector (SBN-FD) separated by about 1,600 feet, uses the BNB to definitively address hints of additional neutrinos types beyond the three currently described in the Standard Model. LBNF/DUNE will be the centerpiece of a U.S.-hosted world-leading neutrino research activities, using the world's most intense neutrino beam and large, sensitive underground detectors to make transformative discoveries.

The Research activity also supports efforts to search for rare processes in muons to detect physics beyond the reach of the LHC. A new Muon g-2 experiment at Fermilab, with four times better precision than previously achieved, is following up on hints of new physics from an earlier experiment, while the Mu2e experiment will search for extremely rare muon decays that, if detected, will provide clear evidence of new physics. The Intensity Frontier subprogram also supports U.S. physicists to participate in select experiments at other facilities, including neutrino experiments in China and Japan. In particular, the Tokai-to-Kamioka (T2K) long-baseline neutrino experiment in Japan is complementary to NOvA, and together they will offer the best available information on neutrino oscillations prior to LBNF/DUNE. There is also a U.S. contingent searching for new physics using the Belle II experiment at the KEK in Japan.

Facility Operations and Experimental Support

There are several distinct facility operations and experimental support efforts in the Intensity Frontier Experimental Physics subprogram. The largest is the Fermilab Accelerator Complex User Facility. This activity includes the operations of all accelerators and beamlines at Fermilab and the operation of the detectors that use those accelerators as well as computing support needed by both the accelerators and detectors. General Plant Project (GPP) and Accelerator Improvement Project (AIP) funding supports improvements to Fermilab facilities.

Fermilab contracts with the South Dakota Science and Technology Authority (SDSTA), an agency of the State of South Dakota, for services at the Sanford Underground Research Facility (SURF) to support DOE experiments. The Nuclear Physics-supported Majorana Demonstrator is currently operating, and the HEP-supported LZ experiment is being installed at SURF, which will be the home of the DUNE far detectors built by the LBNF/DUNE project.

Projects

In support of LBNF/DUNE, a lease with SDSTA provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the DUNE neutrino detector. Other Project Costs (OPC) have been identified for SURF plant support costs provided by SDSTA.

PIP-II will upgrade the Fermilab linear accelerator to increase beam power and sustain high reliability of the Fermilab Accelerator Complex, ultimately providing the world’s highest proton beam intensity of greater than 1.2 megawatts for LBNF/DUNE. CD-1 was approved July 23, 2018, and the project is now completing its preliminary design. Two French institutions with expertise in superconducting radio-frequency (SRF) technology have joined the effort, expanding the list of partners that already includes institutions in India, Italy, and the United Kingdom.

Activities and Explanation of Changes

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Intensity Frontier Experimental Physics $240,980,000	**$193,682,000**	**-$47,298,000**
Research $61,646,000	$41,370,000	-$20,276,000
The FY 2019 Enacted budget supports U.S. leadership on all aspects of the neutrino and muon experiments including NOvA, ICARUS and Muon g-2, and the future projects including LBNF/DUNE and Mu2e. Belle II is anticipated to produce its first physics data results.	The Request will prioritize support for world-leading research efforts on short- and long-baseline neutrino experiments, muon experiments, and technology studies and science planning for LBNF/DUNE. The SBN program is expected to produce its first physics results. The Muon g-2 experiment will achieve the world's most sensitive measurement of the anomalous magnetic dipole moment of a muon.	Funding will be prioritized to support postdoctoral researchers and graduate students who are engaged in intensity frontier research at the national laboratories and universities with the highest scientific merit and potential impact as based on a competitive peer-review process with a focus on delivering the final results of completed experiments (e.g., Daya Bay), and preparing for physics on new experiments (e.g., SBN, Belle II).
Facility Operations and Experimental Support $155,035,000	$136,681,000	-$18,354,000
The FY 2019 Enacted budget supports the optimal operation of the Fermilab Accelerator Complex and the neutrino and muon experiments, the Fermilab NuMI Target Systems accelerator improvement project (AIP), and the Fermilab Utility Corridor general plant project (GPP). Based upon recommendations from reviews conducted by SC in FY 2018, HEP provides increased funding to address the aging infrastructure at the Sanford Underground Research Facility (SURF) to meet DOE expectations of reliable, efficient, and safe operations during the construction of LBNF/DUNE.	The Request will support the Fermilab Accelerator Complex and the neutrino and muon experiments at 88% of optimal operations. The Fermilab Kautz Road Sub-Station Radial Feed Electrical Upgrade GPP will begin. SURF operations will continue to enable operation of the LZ experiment and Majorana Demonstrator. The Request will support additional investments to enhance SURF infrastructure for reliable and efficient operation of the facility during the construction of LBNF/DUNE.	Support will focus on delivering particle beams at peak power and providing detector and computing operations for ongoing experiments (e.g., NOvA, Muon g-2) and new experiments (e.g., SBN) at the Fermilab Accelerator Complex; with operations at 88% of optimal. The FY 2019 Appropriation provided sufficient funding to complete the Fermilab NuMI Target Systems AIP and Utility Corridor GPP, which will result in a decrease in FY 2020. This will be partially offset by the Kautz Road Sub-Station GPP starting in FY 2020, and by the ramp down or conclusion of operations of mature experiments that have achieved their science goals (e.g. MicroBooNE).

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Projects $16,000,000	$9,000,000	-$7,000,000
The FY 2019 Enacted budget supports OPC for the preliminary design and prototyping of the most technologically advanced accelerator components for the PIP-II project, and the OPC for plant support costs at SURF during LBNF/DUNE construction.	The Request will support OPC for R&D for the PIP-II Injector Test Facility and a prototype for the front-end injector, and OPC for plant support costs at SURF during LBNF/DUNE construction.	The OPC for PIP-II will decrease since CD-1 was approved on July 23, 2018. The OPC shifts to preliminary design, which is part of the Total Estimated Costs (TEC). SURF plant support costs will continue as OPC for LBNF/DUNE.
SBIR/STTR $8,299,000	$6,631,000	-$1,668,000
In FY 2019, SBIR/STTR funding is at 3.65% of non-capital funding.	In FY 2020, SBIR/STTR funding will be at 3.65% of non-capital funding.	The decrease in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Cosmic Frontier Experimental Physics

Description

The Cosmic Frontier Experimental Physics subprogram uses measurements of naturally occurring cosmic particles and observations of the universe to probe fundamental physics questions and offer new insight about the nature of dark matter, dark energy, and inflation in the early universe, constraints on neutrinos and other phenomena. The activities in this subprogram use diverse tools and technologies, from ground-based telescopes and space-based missions to large detectors deep underground to address four of the five science drivers:

- *Identify the new physics of dark matter*
  Overwhelming evidence through the years, starting with measurements of motions within galaxies first made in the 1930s, show that dark matter accounts for five times as much matter in the universe as ordinary matter. Direct-detection experiments provide the primary method to search for cosmic dark matter particles' rare interactions with ordinary matter, while indirect-detection experiments search for the products of dark matter annihilation in the core of galaxies. A staged series of direct-detection experiments search for the leading theoretical candidate particles using multiple technologies to cover a wide range in mass with increasing sensitivity. Accelerator-based dark matter searches performed in the Intensity Frontier and the Energy Frontier subprograms are complementary to these direct-detection experiments.
- *Understand cosmic acceleration: dark energy and inflation*
  The nature of dark energy, which drives the accelerating expansion of the universe, continues as one of the most perplexing questions in science. Together, dark energy and dark matter comprise 95% of the matter and energy in the universe, leaving approximately 5% ordinary matter, from which all the stars and galaxies, and we, are made. Steady progress continues in a staged set of dark energy experiments, using complementary fast sky-scanning surveys and deep, high-accuracy surveys, which provide ever-increasing precision. Experiments studying the oldest observable light in the universe, the cosmic microwave background (CMB), are increasing their sensitivity to target the era of cosmic inflation, the rapid expansion in the early universe shortly after the Big Bang.
- *Pursue the physics associated with neutrino mass*
  The study of the largest physical structures in the Universe may reveal the properties of particles with the smallest known cross section, the neutrinos. Experiments studying dark energy and the CMB will put constraints on the number of neutrino species and their masses. The properties of neutrinos affected the evolution of matter distribution in the universe, leading to changes in the CMB observables when measured in different directions. These measurements are complementary to, and a powerful cross check of, the ultra-sensitive measurements made in the Intensity Frontier.
- *Explore the unknown: new particles, interactions, and physical principles*
  High-energy cosmic rays and gamma rays probe energy scales well beyond what may be produced with man-made particle accelerators, albeit not in a controlled experimental setting. Searches for new phenomena and indirect signals of dark matter in these surveys may yield surprising discoveries about the fundamental nature of the universe.

<u>Research</u>

The Cosmic Frontier Experimental Physics subprogram's Research activity supports groups at U.S. academic and research institutions and national laboratories who perform experiments using instruments on the surface, deep underground, and in space. These groups, as part of scientific collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, as well as perform scientific simulations and physics data analyses on the experiments in the subprogram. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. An external peer review of the Cosmic Frontier laboratory research groups was conducted in FY 2016; the next review will occur in FY 2020. In FY 2018, HEPAP evaluated the currently operating portfolio of experiments in the Cosmic Frontier and assessed the priority of their science output in the context of the science drivers. In early FY 2019, HEP conducted a Basic Research Needs workshop to assess the science landscape and new opportunities for dark matter particle searches and to identify which areas would be suitable for small projects in the HEP program. The findings from these reviews, in combination with input on strategic directions from regular, open community workshops, will inform funding decisions in subsequent years.

Facility Operations and Experimental Support

This activity supports the DOE share of personnel and expenses necessary for the successful pre-operations planning activities and maintenance, operations, and data collection and processing during the operating phase of Cosmic Frontier experiments. These experiments are typically not sited at national laboratories. They are located at ground-based telescopes and observatories, in space, or deep underground. Support is provided for the experiments currently operating as well as for planning and pre-operations activities for the next generation experiments in the design or fabrication phase. HEP conducted a peer review of all Cosmic Frontier operating experiments in FY 2015. HEP continues its series of reviews of each experiment to ensure readiness from fabrication to the science operations phase. HEP uses the findings from the reviews to monitor the experiments and inform decisions concerning the level of operations support needed in subsequent years.

Projects

Two experiments will use different survey types and methods to measure the effect of dark energy on the expansion of the universe, which allows differentiation between models of dark energy. The LSSTcam will scan half of the sky repeatedly with optical and near-infrared imaging sensors, building up a “cosmic cinematography” of the changing universe, while DESI will study 30 million galaxies and quasars with spectroscopy over two-thirds of the age of the universe. Two experiments will use different technologies to search for dark matter: LZ will use a liquid xenon detector and SuperCDMS-SNOLAB will use low-temperature solid-state detectors. LZ is better at detecting heavier dark matter particles while SuperCDMS-SNOLAB will be sensitive to lighter dark mass particles, so the two will combine to provide the largest search currently feasible. Technology R&D and pre-conceptual design studies for the next generation Cosmic Microwave Background (CMB-S4) experiment will begin.

High Energy Physics
Cosmic Frontier Experimental Physics

Activities and Explanation of Changes

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Cosmic Frontier Experimental Physics $101,036,000	**$57,468,000**	**-$43,568,000**
Research $50,741,000	$31,140,000	-$19,601,000
The FY 2019 Enacted budget supports world-leading research efforts in support of design and optimization on dark matter and dark energy experiments in their fabrication and commissioning phases, as well as on planning for future experiments, including CMB-S4.	The Request will prioritize support for world-leading research efforts on all phases of dark matter and dark energy experiments, as well as technology studies and planning for a CMB-S4 experiment. The Dark Energy Survey (DES) imaging experiment will release all its data from its 5-year survey.	Support prioritizes postdoctoral researchers and graduate students who are engaged in cosmic frontier research at the national laboratories and universities with the highest scientific merit and potential impact based on a competitive peer-review process, with a focus on delivering the final results of completed experiments (e.g., DES), and preparing for physics on new experiments (e.g., LZ, DESI).
Facility Operations and Experimental Support $20,076,000	$23,230,000	+$3,154,000
The FY 2019 Enacted budget supports the start of installation and commissioning activities for the LSSTcam, and early planning for the LSST facility and science operations. Planning, commissioning, and pre-operations activities begins for DESI, LZ, and SuperCDMS-SNOLAB. Support for the currently operating experiments continues.	The Request will support experiments in various phases: DESI will start science operations; LSSTcam will continue commissioning and integration on to the telescope; the full LSST facility will ramp up pre-operations planning; LZ will start full commissioning efforts; and SuperCDMS-SNOLAB will continue commissioning and pre-operations activities.	The increase will support the LSSTcam, DESI, LZ, and SuperCDMS-SNOLAB projects as they transition to experimental operations, installation, commissioning, and pre-operations activities, which will be partially offset by the ramp down or conclusion of operations of mature experiments that have achieved their science goals (e.g. High Altitude Water Cherenkov (HAWC) Observatory).
Projects $27,350,000	$1,000,000	-$26,350,000
The FY 2019 Enacted budget supports the completion of fabrication and installation of the LZ dark matter project, and supports the fabrication of the DESI dark energy project and the SuperCDMS-SNOLAB dark matter project, as well as support for technology R&D and planning for a future CMB-S4 project.	The Request will support technology R&D and planning for a future CMB-S4 project.	The FY 2019 Appropriation provided sufficient funding to complete the TEC funding for the LZ, SuperCDMS-SNOLAB, and DESI projects.

FY 2019 Enacted		FY 2020 Request		Explanation of Changes FY 2020 Request vs FY 2019 Enacted
SBIR/STTR	$2,869,000		$2,098,000	-$771,000
In FY 2019, SBIR/STTR funding is at 3.65% of non-capital funding.		In FY 2020, SBIR/STTR funding will be at 3.65% of non-capital funding.		The decrease in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics)

Description

The Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics) subprogram provides the mathematical, phenomenological, computational and technological framework to understand and extend our knowledge of the dynamics of particles and fields, and the nature of space and time. This research is essential for proper interpretation and understanding of the experimental research activities described in other HEP subprograms, and cuts across all five science drivers and the Energy, Intensity, and Cosmic Frontier Experimental Physics subprograms.

Theory

The HEP theory activity supports world-leading research groups at U.S. academic and research institutions and national laboratories. Both university and laboratory research groups play important roles in addressing the leading research areas discussed above. Laboratory groups are typically more focused on data-driven theoretical investigations and precise calculations of experimentally observable quantities. University groups usually focus on building models of physics beyond the Standard Model and studying their phenomenology as well as on formal and mathematical theory. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the Theory laboratory research groups was conducted in FY 2018; the next review is planned for FY 2022. The findings from this review, in combination with input on strategic directions from regular, open community workshops as well as a planned, future Basic Research Needs workshop, will inform funding decisions in subsequent years.

Computational HEP

The Computational HEP activity supports advanced simulations and computational science that extends the boundaries of scientific discovery to regions not directly accessible by experiments, observations, or traditional theory. Computation is necessary at all stages of HEP experiments—from planning and constructing accelerators and detectors, to theoretical modeling, to supporting computationally intensive experimental research and large-scale data analysis. Computational HEP priorities are to promote computing research for HEP future needs, by exploiting latest architectures like massively-parallel high performance computing platforms and future exascale computer systems, and developing advanced AI-ML techniques for new tracking and analysis algorithms. Computational HEP partners with the Advanced Scientific Computing Research (ASCR) program, including via the Scientific Discovery through Advanced Computing (SciDAC) activity, and with ASCR facilities and projects to optimize the HEP computing ecosystem for the near and long term future.

Quantum Information Science

The HEP QIS activity supports foundational research on connections between cosmological black holes and qubit research as well as quantum field theory techniques and algorithms, quantum computing for HEP experiments, development and use of specialized quantum controls, and precision sensors that may yield information on fundamental physics beyond the Standard Model, and applications of HEP research to advance QIS. At least one new Quantum Information Science Center (QIS Center), jointly supported with ASCR and BES programs, will apply concepts and technology from the relevant foundational core research in the corresponding programs and foster partnerships in support of the SC mission. The HEP QIS research activity is part of a broader SC initiative that is conducted in coordination with SC programs, other federal agencies, and the private sector where relevant.

High Energy Physics
Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics)

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Theoretical, Computational, and Interdisciplinary Physics (formerly Theoretical and Computational Physics)	**$89,834,000**	**$94,705,000**	**+$4,871,000**
Theory	$45,760,000	$32,650,000	-$13,110,000
The FY 2019 Enacted budget supports world-leading theoretical research program at universities and national laboratories.		The Request will support world-leading research that addresses the neutrino mass, the interpretation of experimental results, the development of new ideas for future projects, and the advancement of the theoretical understanding of nature.	Support prioritizes postdoctoral researchers and graduate students who are engaged in theoretical physics research at the national laboratories and universities, with a focus on understanding the results of current experiments, supporting new initiatives in neutrino and dark matter physics, and connecting fundamental theory to the development of quantum information science.
Computational HEP	$13,351,000	$20,290,000	+$6,939,000
The FY 2019 Enacted budget supports transformative computational science and SciDAC 4 activities including use of current and future high performance computing platforms and machine learning/deep learning applications across the program and coordinated with other DOE investments.		The Request will support transformative computational science, AI-ML, high performance computing, and SciDAC 4 activities to provide cross cut computational science tools for HEP science.	The increased funding will support new AI-ML research to explore how DOE high performance computing resources can scale up the optimization, performance, and validation studies of AI-ML tracking models, use pattern recognition to develop production-quality tracking for online triggering systems for HEP experiments, and use statistics and AI-ML to better analyze simulated data.
Quantum Information Science	$27,500,000	$38,308,000	+$10,808,000
The FY 2019 Enacted budget supports new foundational QIS research and supporting research technology. HEP employs the latest developments in QIS, and contribute to the national effort, and promote American competitiveness.		The Request will support interdisciplinary HEP-QIS consortia and exploratory Pioneering Pilots to strengthen foundational HEP-QIS research, quantum computing, and quantum research technology.	The increased funding will support at least one multi-disciplinary, multi-institutional QIS center in collaboration with ASCR and BES via a merit reviewed process, which will be conducted early in FY 2020.

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
	The Request also will support at least one new QIS Center in partnership with ASCR and BES.	
SBIR/STTR $3,223,000	$3,457,000	+$234,000
In FY 2019, SBIR/STTR funding is at 3.65% of non-capital funding.	In FY 2020, SBIR/STTR funding will be at 3.65% of non-capital funding.	The increase in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Advanced Technology R&D

Description

The Advanced Technology Research and Development (R&D) subprogram fosters cutting-edge research in the physics of particle beams, accelerator R&D, and particle detection—all of which are necessary for continued progress in high energy physics. Long-term multi-purpose accelerator research, applicable to fields beyond HEP, is carried out under the Accelerator Stewardship subprogram.

HEP General Accelerator R&D

The HEP General Accelerator R&D (GARD) activity supports the science underlying the technologies used in particle accelerators and storage rings, as well as the fundamental physics of charged particle beams. Long-term research goals include developing technologies to enable breakthroughs in particle accelerator size, cost, beam intensity, and control. The GARD activity supports groups at U.S. academic and research institutions and national laboratories performing research activity categorized into five areas: accelerator and beam physics; advanced acceleration concepts; particle sources and targetry; radio-frequency acceleration technology; and superconducting magnet and materials. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the GARD laboratory research groups was conducted in FY 2018; the next review is planned for FY 2022. The findings from this review, in combination with input on strategic directions from regular, open community workshops as well as future Basic Research Needs workshops, will inform funding decisions in subsequent years.

The GARD activity also supports the Traineeship Program for Accelerator Science and Technology to revitalize education, training, and innovation in the physics of particle accelerators for the benefit of HEP and other SC programs that rely on these enabling technologies. The Traineeship Program is aimed at university and national laboratory consortia to provide the academic training and research experience needed to meet DOE's anticipated workforce needs. HEP holds a competition for traineeship awards for graduate level students to increase workforce development in areas of critical need. These traineeships leverage existing GARD research activities as well as the capabilities and assets of DOE laboratories.

Detector R&D

The Detector R&D activity supports the development of the next generation instrumentation and particle detectors necessary to maintain scientific leadership in a worldwide experimental endeavor that is broadening into new research areas. To meet this challenge, HEP aims to foster an appropriate balance between evolutionary, near-term, low-risk detector R&D and revolutionary, long-term, high-risk detector R&D, while training the next generation of experts. The Detector R&D activity consists of groups at U.S. academic and research institutions and national laboratories performing research into the fundamental physics underlying the interactions of particles and radiation in detector materials. This activity also supports technology development that turns these insights into working detectors. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the Detector R&D laboratory research groups was conducted in FY 2016; the next review will occur in FY 2020. The findings from this review, in combination with input on strategic directions from regular, open community workshops as well as a planned, future Basic Research Needs workshop, will inform funding decisions in subsequent years.

Facility Operations and Experimental Support

This activity supports GARD laboratory experimental and test facilities: BELLA, the laser-driven plasma wakefield acceleration facility at LBNL; FACET-II, the beam-driven plasma wakefield acceleration facility at SLAC National Accelerator Laboratory (SLAC); and superconducting radio-frequency accelerator and magnet facilities at Fermilab. This activity supports the test beam at Fermilab, and detector test and fabrication facilities such as the Microsystems Laboratory at LBNL and the Silicon Detector Facility at Fermilab. Accelerator Improvement Projects (AIP) support improvements to GARD facilities.

Projects

The Advanced Technology R&D subprogram supports the development of new tools for particle physics through the development of more advanced accelerators and detectors. Plasma wakefield accelerators may have a transformative impact on the size, capabilities, and cost of future machines. FACET-II will be the world's premier beam driven plasma wakefield acceleration facility and provide intense ultra-short electron beams for other applications in accelerator and related sciences.

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Advanced Technology R&D	**$113,506,000**	**$91,707,000**	**-$21,799,000**
HEP General Accelerator R&D	$48,447,000	$40,873,000	-$7,574,000
The FY 2019 Enacted budget supports world-leading research activities including laser and electron-beam driven plasma acceleration, high intensity beam studies, beam manipulation and control techniques, high-power targets, high-gradient accelerator structures, superconducting radio-frequency cavities with high quality factors and high accelerating gradients, and low temperature and high temperature superconductors for high-field magnet application. The Traineeship Program for Accelerator Science and Technology is supported.		The Request will support world-leading General Accelerator R&D that will enable transformative technologies for the next-generation of accelerators for High Energy Physics. The Request also provides support for the Traineeship Program for Accelerator Science and Technology.	Support will be prioritized to focus on research activities in superconducting magnet development and ultrafast lasers, and on cross-cutting Accelerator R&D which leverages synergistic efforts at the national laboratories. Also, includes an increase for the Traineeship Program for Accelerator Science and Technology.
Detector R&D	$23,694,000	$16,700,000	-$6,994,000
The FY 2019 Enacted budget supports world-leading Detector R&D activities at universities and national laboratories, with emphasis on long-term, high-risk, and high potential impact R&D efforts.		The Request will support cutting-edge Detector R&D activities at universities and national laboratories, targeted at the most promising, high-impact directions led by U.S. efforts.	Support will prioritize Detector R&D that exploits collaborative opportunities between the national laboratories and the universities.
Facility Operations and Experimental Support	$27,625,000	$30,878,000	+$3,253,000
The FY 2019 Enacted budget supports the operation of accelerator, test beam, and detector facilities at Fermilab, LBNL, and SLAC. Commissioning activities for FACET-II installation will begin.		The Request will support the operation of accelerator, test beam, and detector facilities at Fermilab, LBNL and SLAC and improvements to superconducting radio-frequency facilities. The Request also includes support for final commissioning, installation, and 1,500 hours (50% of optimal) for initial operations for FACET-II.	The increased funding will support the commissioning and installation of the electron beam systems, 1,500 hours of FACET-II operations, and improving superconducting radio-frequency (SRF) facilities and capabilities. This will be partially offset by reduced support to detector test facilities at SLAC and LBNL.

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Projects $10,000,000	$—	-$10,000,000
The FY 2019 Enacted budget supports the completion of fabrication and installation of FACET-II.	No funding is requested for this activity. The FY 2019 Appropriation provided sufficient funding to complete the FACET-II project.	FACET-II project receives final funding in FY 2019.
SBIR/STTR $3,740,000	$3,256,000	-$484,000
In FY 2019, SBIR/STTR funding is at 3.65% of non-capital funding.	In FY 2020, SBIR/STTR funding will be at 3.65% of non-capital funding.	The decrease in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Accelerator Stewardship

Description

The Accelerator Stewardship subprogram has three principal activities: facilitating access to unique state-of-the-art SC accelerator R&D infrastructure for the private sector and other users; supporting innovative early-stage applied research to adapt accelerator technology for medical, industrial, security, and defense applications; and driving a limited number of specific accelerator applications towards practical, testable prototypes in a five to seven year timeframe. HEP manages this subprogram as a coordinated interagency initiative, consulting with other SC programs (principally NP, BES, and FES), other DOE program offices (principally EM and NNSA), and other federal stakeholders[a] of accelerator technology, most notably NIH, DOD, NSF, and DHS. Ongoing interagency consultation guides R&D investments, ensuring agency priorities are addressed, exploiting synergies where possible, and identifying new cross-cutting areas of research.

Research

The Research activity supports both near-term translational R&D and long-term basic accelerator R&D, which is conducted at national laboratories, universities, and in the private sector. The needs for applications have been specifically identified by federal stakeholders and developed further by technical workshops. Near-term R&D funding opportunities are specifically structured to foster strong partnerships with the private sector to improve health outcomes while lowering cost, develop technologies that may destroy pollutants and pathogens, detect contraband and radioactive material, and support new tools of science. Long-term R&D funding is targeted at scientific innovations enabling breakthroughs in particle accelerator size, cost, beam intensity, and control.

Facility Operations and Experimental Support

The Facility Operations and Experimental Support activity supports the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF), which is an SC User Facility providing a unique combination of high quality electron and infrared laser beams in a well-controlled user-friendly setting. Beam time at the BNL ATF is awarded based on merit-based peer review process. The facility remains at the cutting edge of science and works to increase its cost efficiency through ongoing facility R&D. Accelerator Improvement Projects (AIP) support improvements to Accelerator Stewardship facilities.

[a] Partner agencies for the Accelerator Stewardship subprogram currently are: the National Institutes of Health's National Cancer Institute; the Department of Defense's Office of Naval Research and Air Force Office of Scientific Research; the NSF's Physics Division and Chemical, Bioengineering, Environmental and Transport Systems Division; Department of Homeland Security's Domestic Nuclear Detection Office.

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Accelerator Stewardship	**$15,724,000**	**$12,877,000**	**-$2,847,000**
Research	$9,083,000	$7,930,000	-$1,153,000
The FY 2019 Enacted budget supports new research activities at laboratories, universities, and in the private sector for technology R&D areas such as accelerator technology for industrial and security uses, laser, and ion-beam therapy.		The Request will support new research activities at laboratories, universities, and in the private sector for technology R&D areas such as accelerator technology for industrial, medical and security uses, and advanced laser technology R&D.	Support will emphasize transformative R&D for security applications and implementing priority R&D topics identified by a Basic Research Needs workshop planned for the spring of FY 2019.
Facility Operations and Experimental Support	$6,067,000	$4,477,000	-$1,590,000
The FY 2019 Enacted budget supports the BNL ATF operations at optimal levels.		The Request will support the BNL ATF operations at 74% of optimal levels and support facility refurbishments to provide increased reliability and expanded capability to users.	Operating hours will be slightly reduced to 74% of optimal and approximately 30 less users are estimated as compared to FY 2019 estimates.
SBIR/STTR	$574,000	$470,000	-$104,000
In FY 2019, SBIR/STTR funding is at 3.65% of non-capital funding.		In FY 2020, SBIR/STTR funding will be at 3.65% of non-capital funding.	The decrease in funding will represent mandated percentages for non-capital funding.

Description
This subprogram supports all line-item construction for the entire HEP program. All Total Estimated Costs (TEC) are funded in this subprogram, including both engineering design and construction.

Proton Improvement Plan II (PIP-II)
The PIP-II project will enhance the Fermilab accelerator complex to enable it to deliver higher-power proton beams to the neutrino-generating target for groundbreaking discovery in neutrino physics. The project will design and construct an 800 MeV superconducting radio-frequency (SRF) proton linear accelerator, beam transfer line and infrastructure. PIP-II will modify the existing Fermilab Booster, Recycler and Main Injector accelerators to accept the increased beam intensity. Some of the new components and the cryoplant will provide through international, in-kind contributions.

The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-1 (Approve Alternative Selection and Cost Range), approved on July 23, 2018. The TPC cost range is $653,000,000 to $928,000,000. The funding profile supports the currently estimated TPC of $721,000,000. The CD-4 milestone is 1Q FY 2030. CD-0 established the mission need in FY 2015.

Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE)
The LBNF/DUNE construction project is a federal, state, private, and international partnership developing and implementing the technologies of particle accelerators and detectors to enable world-leading research into the fundamental physics of neutrinos, which are the most ubiquitous particles in the universe while at the same time among the most mysterious. LBNF/DUNE will study the transformations of muon neutrinos that occur as they travel to a large detector in South Dakota, 800 miles away from Fermilab, where they are produced in a high-energy beam. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, which are expected to help explain the fundamental physics of neutrinos and the puzzling imbalance of matter and antimatter that enables our existence in a matter-dominated universe.

The LBNF/DUNE project comprises a national flagship particle physics initiative. LBNF/DUNE will be the first-ever large-scale international science facility hosted by the U.S. LBNF/DUNE project consists of two multinational collaborative efforts. LBNF is responsible for the beamline at Fermilab and other experimental and civil infrastructure at Fermilab and at the Sanford Underground Research Facility (SURF) in South Dakota. DUNE is an international scientific collaboration responsible for defining the scientific goals and technical requirements for the beam and detectors, as well as the design, construction and commissioning of the detectors and subsequent research.

DOE's High Energy Physics program manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/Fermilab leadership and minority participation by a small number of international partners including CERN, will construct a megawatt-class neutrino source and related facilities at Fermilab (the "Near Site"), as well as underground caverns and cryogenic facilities in South Dakota (the "Far Site) needed to house the DUNE detectors. DUNE has international leadership and participation by about 1,160 scientists and engineers from 175 institutions in 32 countries. DOE will fund less than a third of DUNE.

The most recent approved DOE Order 413.3B is CD-3A, approval for Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation. The preliminary Total Project Cost (TPC) range is $1,260,000,000 to $1,860,000,000, as approved on September 1, 2016 with a preliminary CD-4 date of 4Q FY 2030. Updated planning and analysis has the TPC point estimate for LBNF/DUNE of $1,850,000,000 and was reviewed by an Independent Project Review held January 8-10, 2019.

Muon to Electron Conversion Experiment (Mu2e)

Mu2e, under construction at Fermilab, will search for evidence that a muon can change directly into an electron, a process that probes energy scales beyond the collision energy of the Large Hadron Collider. If observed, this major discovery would signal the existence of new particles or new forces beyond the Standard Model.

The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-3 (Approve Start of Construction), concurrent with completion of the final design, approved on July 14, 2016. In FY 2015, CD-2 established the scope, cost, and schedule baseline, and CD-3B initiated civil construction and long-lead procurement of the Transport Solenoid modules. Total Project Cost was approved at $273,677,000. The CD-4 milestone is 1Q FY 2023.

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Construction	**$180,000,000**	**$120,000,000**	**-$60,000,000**
18-SC-42, Proton Improvement Plan II, FNAL	$20,000,000	$20,000,000	$—
The FY 2019 Enacted budget supports the development of the preliminary design, the fabrication of prototype components, and early site preparation that is designed to mitigate environmental impacts.		The Request will support engineering design work for conventional facilities and technical systems, continuation of site-preparation activities and initiation of construction for cryogenic plant support systems, as well as continued fabrication of prototype accelerator system components.	Activities started in FY 2019 will continue as planned through FY 2020.
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL	$130,000,000	$100,000,000	-$30,000,000
The FY 2019 Enacted budget supports the Far Site pre-construction activities to support the eventual excavation of the underground equipment caverns and connecting drifts (tunnels). In addition, the project will continue to do design work for the Near Site, cryogenic systems, and the DUNE detectors.		The Request will support: continuation of pre-construction activities to support the Far Site cavern excavation; design and procurement activities for Far Site cryogenics systems; and beamline and conventional facilities design and site preparation at the Near Site. The Request will also support start of construction and fabrication for technical systems where design is final and authorized by CD-3, including U.S. contributions to the DUNE detectors.	Support will focus on the completion of the pre-excavation activities such as the systems to remove the excavated rock to its nearby disposal site; the start of design and procurement activities for cryogenics systems, Near Site beamline and conventional facilities; and U.S. contributions to design and construction of the DUNE detectors.
11-SC-41, Muon to Electron Conversion Experiment, FNAL	$30,000,000	$—	-$30,000,000
The FY 2019 Enacted budget supports the completion of the procurements and the beginning of equipment installation.		No funding is requested for this activity. The FY 2019 Appropriation provided final funding for the project. In FY 2020, fabrication will continue for the particle detectors and accelerator components including superconducting solenoid magnets and the muon stopping target.	The Mu2e project receives final funding in FY 2019.

High Energy Physics
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Capital Operating Expenses Summary						
Capital Equipment	N/A	N/A	91,556	125,260	101,935	-23,325
Minor Construction Activities						
General Plant Projects (GPP)	N/A	N/A	3,938	8,000	7,500	-500
Accelerator Improvement Projects (AIP)	N/A	N/A	4,445	5,600	—	-5,600
Total, Capital Operating Expenses	**N/A**	**N/A**	**99,939**	**138,860**	**109,435**	**-29,425**

Capital Equipment

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Capital Equipment						
Major Items of Equipment (MIE)[a]						
Energy Frontier Experimental Physics						
HL-LHC Accelerator Upgrade Project[b]	236,672	—	21,572	50,000	50,000	—
HL-LHC ATLAS Detector Upgrade[c]	133,850	—	—	27,500	23,460	-4,040
HL-LHC CMS Detector Upgrade[d]	121,800	—	—	13,750	23,475	+9,725
Cosmic Frontier Experimental Physics						
Large Synoptic Survey Telescope Camera (LSSTcam)[e]	150,300	140,500	9,800	—	—	—
Dark Energy Spectroscopic Instrument[f] (DESI)	45,250	22,300	17,500	5,450	—	-5,450

[a] Each MIE located at a DOE facility Total Estimated Cost (TEC) > $5M and each MIE not located at a DOE facility TEC > $2M.

[b] Critical Decision CD-2/3b for HL-LHC Accelerator Upgrade project was approved on February 11, 2019. The TPC is $242,720,000.

[c] Critical Decision CD-1 for HL-LHC ATLAS Detector Upgrade Project was approved September 21, 2018. The estimated cost range was $149,000,000 to $181,000,000.

[d] Critical Decision CD-0 for HL-LHC CMS Detector Upgrade Project was approved April 13, 2016. The estimated cost range was $125,000,000 to $155,000,000.

[e] Critical Decision CD-3 for the LSSTcam project was approved on August 27, 2015. The TPC is $168,000,000.

[f] Critical Decision CD-3 for DESI project was approved on June 22, 2016. The TPC is $56,328,000.

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
LUX-ZEPLIN[a] (LZ)	52,050	23,500	14,100	14,450	—	-14,450
SuperCDMS-SNOLAB[b]	15,725	5,775	7,400	2,550	—	-2,550
Advanced Technology R&D						
FACET II[c]	20,500	500	10,000	10,000	—	-10,000
Total MIEs	N/A	N/A	80,372	123,700	96,935	-26,765
Total Non-MIE Capital Equipment	N/A	N/A	11,184	1,560	5,000	+3,440
Total, Capital Equipment	**N/A**	**N/A**	**91,556**	**125,260**	**101,935**	**-23,325**

Minor Construction Activities

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
General Plant Projects (GPP)						
Greater than or equal to $5M and less than $20M						
Industrial Center Building addition	8,428	6,500	1,928	—	—	—
Utility Corridor	8,000	—	—	8,000	—	-8,000
Kautz Road Sub-Station	7,500	—	—	—	7,500	+7,500
Total GPPs (greater than or equal to $5M and less than $20M)	N/A	N/A	1,928	8,000	7,500	-500
Total GPPs less than $5M[d]	N/A	N/A	2,010	—	—	—
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**3,938**	**8,000**	**7,500**	**-500**

[a] Critical Decision CD-3 for LZ project was approved February 9, 2017. The TPC is $55,500,000.

[b] Critical Decisions CD-2/3 for SuperCDMS-SNOLAB project were approved May 2, 2018. The TPC is $18,600,000.

[c] Critical Decisions CD-2/3 for FACET-II project were approved June 8, 2018. The TPC is $25,600,000.

[d] GPP activities less than $5M include design and construction for additions and/or improvements to land, buildings, replacements or additions to roads, and general area improvements.

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
	(dollars in thousands)					
Accelerator Improvement Projects (AIP)						
Greater than or Equal to $5M and less than $20M						
Section 10 Injector Infrastructure	5,000	3,955	1,045	—	—	—
NuMI Target Systems	5,600	—	—	5,600	—	-5,600
Total AIPs (greater than or equal to $5M and less than $20M)	N/A	N/A	1,045	5,600	—	—
Total AIPs less than $5M[a]	N/A	N/A	3,400	—	—	—
Total, Accelerator Improvement Projects (AIP)	**N/A**	**N/A**	**4,445**	**5,600**	**—**	**-5,600**
Total, Minor Construction Activities	**N/A**	**N/A**	**8,383**	**13,600**	**7,500**	**-6,100**

[a] AIP activities less than $5M include minor construction at an existing accelerator facility.

High Energy Physics
Major Items of Equipment Description(s)

Energy Frontier Experimental Physics MIEs:
The *High Luminosity Large Hadron Collider Accelerator Upgrade Project (HL-LHC Accelerator Upgrade Project)* received CD-2/3b approval on February 11, 2019 with a TPC of $242,720,000. Following the major upgrade, the CERN LHC machine will further increase the particle collision rate by a factor of three times to explore new physics beyond its current reach. This project will deliver components for which the U.S. scientists have critical expertise: interaction region focusing quadrupole magnets, and special superconducting RF crab cavities that are capable of generating transverse electric fields. The magnets will be assembled at Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, and Fermilab, exploiting special expertise and unique capabilities at each laboratory. The FY 2020 Request of TEC funding of $50,000,000 will support the production of quadrupole magnets and crab cavities.

The *High Luminosity Large Hadron Collider ATLAS Detector Upgrade Project (HL-LHC ATLAS)* received CD-1 approval on September 21, 2018 with an estimated cost range of $149,000,000 to $181,000,000, and CD-2 is planned for FY 2020. The ATLAS detector will integrate a factor of ten higher amount of data per run, compared to the period prior to the HL-LHC upgrades, making the physical conditions in which the detectors run very challenging. To operate for an additional decade in these new conditions, the ATLAS detector will require upgrades to the silicon pixel and strip tracker detectors, the muon detector systems, the calorimeter detectors and associated electronics, and the trigger and data acquisition systems. The National Science Foundation (NSF) is preparing a Major Research Equipment and Facility Construction (MREFC) Project to provide different scope to the HL-LHC ATLAS detector. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2020 Request of TEC funding of $23,460,000 will support further procurement of components and baselining of the project.

The *High Luminosity Large Hadron Collider CMS Detector Upgrade Project (HL-LHC CMS)* received CD-0 approval on April 13, 2016 with an estimated cost range of $125,000,000 to $155,000,000. The project is expected to obtain CD-1 approval in the spring of 2019, and CD-2 is planned for FY 2020. The CMS detector will integrate a factor of ten higher amount of data per run, compared to the period prior to the HL-LHC upgrades, making the physical conditions in which the detectors run very challenging. To operate for an additional decade in these new conditions, the CMS detector will require upgrades to the silicon pixel tracker detectors, outer tracker detector, the muon detector systems, the calorimeter detectors and associated electronics, the trigger and data acquisition systems and the addition of a novel timing detector. NSF is preparing a MREFC Project to provide different scope to the HL-LHC CMS detector. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2020 Request of TEC funding of $23,475,000 will support further procurement of components and baselining of the project.

Cosmic Frontier Experimental Physics MIEs:
The *Large Synoptic Survey Telescope Camera (LSSTcam*) project received CD-2 approval on January 7, 2015, with a DOE TPC of $168,000,000 and a project completion date in FY 2022. CD-3 was approved on August 27, 2015. The project is fabricating a state-of-the-art three billion pixel digital imaging camera for the next-generation, wide-field, ground-based optical and near-infrared LSST facility, located in Chile. LSST is designed to provide deep images of half the sky every few nights, enabling study of the nature of dark energy. LSSTcam is DOE's responsibility in the collaboration with the NSF, which leads the LSST project, along with private and foreign contributions. The project will complete its camera components, including testing and integration, in FY 2020. It will then be shipped to Chile for installation and commissioning on the LSST telescope facility in Chile. The FY 2018 Appropriation provided sufficient funds to complete all remaining LSSTcam project deliverables.

The *Dark Energy Spectroscopic Instrument (DESI)* project received CD-2 approval on September 17, 2015 with a TPC of $56,328,000, and a project completion date of FY 2021. CD-3 was approved on June 22, 2016. DESI will fabricate a next-generation, fiber-fed, ten-arm spectrograph for operation on NSF's Mayall 4-meter telescope at Kitt Peak National Observatory in Arizona, with operations of the telescope supported by DOE. DESI will measure the effects of dark energy on the expansion of the universe using dedicated spectroscopic measurements and will provide a strong complement to the

LSST imaging survey. The FY 2019 Appropriation provided sufficient funds to complete all remaining project deliverables. In FY 2020, the project will finish installation of the focal plane and spectrograph and complete commissioning.

The *LUX-ZEPLIN (LZ)* project received CD-2 approval on August 8, 2016 with a TPC of $55,500,000, and a project completion date in FY 2022. CD-3 was approved on February 9, 2017. LZ is one of two MIEs selected to meet the Dark Matter Second Generation Mission Need and the concept for the experiment was developed by a merger of the LUX and ZEPLIN collaborations from the U.S. and the U.K. respectively. The project will fabricate a detector using seven tons of liquid xenon inside a time projection chamber to search for xenon nuclei that recoil in response to collisions with an impinging flux of dark matter particles known as Weakly Interacting Massive Particles (WIMPs). The detector will be located 4,850 feet deep in the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The FY 2019 Appropriation provided sufficient funds to complete all remaining project deliverables. In FY 2020, the project will finish underground installation, functional testing, and filling of the detector's chambers with liquid xenon, liquid scintillator, and water.

The *Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB)* project received CD-2/3 approval on May 2, 2018 with a TPC of $18,600,000. SuperCDMS-SNOLAB is one of the two MIEs selected to meet the Dark Matter Second Generation Mission Need. The project will fabricate instrumentation that uses ultra-clean, cryogenically-cooled silicon (Si) and germanium (Ge) detectors to search for Si or Ge nuclei recoiling in response to collisions with WIMPs, and will optimize to detect low mass WIMPs to cover a range of masses complementary to that of LZ's sensitivity. The detector will be located 2 km deep in the SNOLAB facility in Sudbury, Ontario, Canada. The FY 2019 Appropriation provided sufficient funds to complete all remaining project deliverables in FY 2020, including installation of the seismic platform and assembly of the shielding, cryostat, and calibration system.

<u>Advanced Technology R&D MIE:</u>
The *Facility for Accelerator and Experimental Tests II (FACET-II)* project received CD-2/3 on June 8, 2018 with a TPC of $25,600,000. FACET-II will be the world's premier beam driven plasma wakefield acceleration facility. FACET-II is being designed to deliver beams using only one third of the SLAC linear accelerator. FACET-II installation and commissioning work in the SLAC accelerator housing will be constrained by the installation of the Linac Coherent Light Source II (LCLS-II). The FY 2019 Appropriation provided sufficient funds to complete all remaining deliverables. In FY 2020, the project will be completing its Accelerator Readiness Review and final checks of its electronic control systems.

<u>General Plant Projects $5 Million to less than $10 Million</u>

Kautz Road Sub-Station
General Plant Project Details

Project Name:	Kautz Road Sub-Station Radial Feed Electrical Upgrade
Location/Site:	Fermilab Accelerator Complex, Main Ring
Type:	GPP
Total Estimated Cost:	$7,500,000
Construction Design:	$500,000
Project Description:	The KRSS Radial Feed Electrical Upgrade project will replace/upgrade existing electrical feeders that serve the Main Ring area of the site to improve reliability, increase the capacity of the Fermilab site wide electrical system and bring the service up to modern standards.

High Energy Physics
Construction Project Summary

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
18-SC-42, Proton Improvement Plan II, FNAL[a]						
TEC	638,965	—	1,000	20,000	20,000	—
OPC	82,035	33,935	23,100	15,000	5,000	-10,000
TPC	**721,000**	**33,935**	**24,100**	**35,000**	**25,000**	**-10,000**
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment, FNAL						
TEC	1,755,000	111,781	95,000	130,000	100,000	-30,000
OPC	95,000	85,625	1,000	1,000	4,000	+3,000
TPC	**1,850,000**	**197,406**	**96,000**	**131,000**	**104,000**	**-27,000**
11-SC-41, Muon to Electron Conversion Experiment, FNAL						
TEC	250,000	175,600	44,400	30,000	—	-30,000
OPC	23,677	23,677	—	—	—	—
TPC	**273,677**	**199,277**	**44,400**	**30,000**	**—**	**-30,000**
Total, Construction						
TEC	**N/A**	**N/A**	**140,400**	**180,000**	**120,000**	**-60,000**
OPC	**N/A**	**N/A**	**24,100**	**16,000**	**9,000**	**-7,000**
TPC	**N/A**	**N/A**	**164,500**	**196,000**	**129,000**	**-67,000**

[a] The Proton Improvement Plan II was not included in the Construction Project Summary table in the FY 2019 President's Budget Request as TEC funding was not requested for FY 2019.

High Energy Physics
Funding Summary

(dollars in thousands)

	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Research	**369,565**	**380,847**	**301,357**	**-79,490**
Facilities Operations				
Scientific User Facilities Operations	136,820	139,717	126,217	-13,500
Other Facilities	123,715	121,086	113,529	-7,557
Total, Facilities Operations	**260,535**	**260,803**	**239,746**	**-21,057**
Projects[a]				
Major Items of Equipment	112,300	141,350	96,935	-44,415
Other Projects	1,100	1,000	1,000	—
Construction	164,500	196,000	129,000	-67,000
Total, Projects	**277,900**	**338,350**	**226,935**	**-111,415**
Total, High Energy Physics	**908,000**	**980,000**	**768,038**	**-211,962**

[a] Includes Other Project Costs.

High Energy Physics
Scientific User Facility Operations

The treatment of user facilities is distinguished between two types: TYPE A facilities that offer users resources dependent on a single, large-scale machine; TYPE B facilities that offer users a suite of resources that is not dependent on a single, large-scale machine.

Definitions:

Achieved Operating Hours – The amount of time (in hours) the facility was available for users.

Planned Operating Hours –

- For Past Fiscal Year (PY), the amount of time (in hours) the facility was planned to be available for users.
- For Current Fiscal Year (CY), the amount of time (in hours) the facility is planned to be available for users.
- For the Budget Fiscal Year (BY), based on the proposed Budget Request the amount of time (in hours) the facility is anticipated to be available for users.

Optimal Hours – The amount of time (in hours) a facility would be available to satisfy the needs of the user community if unconstrained by funding levels.

Percent of Optimal Hours – An indication of utilization effectiveness in the context of available funding; it is not a direct indication of scientific or facility productivity.

- For BY and CY, Planned Operating Hours divided by Optimal Hours expressed as a percentage.
- For PY, Achieved Operating Hours divided by Optimal Hours.

Unscheduled Downtime Hours - The amount of time (in hours) the facility was unavailable to users due to unscheduled events. NOTE: For type "A" facilities, zero Unscheduled Downtime Hours indicates Achieved Operating Hours equals Planned Operating Hours.

(dollars in thousands)

	FY 2018 Enacted	FY 2018 Current	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
TYPE A FACILITIES					
Fermilab Accelerator Complex	**$132,000**	**$130,284**	**$132,650**	**$115,740**	**-$16,910**
Number of Users	2,393	2,489	2,489	2,100	-389
Achieved operating hours	N/A	5,026	N/A	N/A	N/A
Planned operating hours	4,800	4,800	5,740	4,200	-1,540
Optimal hours	4,800	4,800	5,740	4,800	-940
Percent optimal hours	100.0%	104.7%	100.0%	87.5%	-12.5%
Unscheduled downtime hours	N/A	482	N/A	N/A	N/A

	(dollars in thousands)				
	FY 2018 Enacted	**FY 2018 Current**	**FY 2019 Enacted**	**FY 2020 Request**	**FY 2020 Request vs FY 2019 Enacted**
Accelerator Test Facility (BNL)	**$4,820**	**$5,517**	**$6,067**	**$4,477**	**-$1,590**
Number of Users	97	91	118	87	-31
Achieved operating hours	N/A	2,529	N/A	N/A	N/A
Planned operating hours	2,360	2,360	2,500	1,845	-655
Optimal hours	2,050	2,500	2,500	2,500	—
Percent optimal hours	115.1%	101.2%	100.0%	73.8%	-26.2%
Unscheduled downtime hours	N/A	245	N/A	N/A	N/A
FACET-II (SLAC)	**N/A**	**N/A**	**$1,000**	**$6,000**	**+$5,000**
Number of Users	N/A	N/A	N/A	200	+200
Achieved operating hours	N/A	N/A	N/A	N/A	N/A
Planned operating hours	N/A	N/A	N/A	1,500	+1,500
Optimal hours	N/A	N/A	N/A	3,000	+3,000
Percent optimal hours	N/A	N/A	N/A	50.0%	N/A
Unscheduled downtime hours	N/A	N/A	N/A	N/A	N/A
Total Facilities	**$136,820**	**$135,801**	**$139,717**	**$126,217**	**-$13,500**
Number of Users	2,490	2,580	2,607	2,387	-220
Achieved operating hours	N/A	7,555	N/A	N/A	N/A
Planned operating hours	7,160	7,160	8,240	7,545	-695
Optimal hours	6,850	7,300	8,240	10,300	+2,060
Percent of optimal hours[a]	100.5%	104.6%	100.0%	85.2%	-14.8%
Unscheduled downtime hours	N/A	727	N/A	N/A	N/A

[a] For total facilities only, this is a "funding weighted" calculation FOR ONLY TYPE A facilities: $\frac{\sum_{1}^{n}[(\%OH\ for\ facility\ n)\times(funding\ for\ facility\ n\ operations)]}{Total\ funding\ for\ all\ facility\ operations}$

High Energy Physics
Scientific Employment

	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Number of permanent Ph.D.'s (FTEs)	890	830	725	-105
Number of postdoctoral associates (FTEs)	350	340	255	-85
Number of graduate students (FTEs)	520	500	375	-125
Other[a]	1,815	1,745	1,475	-270

[a] Includes technicians, engineers, computer professionals, and other support staff.

18-SC-42, Proton Improvement Plan II (PIP-II)
Fermi National Accelerator Laboratory
Project is for Design and Construction

1. Summary, Significant Changes, and Schedule and Cost History

Summary

The FY 2020 Request for Proton Improvement Plan II (PIP-II) is $20,000,000. Initial construction funding was provided in FY 2018 through the Consolidated Appropriations Act. The current preliminary Total Project Cost (TPC) range is $653,000,000 to $928,000,000 with a point estimate of $721,000,000.

The PIP-II project will enhance the Fermilab accelerator complex by providing the capability to deliver higher-power proton beams to the neutrino-generating target for groundbreaking discovery in neutrino physics, a major field of fundamental research in high energy particle physics.

The project will design and construct an 800 MeV superconducting radiofrequency (SRF) proton linac, beam transfer line, and infrastructure needed to support linac operation. It also will modify the existing Booster, Recycler, and Main Injector synchrotrons to accept the increased beam intensity. Some of the new linac components and the cryoplant will be international, in-kind contributions not funded by DOE.

Conceptual design work was completed and reviewed in FY 2018. DOE provided funds to the project in FY 2018 and FY 2019 for site-preparation activities, preliminary engineering design work, and R&D with the PIP-II Injector Test Facility, a prototype for the front-end injector, to reduce technical risks for the project.

The FY 2020 Request will continue site preparation activities, engineering design work for the conventional facilities and technical systems, procurement of prototype accelerator system components, and initiate construction of cryogenic plant support systems. Technical system R&D activities will continue.

Significant Changes

This Construction Project Data Sheet (CPDS) is new. This project was initiated in FY 2018 Appropriations. This is the first project data sheet identifying FY 2018 and FY 2019 funding.

The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-1 (Approve Alternative Selection and Cost Range), approved on July 23, 2018. The TPC cost range is $653,000,000 to $928,000,000. The funding profile supports the currently estimated TPC of $721,000,000. The CD-4 milestone is 1Q FY 2030. CD-0 established the mission need in FY 2015.

A Federal Project Director has been assigned to this project and has approved this CPDS. The FPD completed Level 3 certification in FY 2018, and Level 4 certification is in process.

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2020	11/12/2015	7/23/2018	7/23/2018	3Q FY 2020	4Q FY 2021	4Q FY 2021	TBD	1Q FY 2030

CD-0 – Approve Mission Need for a construction project with a conceptual scope and cost range
Conceptual Design Complete – Actual date the conceptual design was completed (if applicable)
CD-1 – Approve Alternative Selection and Cost Range
CD-2 – Approve Performance Baseline
Final Design Complete – Estimated/Actual date the project design will be/was complete (d)
CD-3 – Approve Start of Construction

D&D Complete – Completion of D&D work
CD-4 – Approve Start of Operations or Project Closeout

Fiscal Year	Performance Baseline Validation	CD-3A
FY 2020	2Q FY 2020	3Q FY 2020

CD-3A – Approve long-lead procurement of niobium for SRF cavities, other long lead components for SRF cryomodules, completion of the remaining site preparation work, and construction of the building that will house the cryogenic plant.

Project Cost History

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2020[a]	91,000	547,965	638,965	82,035	N/A	82,035	721,000

2. Project Scope and Justification

Scope

Specific scope elements of the PIP-II project include construction of (a) the SRF linac, (b) cryoplant to support SRF operation, (c) beam transfer line, (d) modifications to the Booster, Recycler and Main Injector synchrotrons, and (e) conventional facilities:

a) 800-MeV Superconducting H^- Linac consisting of a 2.1 MeV warm front-end injector and five types of SRF cryomodules that are CW-capable but operating initially in pulsed mode. The cryomodules include Half Wave Resonator cavities (HWR) at 162.5 MHz, two types of Single Spoke Resonator cavities (SSR1 and SSR2) at 325 MHz, Low-Beta and High-Beta elliptical cavities at 650 MHz (LB-650 and HB-650). The warm front-end injector consists of an H^- ion source, Low Energy Beam Transport (LEBT), Radiofrequency Quadrupole (RFQ) and Medium Energy Beam Transport (MEBT) that prepare the beam for injection into the SRF cryomodules. The scope includes the associated electronic power sources, instrumentation and controls to support linac operation.

   The PIP-II Injector Test Facility at Fermilab is an R&D prototype for the front-end injector consisting of H^- ion source, LEBT, RFQ, MEBT, HWR, and SSR1 cryomodule. It is being developed with participation and in-kind contributions from the India Department of Atomic Energy (DAE) Labs.

b) Cryoplant with storage and distribution system to support SRF linac operation. The cryoplant is an in-kind contribution by the India DAE Labs that is similar to the cryoplant being designed and constructed for a high-intensity superconducting proton accelerator project in India[b]
c) Beam Transfer Line from the Linac to the Booster Synchrotron, including accommodation of an 800-MeV beam dump and future delivery of beam to the Fermilab Muon Campus.
d) Modification of the Booster, Recycler and Main Injector synchrotrons to accommodate a 50% increase in beam intensity and construction of a new injection area in the Booster to accommodate 800-MeV injection.

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $653,000,000 to $928,000,000. The TPC point estimate is $721,000,000.
[b] See Section 8.

e) Civil construction of conventional facilities, including housings, service buildings, roads, access points and utilities with the special capabilities required for the linac and beam transport line. The linac housing will be constructed with adequate length to accommodate a future possible extension of the linac energy to 1.0 GeV.

Significant pieces of the linac and cryogenic scope (a and b, above) will be delivered as in-kind international contributions not funded by DOE. These include assembly and/or fabrication of linac SRF components and the cryoplant. The rationale or motivation behind these contributions are institutional and/or industrial technical capability, and interest in SRF technology. The construction phase scope of in-kind contributions is divided between U.S. DOE Labs, India Department of Atomic Energy (DAE) Labs, Italy National Institute for Nuclear Physics (INFN) Labs, French Atomic Energy Commission (CEA) and National Center for Scientific Research (CNRS)-National Institute of Nuclear and Particle Physics (IN2P3) Labs, and UK Science & Technology Facilities Council (STFC) Labs, tentatively as indicated in the following table of Scope Responsibilities for PIP-II.[a]

Construction-phase Scope Responsibilities for PIP-II Linac RF Components

Components	Quantity	Freq. (MHz)	SRF Cavities	Responsibility for Cavity Fabrication	Responsibility for Module Assembly	Responsibility for RF Amplifiers	Cryogenic Cooling Source
RFQ	1	162.5	—	—	U.S. DOE (LBNL)	U.S. DOE (FNAL)	N/A
HWR Cryomodule	1	162.5	8	U.S. DOE (ANL)	U.S. DOE (ANL)	U.S. DOE (FNAL)	India DAE Labs
SSR1 Cryomodule	2	325	16	U.S. DOE (FNAL), India DAE Labs	U.S. DOE (FNAL)	India DAE Labs	India DAE Labs
SSR2 Cryomodule	7	325	35	France CNRS (IN2P3 Lab)	U.S. DOE (FNAL)	India DAE Labs	India DAE Labs
LB-650 Cryomodule	11	650	33	Italy INFN (LASA)	France CEA (Saclay Lab)	India DAE Labs	India DAE Labs
HB-650 Cryomodule	4	650	24	UK STFC Labs	UK STFC Labs, U.S. DOE (FNAL)	India DAE Labs	India DAE Labs

Justification

Fermilab's high-energy neutrino beam, which is the world's most intense, is inadequate for further groundbreaking discovery in neutrino physics, a major field of fundamental research in high energy particle physics. Increasing the neutrino beam intensity requires increasing the proton beam power. The need for higher proton beam power comes at a time when critical components of the Fermilab accelerator complex (the linac and booster synchrotron) are approaching 50 years old and are in need of replacement.

PIP-II was identified as one of the highest priorities in the 10-year strategic plan for U.S. High Energy Physics developed by the High Energy Physics Program Prioritization Panel (P5) and unanimously approved by the High Energy Physics Advisory Panel (HEPAP), advising DOE and NSF, in 2014.[b]

The PIP-II project will enhance the Fermilab accelerator complex by enabling the capability to deliver higher-power proton beams to the neutrino-generating target that serves the LBNF/DUNE program.[c] The higher proton beam power will come from a 1.2 megawatt (MW) beam on target over an energy range of 60-120 GeV, a significant increase of beam power beyond the current proton beam capability.

The project is being conducted in accordance with the project management requirements in DOE Order 413.3B, Program and Project Management for the Acquisition of Capital Assets.

[a] See Section 8.

[b] "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context," HEPAP, 2014.

[c] LBNF/DUNE is the DOE Long Baseline Neutrino Facility / Deep Underground Neutrino Experiment.

Key Performance Parameters (KPPs)

The Threshold KPPs represent the minimum acceptable performance that the project must achieve. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion. The Objective KPPs represent the desired project performance. The KPPs shown below were approved at CD-1 and are preliminary. These KPPs will be updated and final versions will be approved at CD-2.

Performance Measure	Threshold	Objective
SRF Linac and Beam Transfer Line	700 MeV proton beam delivered to the Booster Injection Region	800 MeV proton beam delivered to the Booster Injection Region
Booster, Recycler and Main Injector Synchrotron Modifications	Booster injection region, Recycler and Main Injector RF Upgrades installed. Linac beam injected and circulated in the Booster	8 GeV proton beam transmitted through Recycler and Main Injector to the Main Injector beam dump
Cryogenic Infrastructure	Cryogenic plant and distribution lines ready to support pulsed RF operation, and operated to 2°K	Cryogenic plant and distribution lines ready to support CW RF operation, and operated to 2°K
Civil Construction	Tunnel enclosures and service buildings ready to support 700 MeV SRF Linac and Beam Transfer Line to the Booster	Tunnel enclosures ready to support 1 GeV SRF linac and transfer line to the Booster. Service Buildings ready to support 800 MeV SRF Linac and Beam Transfer Line to the Booster

3. Financial Schedule[a]

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[b]
Total Estimated Cost (TEC)			
Design			
FY 2018	1,000	1,000	—
FY 2019	20,000	20,000	20,000[c]
FY 2020	15,000	15,000	15,000
Outyears	55,000	55,000	56,000
Total, Design	91,000	91,000	91,000
Construction			
FY 2020	5,000	5,000	5,000
Outyears	542,965	542,965	542,965
Total, Construction	547,965	547,965	547,965

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $653,000,000 to $928,000,000. The TPC point estimate is $721,000,000.

[b] Costs through FY 2018 reflect actual costs; costs for FY 2019 and the outyears are estimates.

[c] Includes initiation of civil engineering design and site preparation for the cryoplant housing.

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[b]
Total Estimated Costs (TEC)			
FY 2018	1,000	1,000	—
FY 2019	20,000	20,000	20,000
FY 2020	20,000	20,000	20,000[a]
Outyears	597,965	597,965	598,965
Total, TEC	**638,965**	**638,965**	**638,965**
Other Project Costs (OPC)			
FY 2016	18,715	18,715	12,724
FY 2017	15,220	14,155	17,494
FY 2018	23,100	24,165[b]	22,214
FY 2019	15,000	15,000	15,000
FY 2020	5,000	5,000	5,000
Outyears	5,000	5,000	9,603
Total, OPC	**82,035**	**82,035**	**82,035**
Total Project Costs (TPC)			
FY 2016	18,715	18,715	12,724
FY 2017	15,220	14,155	17,494
FY 2018	24,100	25,165	22,214
FY 2019	35,000	35,000	35,000
FY 2020	25,000	25,000	25,000
Outyears	602,965	602,965	608,568
Total, TPC	**721,000**	**721,000**	**721,000**

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	76,000	N/A	N/A
Contingency	15,000	N/A	N/A
Total, Design	91,000	N/A	N/A

[a] Planned TEC activities are completion of site preparation and initiation of procurement for the cryoplant housing and the cryomodules.

[b] $1,065,000 of FY 2017 funding was attributed towards the Other Project Costs activities in FY 2018.

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Construction			
Site Work	20,000	N/A	N/A
Civil Construction	81,000	N/A	N/A
Technical Equipment	246,965	N/A	N/A
Contingency	200,000	N/A	N/A
Total, Construction	547,965	N/A	N/A
Total, TEC	**638,965**	**N/A**	**N/A**
Contingency, TEC	*215,000*	*N/A*	*N/A*
Other Project Cost (OPC)			
OPC except D&D			
R&D	50,935	N/A	N/A
Conceptual Planning	15,000	N/A	N/A
Conceptual Design	4,000	N/A	N/A
Contingency	12,100	N/A	N/A
Total, OPC	**82,035**	**N/A**	**N/A**
Contingency, OPC	*12,100*	*N/A*	*N/A*
Total Project Cost	**721,000**	**N/A**	**N/A**
Total, Contingency (TEC+OPC)	**227,100**	***N/A***	***N/A***

5. Schedule of Appropriations Requests

(dollars in thousands)

Request	Type	Prior Years	FY 2018	FY 2019	FY 2020	Outyears	Total
FY 2020[a]	TEC	—	1,000	20,000	20,000	597,965	638,965
	OPC	33,935	23,100	15,000	5,000	5,000	82,035
	TPC	33,935	24,100	35,000	25,000	602,965	721,000

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2030
Expected Useful Life (number of years)	20
Expected Future Start of D&D of this capital asset	FY 2050

Fermilab will operate the PIP-II linac as an integral part of the entire Fermilab accelerator facility. Related funding estimates for operations, utilities, maintenance and repairs are incremental to the balance of the Fermilab accelerator complex for which the present cost of operation, utilities, maintenance and repairs is approximately $100 million annually.

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $653,000,000 to $928,000,000. The TPC point estimate is $721,000,000.

Related Funding Requirements
(dollars in thousands)

	Annual Costs		Life Cycle Costs	
	Previous Total Estimate	Current Total Estimate	Previous Total Estimate	Current Total Estimate
Operations	N/A	4,000	N/A	80,000
Utilities	N/A	3,000	N/A	60,000
Maintenance & Repair	N/A	2,000	N/A	40,000
Total—Operations and Maintenance	N/A	9,000	N/A	180,000

7. D&D Information

The new area being constructed in this project is not replacing existing facilities.

	Square Feet
New area being constructed by this project at Fermilab	127,540
Area of D&D in this project at Fermilab	—
Area at Fermilab to be transferred, sold, and/or D&D outside the project, including area previously "banked"	—
Area of D&D in this project at other sites	—
Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked"	127,540
Total area eliminated	—

The one-for-one replacement will be met through banked space. A waiver from the one-for-one requirement to eliminate excess space at Fermilab to offset PIP-II and other projects was approved by DOE Headquarters on November 12, 2009. The waiver identified and transferred to Fermilab 575,104 square feet of excess space to accommodate new facilities including Mu2e, LBNF, DUNE, and other facilities, as-yet unbuilt, from space that was banked at other DOE facilities. The PIP-II Project is following all current DOE procedures for tracking and reporting space utilization.

8. Acquisition Approach

DOE is acquiring the PIP-II project through Fermi Research Alliance (FRA), the Management and Operating (M&O) contractor responsible for Fermilab, rather than have the DOE compete a contract for fabrication to a third party. FRA has a strong relationship with the high energy physics community and its leadership, including many Fermilab scientists and engineers. This arrangement will facilitate close cooperation and coordination for PIP-II with an experienced team of project leaders managed by FRA, which will have primary responsibility for oversight of all subcontracts required to execute the project. The arrangement is expected to include subcontracts for the purchase of components from third party vendors as well as delivery of in-kind contributions from non-DOE partners.

Significant pieces of scope will be delivered as in-kind international contributions, not funded by U.S. DOE. The rationale or motivation behind these contributions are institutional and/or industrial technical capability, and interest in SRF technology. Scientific institutions from several countries, tabulated below, are engaged in discussion of potential PIP-II scope contributions within the framework of international, government-to-government science and technology agreements.

Scientific Agencies and Institutions Discussing Potential Contributions of Scope for PIP-II

Country	Funding Agency	Institutions
U.S.	Department of Energy (DOE)	Fermi National Accelerator Laboratory (FNAL); Lawrence Berkeley National Laboratory (LBNL); Argonne National Laboratory (ANL)
India	Department of Atomic Energy (DAE)	Bhabha Atomic Research Centre (BARC), Mumbai; Inter University Accelerator Centre (IUAC), New Delhi; Raja Ramanna Centre for Advanced Technology (RRCAT), Indore; Variable Energy Cyclotron Centre (VECC), Kolkata
Italy	National Institute for Nuclear Physics (INFN)	Laboratory for Accelerators and Applied Superconductivity (LASA), Milan
France	Atomic Energy Commission (CEA) National Center for Scientific Research (CNRS)	Saclay Nuclear Research Center; National Institute of Nuclear & Particle Physics (IN2P3), Paris
UK	Science & Technology Facilities Council (STFC)	Daresbury Laboratory

For example, joint participation by U.S. DOE and the India DAE in the development and construction of high intensity superconducting proton accelerator projects at Fermilab and in India is codified in Annex I to the “Implementing Agreement between DOE and Indian Department of Atomic Energy in the Area of Accelerator and Particle Detector Research and Development for Discovery Science for High Intensity Proton Accelerators,” signed in January 2015 by the U.S. Secretary of Energy and the India Chairman of DAE. A “Joint R&D Document” subsequently was developed between FNAL and the DAE Labs, outlining the specific roles and goals of the collaborators during the R&D phase of the PIP-II project. This R&D agreement is expected to lead to a similar agreement for the construction phase, describing roles and in-kind contributions. Similar agreements for PIP-II are being developed with Italy, France and the UK.

The Office of Science is putting mechanisms into place to facilitate joint consultation between the partnering funding agencies, such that coordinated oversight and actions will ensure the success of the overall program. Similar mechanisms for international partnering are being employed by the Office of Science successfully for the DOE LBNF/DUNE project and for DOE participation in LHC-related projects hosted by CERN.

Domestic engineering and construction subcontractors will perform the civil construction at Fermilab. An architectural-engineering contract was placed on a time-and-material basis for design of the site preparation scope. Fermilab is developing a procurement for an architectural-engineering contract on a firm fixed price basis for the overall Preliminary and Final Designs with an option for construction support. The general construction subcontract will be placed on a firm-fixed-price basis.

All subcontracts will be competitively bid and awarded based on best value to the government. Fermi Site Office provides contract oversight for FRA’s plans and performance. Project performance metrics for FRA are included in the M&O contractor’s annual performance evaluation and measurement plan.

11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE)
Fermi National Accelerator Laboratory
Project is for Design and Construction

1. Summary, Significant Changes, and Schedule and Cost History

Summary

The FY 2020 Request for Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) is $100,000,000. The preliminary Total Project Cost (TPC) range is $1,260,000,000 to $1,860,000,000, as approved for CD-3A on September 1, 2016 with a preliminary CD-4 date of 4Q FY 2030. The range includes the full cost of the DOE contribution to the LBNF host facility and the DUNE experimental apparatus excluding foreign contributions.

The LBNF/DUNE construction project is a federal, state, private, and international partnership developing and implementing the technologies of particle accelerators and detectors to enable world-leading research into the fundamental physics of neutrinos, which are the most ubiquitous particles in the universe while at the same time among the most mysterious. Neutrinos are intimately involved in nuclear decay processes and high energy nuclear reactions. LBNF/DUNE will study the transformations of muon neutrinos that occur as they travel to a large detector in South Dakota, 800 miles away from Fermilab where they are produced in a high-energy beam. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, which are expected to help explain the fundamental physics of neutrinos and the puzzling matter-antimatter asymmetry that enables our existence in a matter-dominated universe.

The LBNF/DUNE project comprises a national flagship particle physics initiative. LBNF/DUNE will be the first-ever large-scale international science facility hosted by the United States. As part of implementation of High Energy Physics Advisory Panel-Particle Physics Project Prioritization Panel (P5) recommendations, the LBNF/DUNE project consists of two multinational collaborative efforts:

- LBNF is responsible for the beamline at Fermilab and other experimental and civil infrastructure at Fermilab and at the Sanford Underground Research Facility (SURF) in South Dakota. It is currently operated by the South Dakota Science and Technology Authority (SDSTA), an agency of the State of South Dakota, and hosts experiments supported by DOE, NSF, and major research universities.

- DOE entered into a land lease with the SDSTA on May 20, 2016 covering the area on which the DOE funded facilities will be housed and the LBNF and DUNE detector will be built. The lease and related realty actions provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the neutrino detector. Other Project Costs (OPC) funding has been identified in years FY 2018-FY 2026 for plant support costs provided by SDSTA.

- DUNE is an international scientific collaboration responsible for defining the scientific goals & technical requirements for the beam and detectors, as well as the design, construction & commissioning of the detectors and subsequent research program.

DOE’s High Energy Physics program manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/Fermilab leadership and minority participation by a small number of international partners including CERN, will construct a megawatt-class neutrino source and related facilities at Fermilab (the “Near Site”), as well as underground caverns and cryogenic facilities in South Dakota (the “Far Site”) needed to house the DUNE detectors. DUNE has international leadership and participation by about 1,000 scientists and engineers from over 160 institutions in over 30 countries. The mass of the detectors totaling 40 kilotons will be distributed in four cryostats housed in large caverns at SURF. An additional cavern at SURF will accommodate the cryogenic and other utility systems. DOE will fund less than a third of DUNE. DOE continues to refine the development of the design and cost estimates as the U.S. DOE contributions to the multinational effort are now better understood. Fermilab continues to identify and incorporate additional design activities and prototypes into the project design. The cost estimate for the DOE contribution will be updated in FY 2019 as planning continues in preparation for CD-2.

Fermilab and DOE are negotiating contributions from the international partners to LBNF/DUNE. DOE and CERN signed an agreement in May 2017 that CERN will provide in-kind contributions worth $165,000,000 for LBNF/DUNE. In September 2017, the United Kingdom announced an $88,000,000 grant to a UK collaboration that will provide in-kind contributions to LBNF/DUNE and the Proton Improvement Plan II project. In April 2018, DOE and India-Department of Atomic Energy (DAE) signed an agreement providing for neutrino physics collaboration between Fermilab and India, opening the way for advancing LBNF/DUNE project contributions. Fermilab is still finalizing the detailed distribution between the projects. For the DUNE detectors, the collaboration put in place a process to complete a technical design of the detectors and divide the work of building the detectors between the collaborating institutions. The review of the detector design with a complete set of funding responsibilities by the Long Baseline Neutrino Committee will take place in 2019. SC will manage all DOE contributions to the facility and the detectors according to DOE Order 413.3B, and Fermilab will provide unified project management reporting.

FY 2018 funding was used to continue project engineering design activities in preparation for CD-2, and to initiate pre-excavation site preparations for the equipment caverns at the Far Site as approved by CD-3A. FY 2019 funding supports an increase in the level of Far Site preparation at SURF with maintenance and refurbishment activities to the mine shaft, hoists, ventilation systems, and general support infrastructure to allow for safe and reliable access prior to initiating excavation and underground construction.

The FY 2020 Request will support the Far Site civil construction activities for pre-excavation of the underground equipment caverns and connecting drifts (tunnels), as well as design and procurement activities for Far Site cryogenics systems. The Request will also support Near Site (Fermilab) beamline and conventional facilities design and a site-preparation construction subcontract at the Near Site for relocation of existing service roads and utilities including communications, power, and water systems. The Request supports the start of construction and fabrication for technical systems, which will be funded when design is final and authorized by CD-3, including contributions to the DUNE detectors.

Significant Changes

This Construction Project Data Sheet (CPDS) is an update of the FY 2019 CPDS and does not include a new start for FY 2020. This project was initiated with TEC funds in FY 2012.

The most recent approved DOE Order 413.3B is CD-3A, approval for Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation. A Construction Manager/General Contractor (CM/GC) was selected in FY 2017 for delivery of the Far Site conventional facilities scope that was approved at the end of FY 2016. The refurbishment of the Ross Shaft, which will transport materials during the excavation of the caverns and the construction of the detectors, reached the 4,850 foot level, which is where the caverns will be excavated. The final design of the Far Site civil construction and the preliminary design of the beam line began.

Updated planning and analysis has increased the TPC point estimate for LBNF/DUNE to $1,850,000,000 and was reviewed by an Independent Project Review held January 8-10, 2019.

A Federal Project Director with a certification level 4 has been assigned to this project and has approved this CPDS.

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2011	1/8/2010		1Q FY 2011	TBD	4Q FY 2013	TBD	TBD	TBD
FY 2012	1/8/2010		2Q FY 2012	TBD	2Q FY 2015	TBD	TBD	TBD
FY 2016[a]	1/8/2010	12/10/2012	12/10/2012	4Q FY 2017	4Q FY 2019	4Q FY 2019	N/A	4Q FY 2027
FY 2017	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2020	1Q FY 2020	1Q FY 2020	N/A	4Q FY 2030
FY 2018	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030
FY 2019	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030
FY 2020	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030

CD-0 – Approve Mission Need for a construction project with a conceptual scope and cost range
Conceptual Design Complete – Actual date the conceptual design was completed (if applicable)
CD-1 – Approve Alternative Selection and Cost Range
CD-2 – Approve Performance Baseline
Final Design Complete – Estimated/Actual date the project design will be/was complete (d)
CD-3 – Approve Start of Construction
D&D Complete – Completion of D&D work
CD-4 – Approve Start of Operations or Project Closeout

Fiscal Year	Performance Baseline Validation	CD-1R	CD-3A	CD-3B	CD-3(C)
FY 2017	1Q FY 2020	11/5/2015	2Q FY 2016	3Q FY 2018	1Q FY 2020
FY 2018	1Q FY 2021	11/5/2015	9/1/2016	1Q FY 2021	1Q FY 2022
FY 2019	1Q FY 2021	11/5/2015	9/1/2016	1Q FY 2021	1Q FY 2022
FY 2020	1Q FY 2021	11/5/2015	9/1/2016	1Q FY 2021	1Q FY 2022

CD-1R – Refresh of CD-1 approval for the new Conceptual Design.
CD-3A – Approve Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation.
CD-3B – Approve Start of Far Site Construction: procurement of the remaining Far Site scope for conventional facilities, cryogenic systems and detectors.
CD-3(C) – Approve Start of Near Site Construction: procurement of Near Site scope and any remaining LBNF/DUNE scope. (Same as CD-3.)

Project Cost History

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2011	102,000	TBD	TBD	22,180	TBD	TBD	TBD
FY 2012	133,000	TBD	TBD	42,621	TBD	TBD	TBD
FY 2016[c]	127,781	655,612	783,393	89,539	N/A	89,539	872,932
FY 2017	123,781	1,290,680	1,414,461	85,539	N/A	85,539	1,500,000

[a] No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, design funds were provided in each year's appropriation.
[b] Critical Decision CD-1 was approved for the new conceptual design by an ESAAB approval (CD-1R) on November 5, 2015.
[c] No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, design funds were provided in each year's appropriation.

(dollars in thousands)

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC, Except D&D	OPC, D&D	OPC, Total	TPC
FY 2018	234,375	1,199,000	1,433,375	102,625	N/A	102,625	1,536,000
FY 2019	231,000	1,234,000	1,465,000	95,000	N/A	95,000	1,560,000
FY 2020[a b]	259,000	1,496,000	1,755,000	95,000	N/A	95,000	1,850,000

2. Project Scope and Justification

Scope

LBNF/DUNE will be composed of a neutrino beam created by new construction as well as modifications to the existing Fermilab accelerator complex, massive neutrino detectors (at least 40,000 tons in total) and associated cryogenics infrastructure located in one or more large underground caverns to be excavated at least 800 miles "downstream" from the neutrino source, and a much smaller neutrino detector at Fermilab for monitoring the neutrino beam near its source. A primary beam of protons will produce a neutrino beam directed into a target for converting the protons into a secondary beam of particles (pi mesons and muons) that decay into neutrinos, followed by a decay tunnel hundreds of meters long where the decay neutrinos will emerge and travel through the earth to the massive detector. The Neutrinos at the Main Injector (NuMI) beam at Fermilab is an existing example of this type of configuration for a neutrino beam facility. The new LBNF beam line will provide a neutrino beam of lower energy and greater intensity than the NuMI beam, and would point to a far detector at a greater distance than is used with NuMI experiments.

For the LBNF/DUNE project, Fermilab will be responsible for design, construction and operation of the major components of LBNF including: the primary proton beam, neutrino production target, focusing structures, decay pipe, absorbers and corresponding beam instrumentation; the conventional facilities and experiment infrastructure on the Fermilab site required for the near detector; and the conventional facilities and experiment infrastructure at SURF for the large detectors including the cryostats and cryogenics systems.

Justification

Recent international progress in neutrino physics, celebrated by the Nobel Prizes for Physics in 1988, 1995, 2002, and 2015, provides the basis for further discovery opportunities. Determining relative masses and mass ordering of the three known neutrinos will give guidance and constraints to theories beyond the Standard Model of particle physics. The study and observation of the different behavior of neutrinos and antineutrinos will offer insight into the dominance of matter over antimatter in our universe and therefore, the very structure of our universe. The only other source of the matter-antimatter asymmetry, in the quark sector, is too small to account for the observed matter dominance.

Among the technical issues addressed in the alternatives analysis were the preferred detector technology and the neutrino beamline design. After a thorough study, both technologies were found capable of meeting the performance requirements if located underground, only liquid argon could work on the surface, and is less expensive. A low energy neutrino beam to SURF and the current NuMI beam were compared. The new LBNF beam with its lower energy and longer distance to the detector was shown to be superior.

The project is being conducted in accordance with the project management requirements in DOE Order 413.3B, Program and Project Management for the Acquisition of Capital Assets.

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $1,260,000,000 to $1,860,000,000. An Independent Project Review was held January 8-10, 2019.

[b] No construction, other than site preparation, approved civil construction or long-lead procurement will be performed prior to validation of the Performance Baseline and approval of CD-3.

Key Performance Parameters (KPPs)

The Threshold KPPs, represent the minimum acceptable performance that the project must achieve. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion. The Objective KPPs represent the desired project performance.

The preliminary Key Performance Parameters (KPPs) for project completion that were approved by CD-1 in FY 2015 include the primary beam and neutrino beam production systems as well as underground caverns excavated for four separate, 10 kiloton detectors (of liquid-argon, time-projection detectors) at the SURF site, 1000-1500 km from the neutrino source. The DOE contribution for DUNE will include technical components for two of the four detectors, which will be installed and tested with cosmic rays, and components of the cryogenic systems for the detectors, which will be installed and pressure tested. The KPPs will be finalized at CD-2.

Performance Measure	Threshold	Objective
Primary Beam to produce neutrinos directed to the far detector site	Beamline hardware commissioning complete and demonstration of protons delivered to the target	In addition to Threshold KPPs, system enhancements to maximize neutrino flux, enable tunability in neutrino energy spectrum or to improve neutrino beam capability
Far Site-Conventional Facilities	Caverns excavated for 40 kiloton fiducial detector mass[a]; beneficial occupancy granted for cavern space to house 20 kiloton fiducial detector mass[a]	In addition to Threshold KPPs, Beneficial Occupancy granted for remaining cavern space
Detector Cryogenic Infrastructure	DOE-provided components for Cryogenic subsystems installed and pressure tested for 20 kiloton fiducial detector mass	In addition to Threshold KPPs, additional DOE contributions to cryogenic subsystems installed and pressure tested for additional 20 kiloton fiducial detector mass; DOE contributions to cryostats
Long-Baseline Distance between neutrino source and far detector	1,000-1,500 kilometers	1,000-1,500 kilometers
Far Detector	DOE-provided components installed in cryostats to support 20 kiloton fiducial detector mass, with cosmic ray interactions detected in each detector module	In addition to Threshold KPPs, additional DOE contributions to support up to 40 kiloton fiducial detector mass

[a] Fiducial detector mass pertains to the mass of the interior volume of the detection medium (liquid argon) that excludes the external portion of the detection medium where most background events would occur.

3. Financial Schedule[a]

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Recovery Act Costs	Costs[b]
Total Estimated Cost (TEC)				
Design[c]				
FY 2012	4,000	4,000	—	—[d]
FY 2013	3,781	3,781	—	801
FY 2014	16,000	16,000	—	7,109
FY 2015	12,000	12,000	—	15,791
FY 2016	26,000	26,000	—	26,436[e]
FY 2017	48,585	48,585	—	37,257
FY 2018	25,000	25,000	—	39,829[f]
FY 2019	70,000	70,000	—	70,000
FY 2020	20,000	20,000	—	20,000
Outyears	33,634	33,634	—	41,777
Total, Design	259,000	259,000	—	259,000
Construction				
FY 2017	1,415	1,415	—	13,000
FY 2018	70,000	70,000	—	6,347[g]
FY 2019	60,000	60,000	—	60,000
FY 2020	80,000	80,000	—	80,000[h]
Outyears	1,284,585	1,284,585	—	1,336,653
Total, Construction	1,496,000	1,496,000	—	1,496,000
Total Estimated Costs (TEC)				
FY 2012	4,000	4,000	—	–
FY 2013	3,781	3,781	—	801
FY 2014	16,000	16,000	—	7,109

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $1,260,000,000 to $1,860,000,000. Design and international collaboration plans are currently being developed; outyears are preliminary. An Independent Project Review was held January 8-10, 2019.

[b] Costs through FY 2018 reflect actual costs; costs for FY 2019 and the outyears are estimates.

[c] Design Only CPDS was prepared in FY 2012; no CPDS was prepared FY 2013-2015. Funding amounts shown for traceability. FY 2016 and onward CPDS prepared as Design and Construction.

[d] $1,078,000 was erroneously costed to this project in FY 2012, the accounting records were adjusted in early FY 2013.

[e] Costs were for starting Far Site preparation including safety and reliability refurbishment of the underground infrastructure, which was needed prior to initiating excavation of the equipment caverns.

[f] Estimated costs are for continuing project engineering design in preparation for CD-2.

[g] Estimated costs are for initiating excavation of the equipment caverns at the Far Site as approved by CD-3A.

[h] Estimated costs are for the Far Site civil construction excavation activities as well as design and procurement for Far Site cryogenics systems. Also will support beamline and conventional facilities design and a site-preparation construction subcontract at the Near Site (Fermilab).

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Recovery Act Costs	Costs[b]
FY 2015	12,000	12,000	—	15,791
FY 2016	26,000	26,000	—	26,436
FY 2017	50,000	50,000	—	50,257
FY 2018	95,000	95,000	—	46,176
FY 2019	130,000	130,000	—	130,000
FY 2020	100,000	100,000	—	100,000
Outyears	1,318,219	1,318,219	—	1,378,430
Total, TEC	**1,755,000**	**1,755,000**	**—**	**1,755,000**
Other Project Costs (OPC)				
FY 2009 Recovery Act	12,486[a]	12,486	—	—
FY 2010	14,178	14,178	4,696	6,336
FY 2011	7,768	7,750	7,233	11,321
FY 2012	17,000	17,018[b]	557[c]	17,940
FY 2013	14,107	14,107	—	13,232
FY 2014	10,000	10,000	—	11,505
FY 2015	10,000	10,000	—	10,079
FY 2016	86	86	—	2,284
FY 2017	—	—	—	120
FY 2018	1,000	1,000	—	86
FY 2019	1,000	1,000	—	1,000
FY 2020	4,000	4,000	—	4,000
Outyears	3,375	3,375	—	4,611
Total, OPC	**95,000**	**95,000**	**12,486**	**82,514**
Total Project Costs (TPC)				
FY 2009 Recovery Act	12,486	12,486	–	–
FY 2010	14,178	14,178	4,696	6,336
FY 2011	7,768	7,750	7,233	11,321
FY 2012	21,000	21,018	557	17,940
FY 2013	17,888	17,888	—	14,033
FY 2014	26,000	26,000	—	18,614

[a] $13,000,000 of Recovery Act funding was originally planned for the conceptual design; the difference of $512,000 relates to pre-conceptual design activities needed prior to approval of mission need (CD-0).

[b] $18,000 of FY 2011 funding was attributed towards the Other Project Costs activities in FY 2012.

[c] During FY 2012, $1,000 of Recovery Act funding was recategorized from pre-conceptual design and so became part of the OPC. $3,000 was deobligated and expired because Recovery Act funds are no longer available for obligation.

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Recovery Act Costs	Costs[b]
FY 2015	22,000	22,000	—	25,870
FY 2016	26,086	26,086	—	28,720
FY 2017	50,000	50,000	—	50,377
FY 2018	96,000	96,000	—	46,262
FY 2019	131,000	131,000	—	131,000
FY 2020	104,000	104,000	—	104,000
Outyears	1,321,594	1,321,594	—	1,383,041
Total, TPC	**1,850,000**	**1,850,000**	**12,486**	**1,837,514**

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	234,000	208,000	N/A
Contingency	25,000	23,000	N/A
Total, Design	259,000	231,000	N/A
Construction			
Far Site Civil Construction[a]	521,000	360,375	N/A
Fermilab Site Civil Construction[b]	370,000	317,375	N/A
Far Site Technical Infrastructure[c]	117,000	108,125	N/A
Fermilab Site Beamline[c]	107,000	125,125	N/A
DUNE Detectors	84,000	82,000	N/A
Contingency	297,000	241,000	N/A
Total, Construction	1,496,000	1,234,000	N/A
Total, TEC	**1,755,000**	**1,465,000**	**N/A**
Contingency, TEC	*322,000*	*264,000*	*N/A*

[a] Far Site civil construction involves excavation of caverns at SURF, 4850 ft. below the surface, for technical equipment including particle detectors and cryogenic systems.

[b] Fermilab Site civil construction involves construction of the housing for the neutrino-production beam line and the near detector.

[c] Technical equipment in the DOE scope, estimated here, will be supplemented by in-kind contributions of additional technical equipment, for the accelerator beam and particle detectors, from non-DOE partners as described in Section 1.

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Other Project Cost (OPC)			
OPC except D&D			
R&D	20,625	20,625	N/A
Conceptual Planning	30,000	30,000	N/A
Conceptual Design	35,000	35,000	N/A
Other OPC Costs	9,375	9,375	N/A
Total, OPC	**95,000**	**95,000**	**N/A**
Total Project Cost	**1,850,000**	**1,560,000**	**N/A**
Total, Contingency (TEC+OPC)	***322,000***	***264,000***	***N/A***

5. Schedule of Appropriations Requests[a]

(dollars in thousands)

Request	Type	Prior Years	FY 2018	FY 2019	FY 2020	Outyears[b]	Total
FY 2011	TEC	102,000	—	—	—	—	102,000
	OPC	22,180	—	—	—	—	22,180
	TPC	124,180	—	—	—	—	124,180
FY 2012	TEC	133,000	—	—	—	—	133,000
	OPC	42,621	—	—	—	—	42,621
	TPC	175,621	—	—	—	—	175,621
FY 2016	TEC	51,781	—	—	—	731,612	783,393
	OPC	89,539	—	—	—	—	89,539
	TPC	141,320	—	—	—	731,612	872,932
FY 2017	TEC	106,802	—	—	—	1,307,659	1,414,461
	OPC	85,539	—	—	—	—	85,539
	TPC	192,341	—	—	—	1,307,659	1,500,000
FY 2018	TEC	111,781	54,900	—	—	1,266,694	1,433,375
	OPC	85,625	100	—	—	16,900	102,625
	TPC	197,406	55,000	—	—	1,283,594	1,536,000
FY 2019	TEC	111,781	54,900	113,000	—	1,185,319	1,465,000
	OPC	85,625	100	1,000	—	8,275	95,000
	TPC	197,406	55,000	114,000	—	1,193,594	1,560,000
FY 2020[c]	TEC	111,781	95,000	130,000	100,000	1,318,219	1,755,000
	OPC	85,625	1,000	1,000	4,000	3,375	95,000
	TPC	197,406	96,000	131,000	104,000	1,321,594	1,850,000

[a] Design and international collaboration plans are currently being developed; outyears are preliminary.

[b] Outyear requests are grouped as the project is pre-CD-2 and has not been baselined. All estimates are preliminary. For the first column of Request Year, the outyears represent the time period beyond that specific requested Budget Year.

[c] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 was $1,260,000,000 to $1,860,000,000. An Independent Project Review was held January 8–10, 2019.

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2030
Expected Useful Life (years)	20
Expected Future Start of D&D of this capital asset	FY 2050

Operations and maintenance funding of this experiment will become part of the existing Fermilab accelerator facility. Annual related funding estimates include the incremental cost of 20 years of full operation, utilities, maintenance and repairs with the accelerator beam on. The estimates also include operations and maintenance for the remote site of the large detector.

Related Funding Requirements
(dollars in thousands)

	Annual Costs		Life Cycle Costs	
	Previous Total Estimate	Current Total Estimate	Previous Total Estimate	Current Total Estimate
Operations	9,000	9,000	180,000	180,000
Utilities	8,000	8,000	160,000	160,000
Maintenance & Repair	1,000	1,000	20,000	20,000
Total—Operations and Maintenance	18,000	18,000	360,000	360,000

7. D&D Information

The new area being constructed in this project is replacing existing facilities.

	Square Feet
New area being constructed by this project at Fermi National Accelerator Laboratory	48,200
New area being constructed by this project at Sanford Underground Research Facility (SURF)....................	93,800
Area of D&D in this project at Fermi National Accelerator Laboratory	—
Area at Fermi National Accelerator Laboratory to be transferred, sold, and/or D&D outside the project, including area previously "banked"..	48,200
Area of D&D in this project at other sites..	—
Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked"..	93,800
Total area eliminated	—

The one-for-one replacement has been met through banked space. A waiver from the one-for-one requirement to eliminate excess space at Fermilab to offset the LBNF/DUNE project was approved by DOE Headquarters on November 12, 2009. The waiver identified and transferred to Fermilab 575,104 square feet of excess space to accommodate the new LBNF/DUNE facilities and other as yet unbuilt facilities from space that was banked at other DOE facilities.

8. Acquisition Approach

The acquisition approach is documented in the Acquisition Strategy approved as part of CD-1. DOE is acquiring design, construction, fabrication, and operation of LBNF through the M&O contractor responsible for Fermilab, Fermi Research Alliance (FRA). FRA and Fermilab, through the LBNF Project based at Fermilab, is responsible to DOE to manage and complete construction of LBNF at both the near and remote site locations. FRA and Fermilab are assigned oversight and management responsibility for execution of the international DUNE project, to include management of the DOE contributions to DUNE. The basis for this choice and strategy is that:

- Fermilab is the site of the only existing neutrino beam facility in the U.S. and, in addition to these facilities, provides a source of existing staff and expertise to be utilized for beamline and detector construction.
- Fermilab can best ensure that the design, construction, and installation of key LBNF and DUNE components are coordinated effectively and efficiently with other research activities at Fermilab.
- Fermilab has a DOE-approved procurement system with established processes and acquisition expertise needed to obtain the necessary components and services to build the scientific hardware, equipment and conventional facilities for the accelerator beamline, and detectors for LBNF and DUNE.
- Fermilab has extensive experience in managing complex construction, fabrication, and installation projects involving multiple national laboratories, universities, and other partner institutions, building facilities both on-site and at remote off-site locations.
- Fermilab, through the LBNF Project, has established a close working relationship with SURF and the South Dakota Science and Technology Authority (SDSTA), organizations that manage and operate the remote site for the far detector in Lead, SD;
- Fermilab has extensive experience with management and participation in international projects and international collaborations, including most recently the LHC and CMS projects at CERN, as well as in the increasingly international neutrino experiments and program.

The LBNF/DUNE construction project is a federal, state, private and international partnership. Leading the LBNF/DUNE Project, Fermilab will collaborate and work with many institutions, including other DOE national laboratories (e.g. BNL, LBNL and SLAC), dozens of universities, foreign research institutions, SURF, and the SDSTA. Fermilab will be responsible for overall project management, Near Site conventional facilities, and the beamline. Fermilab will work with SDSTA and SURF to complete the conventional facilities construction at the remote site needed to house and outfit the DUNE far detector. With the DUNE collaboration, Fermilab is also responsible for technical and resource coordination to support the DUNE far and near detector design and construction. DOE will be providing in-kind contributions to the DUNE collaboration for detector systems, as agreed upon with the international DUNE collaboration.

International participation in the design, construction, and operation of LBNF and DUNE will be of essential importance because the field of High Energy Physics is international by nature; necessary talent and expertise are globally distributed, and DOE does not have the procurement or technical resources to self-perform all of the required construction and fabrication work. Contributions from other nations will be predominantly through the delivery of components built in their own countries by their own researchers. DOE will negotiate agreements in cooperation with the Department of State on a bilateral basis with all contributing nations to specify their expected contributions and the working relationships during the construction and operation of the experiment. For the DUNE detector, the process of developing in-kind contributions is being driven by the principal investigators and being reviewed by their funding agencies.

DOE funding for the LBNF/DUNE Project will be provided directly to Fermilab and collaborating DOE national laboratories via approved financial plans, and under management control of the LBNF/DUNE-U.S. Project Office at Fermilab which will also manage and control DOE funding to the combination of university subcontracts and direct fixed-price vendor procurements that are anticipated for the design, fabrication and installation of LBNF and DUNE technical components. All actions will perform in accordance with DOE approved procurement policies and procedures.

Much of the neutrino beamline component design, fabrication, assembly, and installation will be done by Fermilab staff or by subcontract temporary staff working directly with Fermilab personnel. The acquisition approach includes both new procurements based on existing designs, and re-purposed equipment from the Fermilab accelerator complex. Some highly specialized components will be designed and fabricated by or in consultation with long-standing Fermilab collaborators having proven experience with such components.

Delivery of LBNF conventional facilities at the Fermilab Near Site and SURF Far Site will be via the Construction Manager/General Contractor (CM/GC) model. This strategy was chosen to reduce risk, enhance quality and safety performance, provide a more collaborative approach to construction, and offer the opportunity for reduced cost and shortened construction schedules.

For the LBNF Near Site conventional facilities at Fermilab, the laboratory will subcontract with an architect/engineer (A/E) firm for design, and with a CM/GC subcontractor to manage construction of LBNF Near Site facilities.

For the LBNF Far Site conventional facilities at SURF, Fermilab will work with SDSTA, the owner of the site and land, which has been donated to SDSTA by the Barrick Gold Corporation for the sole purpose of facilitating scientific and technological research and development. Fermilab is contracting with an A/E firm for design of LBNF Far Site conventional facilities at SURF and with a CM/GC subcontractor to manage the construction of LBNF Far Site facilities. The CM/GC subcontractor will furnish all labor, equipment and materials for Far Site conventional facilities construction management. Work includes pre-construction construction management services and an option for executing the construction and management of the construction. The CM/GC subcontractor staff has proven experience in the area of construction management and construction of industrial and heavy construction projects. The CM/GC firm will provide support services to the LBNF and A/E teams, including input regarding the selection of materials, building systems and equipment, construction feasibility, value engineering, and factors related to construction, plus cost estimates and schedules, including estimates of alternative designs or materials. The CM/GC will also provide recommendations of actions designed to minimize adverse effects of labor or material shortages, time requirements for procurement and installation and construction completion.

The overall approach to both Near and Far Site enables Fermilab to gain construction management expertise early in the design phase to produce well-integrated designs and well understood constructability, with potential cost and management efficiencies and reduced construction risk as a result.

DOE entered into a land lease with SDSTA on May 20, 2016 covering the area on which the DOE funded facilities housing and supporting the LBNF and DUNE detector will be built. The lease and related realty actions provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the DUNE experiment. Modifications, repairs, replacements, and improvements to SDSTA infrastructure will be funded by the project to ensure safe and reliable operations of the systems required to carry out the DOE mission. Protections for DOE's real property interests in these infrastructure tasks are acquired through the lease with SDSTA, contracts and other agreements such as easements. DOE plans for Fermilab to have responsibility for managing and operating the LBNF and DUNE far detector and facilities for a useful lifetime of 20 years and may contract with SDSTA for day-to-day management and maintenance services. At the end of useful life, federal regulations permit transfer of ownership to SDSTA, which is willing to accept ownership as a condition for the lease. An appropriate decommissioning plan was developed prior to lease signing.