Fermilab

# A Plan for Discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

2011

# About Fermilab

Fermilab is America's only national laboratory fully dedicated to particle physics research. By building some of the most complex and powerful particle accelerators and detectors in the world, scientists at Fermilab expand humankind's understanding of matter, energy, space and time.

Fermilab's 1,900 employees and 2,300 scientific users from universities and laboratories across the country and around the globe carry out a world-leading program of discovery at the three interrelated frontiers of particle physics. At the Intensity Frontier, intense beams from Fermilab's particle accelerators are used to explore neutrino interactions and ultra-rare processes in nature. At the Energy Frontier, Fermilab scientists and users search for signals of new physics phenomena in the data from high-energy particle collisions. At the Cosmic Frontier, scientists use the cosmos as a laboratory to investigate the fundamental laws of physics.

Technologies developed at Fermilab sustain advanced scientific research and spur innovation to meet the challenges of America's future. Fermilab is an R&D center for superconducting radio-frequency cavities, the technology of choice for the next generation of accelerators that also has potential applications in medicine, nuclear energy and materials science. Fermilab scientists develop next-generation particle detectors and computing capabilities that enable future discoveries.

Fermilab inspires and trains the next generation of scientists and engineers. In 2010, students earned more than 100 Ph.D. degrees based on work they did at Fermilab, and about 38,000 K-12 students either participated in activities at Fermilab or received visits in their classrooms by Fermilab staff.

Fermi Research Alliance manages Fermilab for the U.S. Department of Energy's Office of Science. FRA is an alliance of the University of Chicago and the Universities Research Association, a consortium of 86 universities. FRA combines the depth and commitment of the University of Chicago with the broad involvement of URA universities for the benefit of Fermilab, the particle physics community and the nation.

The unique partnership between FRA and the Department of Energy is defined in the contractual relationship between the parties. The Fermi Site Office is the DOE Office of Science program representative located at Fermilab. FSO is responsible for evaluating contract deliverables and providing government approvals on or ahead of schedule to ensure continued progress toward the scientific mission. FSO's fewer than 20 federal employees, as the landlord and stewards of the mission, partner with FRA to ensure that land, facilities, equipment and scientific capabilities are all aligned to deliver particle physics research well into the future.

# About The Plan for Discovery

This *Plan for Discovery* describes Fermilab's long-term scientific strategy. It evolved from the report of the Fermilab Steering Group, convened in 2007 to obtain input from a broad spectrum of U.S. particle and accelerator physics communities and to prepare a report that would provide input to Fermilab, the Particle Physics Project Prioritization Panel, the High Energy Physics Advisory Panel and the funding agencies as they considered options for new particle accelerators and detectors in the United States. A number of key events have occurred in particle physics over the last four years, including the successful startup of the Large Hadron Collider, the extension of the timeline for the International Linear Collider, and the end of Tevatron operations. These events have guided Fermilab in its implementation of the recommendations of the Steering Group and have led to the development of this *Plan for Discovery*. The plan is designed to maintain the nation's leadership in particle physics and keep the laboratory and the United States on the path to discovery at the frontiers of particle physics.

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# Chapter 1

# Executive Summary

Fermilab has developed a twenty-year plan that keeps the laboratory, and the United States, at the forefront of the global quest to discover the fundamental nature of the physical universe. This *Plan for Discovery* builds on the record of excellence in scientific research and technological innovation that Fermilab and its community of users have established over the course of four decades. It makes the best possible use of the laboratory's existing world-class accelerators, experiments and technical infrastructure and systematically builds new capabilities that support groundbreaking particle physics and accelerator science research. Over the next twenty years, in partnership with the particle physics and accelerator science communities, Fermilab will:

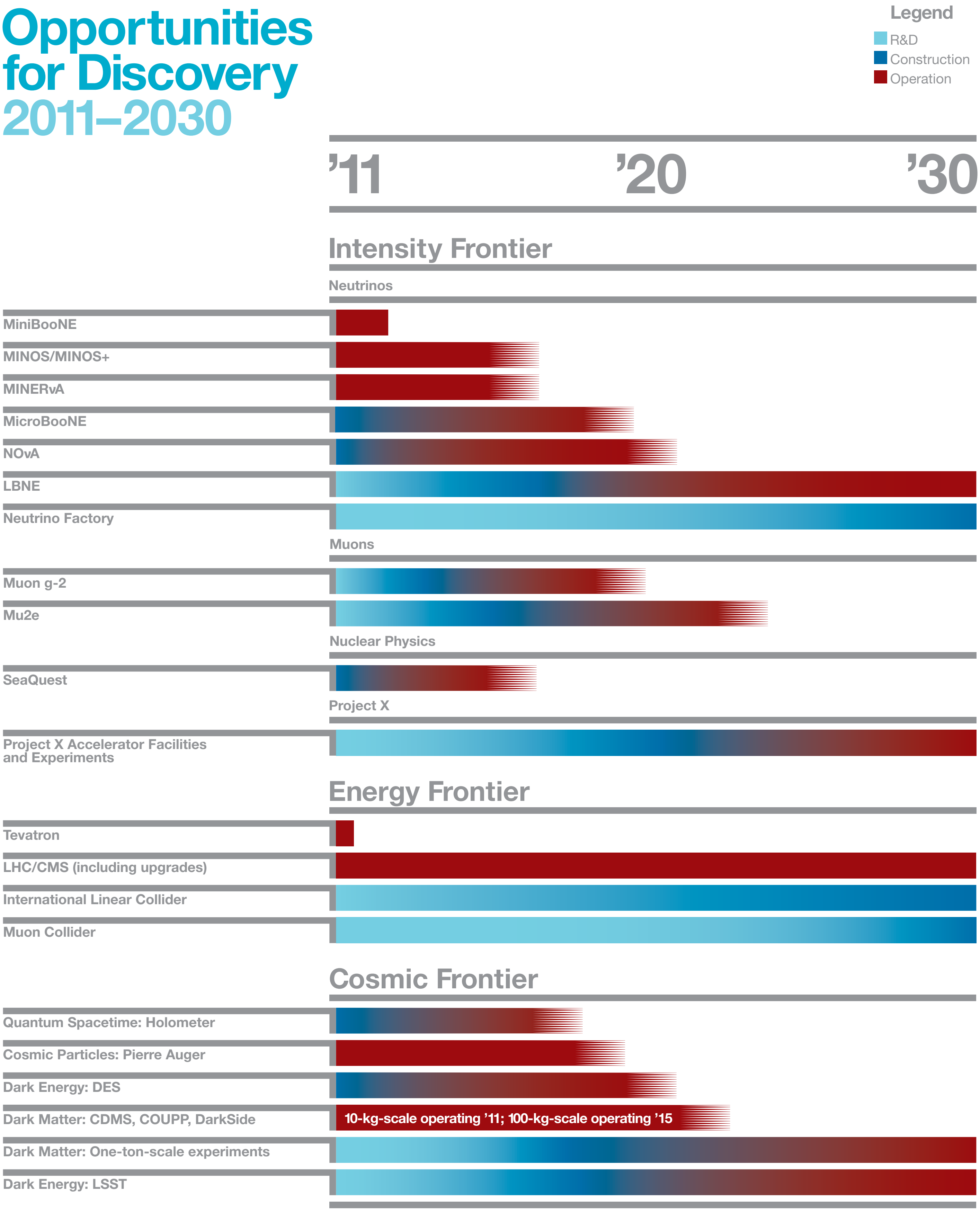
- Use the world's most intense beams of neutrinos, muons, kaons and nuclei to explore new physics in unprecedented breadth and detail.
- Build Project X, the world's most powerful proton accelerator, to propel these experiments to even greater sensitivity and to establish a versatile technical foundation for future accelerators.
- Construct the Long-Baseline Neutrino Experiment, a leap forward in the quest to understand the properties of neutrinos and the origins of a matter-dominated universe.
- Study new physics at the highest energies with experiments at the Large Hadron Collider and contribute to major accelerator, detector and computing upgrades.
- Build and operate world-leading experiments to explore the nature of dark matter, dark energy, cosmic rays and quantum spacetime.
- Build the technological base for future accelerators and particle physics detectors.

The study of the mysterious properties of neutrinos is one of the highest priorities in particle physics. Fermilab today produces the world's most intense high-energy beam of neutrinos. Upgrades to the accelerator complex over the next few years will double the proton beam intensity and support a new suite of experiments with muons and neutrinos.

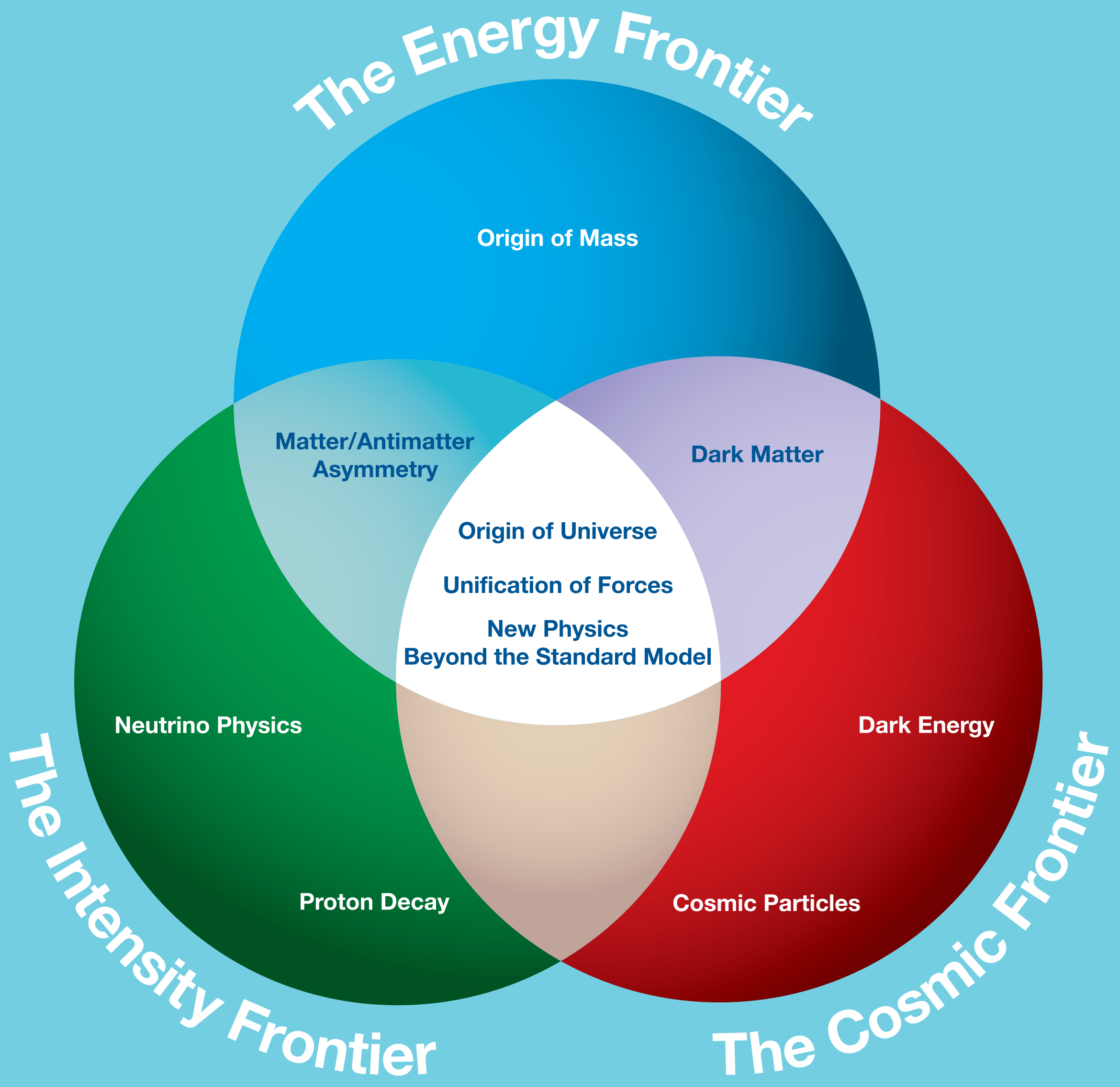
The keys to Fermilab's long-term future are two facilities that could be operating in the 2020s: the Long-Baseline Neutrino Experiment and Project X. LBNE will take the next major step in the quest to measure and understand the properties of neutrinos and determine their connection to the observed excess of matter over antimatter in the universe. The Project X accelerator complex will be unique in the world in its ability to simultaneously deliver high-intensity proton beams in different formats to multiple experimental areas. Project X experiments using neutrinos, muons, kaons and nuclei will provide new windows on phenomena not accessible at particle colliders, and will be essential to break through to a deeper understanding of nature and the origins of matter.

Fermilab's *Plan for Discovery* is strategically aligned with the national particle physics program and takes into account existing and planned facilities around the world. It is pragmatic and flexible enough to meet the challenges posed by new discoveries and changing worldwide economic realities. The plan builds on the laboratory's ongoing experimental and theoretical physics efforts, accelerator and detector R&D programs and computing capabilities. It relies on the creativity and expertise of Fermilab's staff and users from universities and research institutes across the country and around the world. It keeps the laboratory and the U.S. particle physics community on the path to discoveries wherever they may be found, whether in experiments at Fermilab using the highest-intensity beams of particles, at the highest-energy particle colliders around the world, or from measurements of matter and radiation in the cosmos.

# Opportunities for Discovery 2011–2030



**The timeline on this page shows experiments and major accelerators currently in the R&D, construction or operation phases. All experiments currently in the R&D phase require additional levels of approval from the Department of Energy before construction can begin. Construction of a Neutrino Factory or a lepton collider, at Fermilab or at any other worldwide site, would proceed only if discoveries at the LHC or elsewhere point to a need for such a machine.**


The Energy Frontier
Origin of Mass
Matter/Antimatter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Dark Energy
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

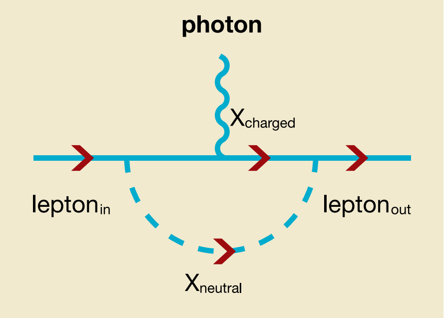
# Chapter 2

# Fermilab’s Future at the Three Frontiers

Particle physics is entering a rich new age of discovery. Deep and long-standing questions about matter, energy, space and time are closer than ever to being answered, thanks to powerful new scientific tools. This search for answers is expected to reveal something profound, just as physicists in the early twentieth century penetrated within the atom and discovered the quantum theory, an epochal event that created new sciences and enabled technologies that shape the modern world.

Fermilab's scientific plan for the next twenty years sets the trajectory for the United States to lead the world in scientific research with intense beams of particles. Building on Fermilab's current world-class neutrino beam facilities and experiments, the plan will double neutrino beam intensity, create muon beams and launch a new set of neutrino and muon physics experiments in this decade. Two key facilities—the Long-Baseline Neutrino Experiment and the Project X accelerator complex—will follow in the 2020s and cement the laboratory's standing as the global leader at the Intensity Frontier of particle physics.

The *Plan for Discovery* also leverages Fermilab's considerable on-site expertise in accelerator and detector technologies and its high-caliber technical and computing infrastructure to enable Energy and Cosmic Frontier discoveries using accelerators, experiments and telescopes around the world.



**Leptons and rare processes**

**A Feynman diagram representing the quantum effect of new particles on the electromagnetic properties of charged leptons. $X_{charged}$ and $X_{neutral}$ represent new heavy particles as predicted, for example, by supersymmetry. Depending on how these particles couple to charged leptons like the muon, this diagram could be a new physics effect on g-2, an EDM, or a process that allows muons to convert to electrons.**

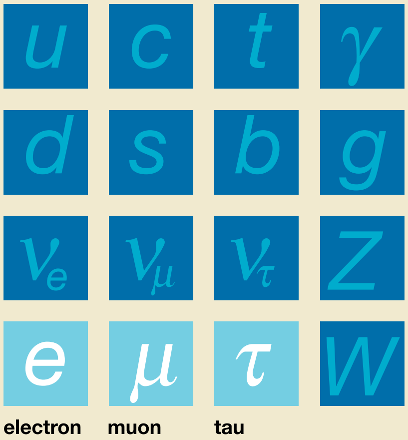
## The Intensity Frontier

Experiments at the Intensity Frontier open new windows on physical phenomena that may not be accessible at particle colliders or through observations of the cosmos. At this frontier, particle physicists study extremely rare fundamental processes using intense beams of particles such as neutrinos, muons, kaons and nuclei. They seek to understand the mysterious properties of neutrinos and search for never-before-seen transitions among particles, hoping for a glimpse of new particles or forces.

Intensity Frontier experiments at Fermilab and other laboratories have recently discovered many surprising properties of neutrinos. Their ability to oscillate from one type to another as they travel over long distances may connect them to even more exotic particles that are otherwise invisible to experiment. A major goal of the worldwide neutrino physics community is to observe CP violation, which reflects the fundamental difference between matter and antimatter, in experiments with neutrinos. Fermilab is now upgrading its accelerator complex to provide higher-intensity and higher-energy beams of neutrinos starting in 2013. These beams will support the next phase of the MINOS experiment and the new NOνA experiment. A major goal of NOνA is to determine the ordering of neutrino masses, a key piece of information for understanding the role of neutrinos in a unified theory of matter. The Long-Baseline Neutrino Experiment, which could be operating in the 2020s, will represent the next giant step in the quest to understand neutrinos and the origins of a matter-dominated universe.

Muons may reveal new forces and new physics through measurements of their detailed properties. Starting in 2016, Fermilab's Muon g-2 experiment will study the magnetic moment of the muon, where possible evidence for new physics has already been detected. Muon g-2 will also search for an electric dipole moment for the muon, which if detected would imply a new source of CP violation. Searches for rare processes involving muons could also reveal a new stratum of physics: later this decade the Mu2e experiment at Fermilab will investigate whether muons can change identity like neutrinos.

The key to Fermilab's long-term leadership at the Intensity Frontier is Project X, a multi-megawatt proton accelerator. Fermilab is pursuing the design and construction of this unique facility in collaboration with national and international partner institutions. Project X's proton beam power and flexibility to support multiple experiments will be unmatched anywhere in the world. It will produce intense beams of neutrinos, muons and kaons and copious quantities of heavy nuclei. Starting in the 2020s, Project X experiments with kaons and muons will be the world's best, observing rare phenomena at up to a thousand times

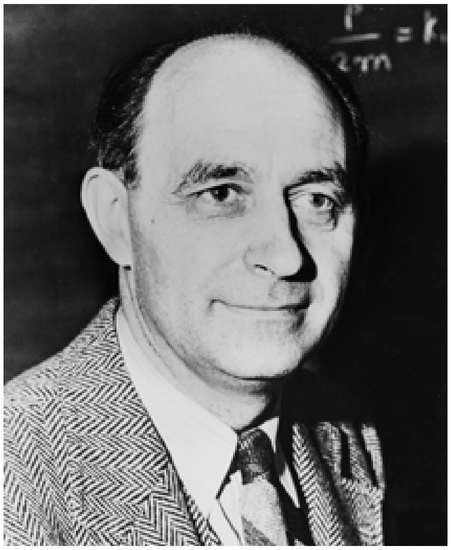


### The charged leptons

**Can one lepton change to another? Scientists have learned that neutrinos can change; experiments at Fermilab and around the world are searching for the answer for the charged leptons.**

## The puzzle of particle families

In the Standard Model, the quarks and leptons arise in families (vertical columns in the table). These families are interconnected by the forces in nature through the phenomenon of mixing. For example, the weak interactions, mediated by the *W* particle, mainly convert a *u* quark into a *d* quark, but can also convert a *u* quark into an *s* or *b* quark. The weak interactions also violate charge-parity symmetry, in other words, these interactions mysteriously sense the “arrow of time” in the universe. The origin of these family patterns, particle masses, and mixings through the weak forces remains a mystery. They are described by, but not predicted or explained by, the Standard Model. This situation is as puzzling as the Periodic Table of the Elements was in the 19th century. The development of the quantum theory in the early 1900s explained the pattern of the atomic elements and, in turn, gave a rational basis for understanding the atom, chemical bonding, the atomic nucleus and the properties of materials. This scientific revolution led to the economic growth of the 20th century. Today, experiments at all three frontiers are attempting to solve the particle puzzle. The Intensity Frontier enables detailed studies of the properties, mass relationships and mixings among the neutrinos and the charged leptons ($e$, $\mu$ and $\tau$), as well as searches for possible departures from the family pattern that would signal new physics. Energy Frontier experiments search for new particles that may extend the pattern. The Cosmic Frontier addresses the mysterious role of gravity, which does not yet fit in an established way into the Standard Model. Physicists expect that profound discoveries could emerge from 21st century research at the frontiers of particle physics, just as the solution to the puzzle of the atom revolutionized science a century ago.



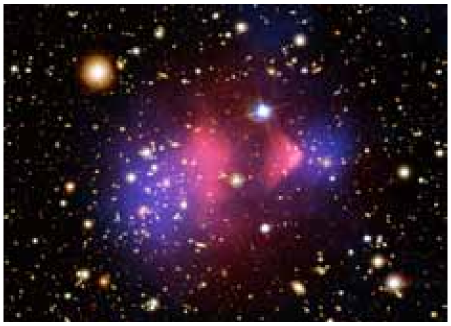
### Physicist Enrico Fermi

**Intensity and Energy Frontier physics have gone hand-in-hand since the early days of particle physics. Henri Becquerel, Marie Curie and Ernest Rutherford were Intensity Frontier pioneers, witnessing the weak interactions in rare decays of atomic nuclei decades before Enrico Fermi codified them into the first theoretical description of the weak force, and more than fifty years before the particles responsible for these forces were produced in a particle accelerator.**

the sensitivity currently achieved and probing energies of hundreds of TeV. These experiments could discover new phenomena or provide the critical clues to explain new physics discovered elsewhere. Project X’s powerful proton beams will support ultra-sensitive electric-dipole-moment searches using heavy, short-lived nuclei. Project X will drive the Long-Baseline Neutrino Experiment to its next phase, and could eventually be coupled to a muon storage ring to create a Neutrino Factory that would be the ultimate tool for the exploration of neutrino physics.

## The Energy Frontier

Energy Frontier accelerators enable the direct detection of new particles and forces. Fermilab’s Tevatron Collider long led the world at the Energy Frontier, passing the baton to CERN’s Large Hadron Collider at the start of its first physics run in 2010. Over the next few years, the Tevatron’s CDF and DØ experiments will conclude the analyses of their full data sets. Over the next two decades, Fermilab and its user community will continue to use their scientific, technical and computing leadership to maximize the discovery potential of the LHC. Fermilab’s accelerator and detector expertise will be used to its fullest extent as the laboratory contributes key components to the upgrades of the LHC detectors and the LHC accelerator. The laboratory’s accelerator and detector R&D programs will continue to develop technologies for the next generation of particle physics instruments, while the physics community makes the discoveries that will point the way to the world’s next new Energy Frontier accelerator.



**Dark matter**

**X ray and optical imaging of the sky combine to reveal clear evidence of dark matter (blue), separated from ordinary, luminous matter (red) by a merger of galaxy clusters.**

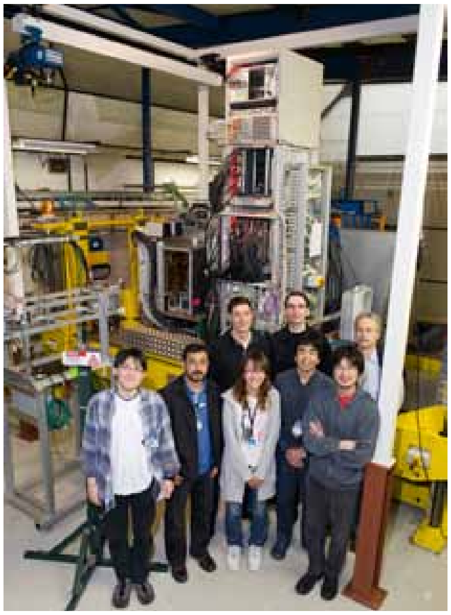
*Photo courtesy of Maruša Bradač.*

## The Cosmic Frontier

At the Cosmic Frontier, careful study of matter and radiation in the universe allows us to probe the inter-relationship of all matter with gravity and with any hidden ingredients that leave an imprint on matter and energy in the cosmos. Research at the Cosmic Frontier has already produced many signatures of new fundamental phenomena, the most prominent being the discoveries of dark matter and dark energy that challenge our basic understanding of physics. For decades Fermilab has been a world leader in studies of the cosmos as a laboratory for fundamental physics. Although these Cosmic Frontier experiments do not use accelerators, they do make use of Fermilab's cutting-edge technical capabilities and expertise in managing widely distributed international consortia of researchers.

Fermilab currently supports four kinds of experimental searches for the direct detection of dark-matter particles. Confirmed detection of dark-matter particles would link to the formation of structure in the cosmos, the possibility of producing dark matter in LHC collisions, and to potential signals of dark-matter annihilation in our galaxy. The effects of dark matter on the evolution of the expanding universe are entwined with the even more mysterious role of dark energy. Here again Fermilab is at the forefront as the leading laboratory for the Dark Energy Survey, which will be the deepest, most precise survey of cosmic structure on the largest scales.

Fermilab also brings its expertise to the Pierre Auger Observatory that studies the highest energy cosmic rays, and is developing a new adaptation of interferometer technology to study directly, in a laboratory experiment, the fine-grained quantum behavior of space and time and its relationship to matter and energy. The cosmos presents some of the most profound mysteries facing physics today, and some of the greatest opportunities for future discoveries.



**At the frontiers of technology**

**The Fermilab Test Beam Facility provides versatile beams for detector R&D to the international particle physics community. Every year more than 200 users test novel detector concepts and technologies at the facility.**

## A Laboratory at the Frontiers

Fermilab's *Plan for Discovery* lays out an ambitious blueprint for the evolution of the laboratory's Intensity Frontier accelerator complex, and for ongoing contributions to particle physics at all three frontiers. The scientific program described in this plan is broad by design, allowing Fermilab the best chance to take advantage of new physics discoveries. This breadth is critical for a successful future for the laboratory and for U.S. particle physics.

Successful execution of this plan requires all aspects of the laboratory to work in concert to build the infrastructure and drive the science that leads to new discoveries. Physicists and accelerator scientists work together with engineering and technical staff to design, build, operate and analyze data from particle detectors and accelerators. Fermilab's theoretical physics group connects the three frontiers as they define and sharpen the scientific cases for projects, provide strategies and tools for the analysis of experimental data, and meld experimental results into the big picture of nature.

Fermilab's computing efforts continue to expand possibilities for experimental and theoretical physicsists and spur innovation in particle physics and other fields of science. The laboratory's accelerator and detector R&D programs develop new tools and breakthrough technologies that have the potential to improve society as well as enable better accelerators and detectors. Every year, more than 200 users from the international particle physics community test new detector concepts and technologies using versatile beams from the Fermilab Test Beam Facility. Accelerator centers and test facilities now under development at Fermilab, including the Illinois Accelerator Research Center and the Advanced Superconducting Test Accelerator, seek to strengthen the connection between advanced accelerator R&D and industrial applications while building technologies for the future of the field of particle physics.

# Chapter 3
# The Intensity Frontier

Experiments at the Intensity Frontier search for new physics phenomena at energies many orders of magnitude higher than in experiments at particle colliders. At this frontier, scientists address central questions in particle physics that may not be addressed for many years at the Energy Frontier. Over the next twenty years, Fermilab's Intensity Frontier program will use protons to produce intense beams of neutrinos, muons and kaons, and high yields of heavy nuclei. Experiments using these beams and nuclei will study rare processes more precisely and with more sensitivity than ever before.

Throughout history many new phenomena in physics were first discovered through the study of rare processes, including the first observation of the weak interactions, the indirect detection of the neutrino and the prediction of the charm quark mass. Major scientific goals at today's Intensity Frontier include the search for CP violation in neutrinos, which may provide the critical information needed to solve the puzzle of the excess of matter over anti-matter in the universe. Intensity Frontier experiments will investigate the mysterious new physics of leptons to understand precisely how and why lepton flavor is not conserved. Experiments to observe and measure ultra-rare kaon decays and search for electric dipole moments of the muon and electron may reveal new forces and new physics.

The initial phase of Fermilab's new program at the Intensity Frontier program is already well underway and builds upon the unique and extensive Fermilab infrastructure to provide a powerful and dramatic suite of experiments with neutrinos and muons. The second phase includes construction of the Long-Baseline Neutrino Experiment and Project X. LBNE's critical scientific mission is to determine if leptons experience CP violation.

Project X will be the world's most intense and flexible particle accelerator, and is the centerpiece of Fermilab's long-term strategy to develop the world's leading Intensity Frontier physics program. Project X will enhance and permit extremely detailed studies of neutrinos at LBNE, enable the study of the rarest processes involving muons and kaons and permit the creation of heavy nuclei that provide unprecedented sensitivity to the detailed properties of electrons, neutrons and nuclei themselves.

## Theoretical Physics at the Intensity Frontier

**The NO*ν*A near detector**

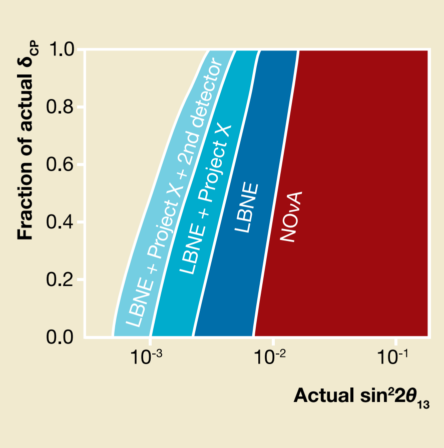
**A scientist conducts tests on the NO*ν*A near detector, which also acts as a prototype for the 15,000-ton far detector in Ash River, Minnesota.**

The Fermilab theory group plays a major role in shaping the Intensity Frontier physics program. Fermilab theorists will continue to mentor the Fermilab neutrino program, from helping to define the physics case for NOνA and LBNE to proposing novel physics searches in short-baseline experiments. Theorists actively consult with experimentalists on all aspects of Intensity Frontier physics at all stages of the Fermilab program: what aspects of physics are investigated by the experiments, and how to place limits and define new physics search strategies.

Flavor physics has been a cornerstone of Fermilab's lattice gauge theory effort. Fermilab theorists have helped craft the case for measuring rare-kaon-decay rates in the LHC era, and are focusing on the constraints these imply for TeV-scale physics. Fermilab's Lattice QCD calculations are important for Intensity Frontier physics, for example by driving the evolution of the precision of quark-flavor physics results, or by determining the hadronic contributions to the magnetic moment of the muon as required by the Muon g-2 experiment.

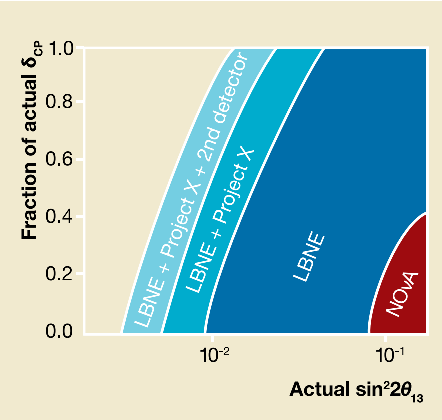
## Neutrino Physics

Experiments in neutrino physics address three fundamental goals. The first goal comprises two parts: measuring $\theta_{13}$, the mixing angle between first- and third-generation neutrinos without which there can be no CP violation; and determining whether the neutrino mass hierarchy is like that of quarks or if it is inverted. The second goal is to observe CP violation in neutrinos, such as an asymmetry between the oscillation rates of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. The third goal is to determine the nature of neutrino mass. Fermilab's long-baseline neutrino program is ideally poised for precision measurements that address the first two goals.



**Sensitivity to $\sin^2 2\theta_{13}$**

**Colored bands show for what fraction of CP-violating phases a given value of $\sin^2 2\theta_{13}$ can be distinguished from zero at the $3\sigma$ confidence level, assuming a normal mass hierarchy.**



**Sensitivity to mass hierarchy**

**Colored bands show for which $\sin^2 2\theta_{13}$ values and for what fraction of possible values of the CP-violating phase the Fermilab neutrino program can distinguish the normal and inverted mass hierarchies at the $3\sigma$ confidence level, assuming the actual hierarchy is normal.**

## Near-Term Neutrino Program

Fermilab's near-term long-baseline neutrino-oscillation experiments—MINOS, which is currently operating; MINOS+, its next phase; and NOνA, currently under construction—provide a powerful evolutionary progression in neutrino measurement capability and are also sensitive to relatively large new physics phenomena. The 735-kilometer-baseline MINOS experiment has already provided the world's most precise measurement of $\Delta m_{23}^2$, as well as highly competitive constraints on many other phenomena in neutrino physics. MINOS+ will search for sterile neutrinos and for non-standard neutrino interactions that could point to new physics. NOνA, with an 810-kilometer baseline, will measure $\theta_{23}$, $|\Delta m_{23}^2|$ and $\theta_{13}$ with greatly increased precision. NOνA will also measure the sign of $\Delta m_{23}^2$ (the neutrino mass hierarchy) provided $\theta_{13}$ is relatively large, as has been hinted by recent results from the T2K, MINOS and Double CHOOZ experiments.

The short-baseline experiments MiniBooNE, MINERνA and MicroBooNE provide a rich ensemble of complementary experiments in this decade. They measure the cross sections and kinematics of neutrino processes to high accuracy, offer a unique discovery potential for new phenomena, and can significantly advance our understanding of the underlying dynamics of neutrino-nucleus interactions, vital to the future worldwide neutrino program.

## LBNE

The LBNE experiment will have an unprecedentedly long baseline of approximately 1300 kilometers. This will significantly enhance the experiment's sensitivity to $\theta_{23}$, $\Delta m_{23}^2$ and $\theta_{13}$. As its main goal, LBNE will search for a CP-violating asymmetry in the oscillation of muon neutrinos and antineutrinos to electron neutrinos and antineutrinos. LBNE will be the first experiment capable of discovering CP violation in the neutrino sector over a large range of possible $\theta_{13}$ values. LBNE's capability to measure $\theta_{13}$ and determine the mass hierarchy will greatly exceed that of NOνA even for small $\theta_{13}$.

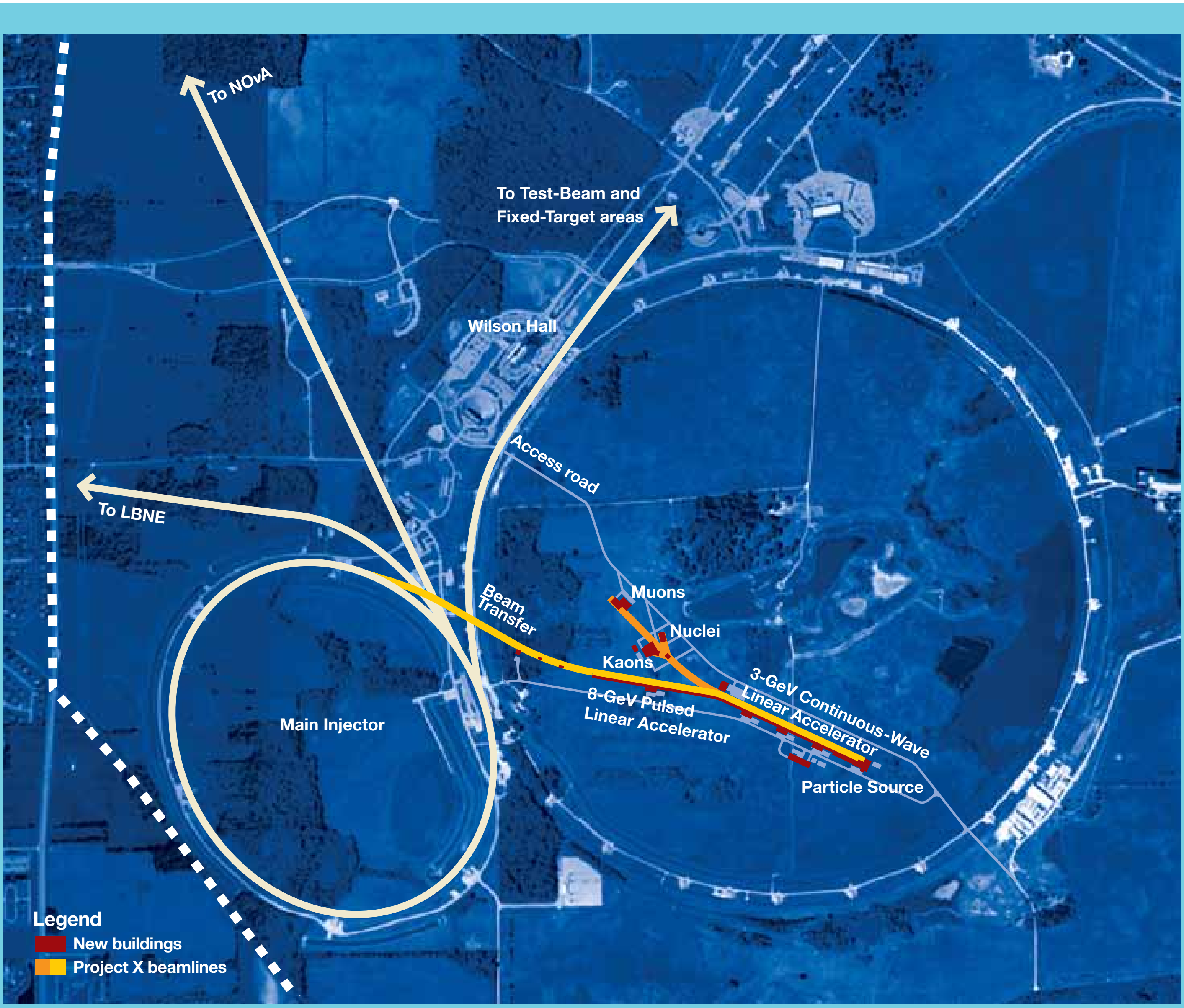
An important aspect of LBNE will be its versatile and massive far detector. This will be either a water Cerenkov detector with a mass of up to 200 kilotons or a liquid-argon time-projection chamber of several tens of kilotons. Such massive detectors are crucial for collecting sufficient event samples over such long distances. Liquid-argon detectors have not yet been realized on such large scales, but Fermilab is playing an active role in the development of this detector technology. The upcoming MicroBooNE experiment will serve as a demonstration of the technology, which is also under active study for dark-matter and neutrinoless-double-beta-decay detection.

Both detector technologies allow for a rich physics program beyond neutrino oscillation studies. This includes a high-sensitivity search for proton decay, which probes the grand-unification scale of order $10^{16}$ GeV, and high-sensitivity studies of neutrinos coming from supernovae within our galaxy.

## Neutrino Program with Project X

Project X provides a significant upgrade path for the neutrino program. Project X supplies a neutrino beam power that is more than three times larger than the Fermilab accelerator complex will produce for NOνA. Its flexible beam energy and power enhance the sensitivity of LBNE, particularly to leptonic CP violation, turning a $3\sigma$ measurement of CP violation with NOνA's 700 kW beam into a $5\sigma$ measurement with Project X. The physics achievable by LBNE in 10 years with Project X would take more than 30 years without it.

Project X will also drive new short-baseline programs to study the physics of neutrino interactions with superior precision. Enhanced short-baseline detectors driven by a Project X beam could become discovery machines for new physics.



## Project X

Project X will be the world's most intense and flexible proton accelerator. The key to Fermilab's long-term world leadership at the Intensity Frontier, it will simultaneously provide 2.3 MW of proton beam power at 60—120 GeV; up to 200 kW at 8 GeV; and 2.9 MW at 3 GeV. Fermilab is pursuing the design and construction of this unique facility in collaboration with national and international partners.

## Experiments at Project X

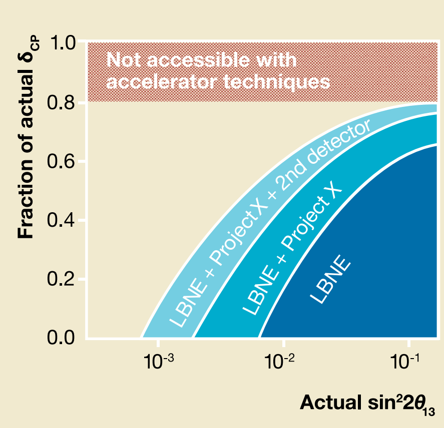
Project X will produce intense beams of neutrinos, kaons and muons, and will produce copious quantities of heavy nuclei. Starting in the 2020s, experiments using Project X beams will be essential to break through to a deeper understanding of nature and the origins of matter, either discovering new phenomena or providing the critical clues that explain new physics discovered elsewhere.

**Neutrinos:** Long- and short-baseline neutrino experiments will search for leptonic CP violation and study the physics of neutrino interactions with unmatched precision

**Muons:** Experiments could discover unexpected lepton-flavor violations or subtle new physics at the quantum-loop level

**Kaons:** Ultra-rare kaon-decay experiments will either test the Standard Model with uniquely high precision or discover new physics at the 1000-TeV scale

**Nuclei:** Ultra-sensitive electric dipole moment searches will approach limits of $10^{-31}$ e-cm or discover a new type of CP violation in the strong interaction



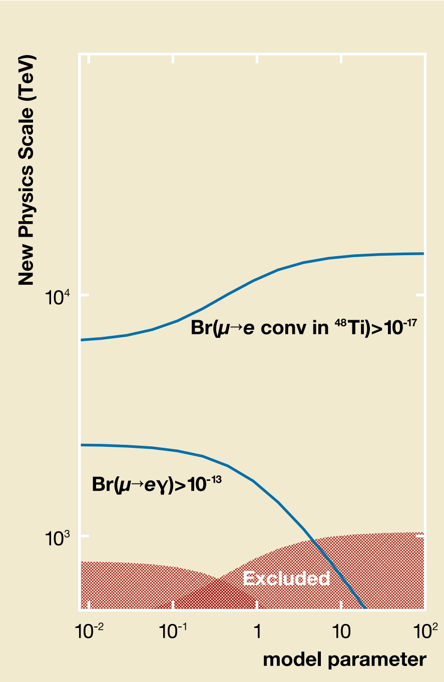
**Sensitivity to CP violation**

**Sensitivity of the Fermilab neutrino program for detecting CP violation at a 3$\sigma$ confidence level. NOvA is unable to detect CP violation at this level of significance over the plotted range of $\theta_{13}$.**

### The Neutrino Factory

The ultimate stage of Fermilab's neutrino physics program is the construction of a Neutrino Factory. Such a facility would use the high-intensity proton beam from Project X to produce a high-quality muon beam that can be accelerated and circulated in a storage ring. The muons would decay, yielding superb, background-free beams of electron and muon neutrinos. Neutrino detectors would be located at distances of up to several thousand kilometers, making the Neutrino Factory an ideal tool to study perturbations of the oscillation pattern induced by the matter through which the neutrinos travel.

Small values of $\theta_{13}$ require a high-energy Neutrino Factory. For large $\theta_{13}$ a low-energy Neutrino Factory is optimal, as the high-energy facility would suffer from larger backgrounds due to CP-conserving electron-muon oscillations. Fermilab is studying both a high-energy Neutrino Factory with a 25 GeV muon beam and a low-energy option with a 5 GeV muon beam. The Neutrino Factory would provide high-intensity beams of both electron and muon neutrinos, which would enable superior measurements of the parameters of the neutrino mass and mixing matrices. The Neutrino Factory would study up to 12 of the 18 known three-flavor oscillation channels, thus exhaustively covering the landscape of both standard and non-standard neutrino physics. The low-background environment of a Neutrino Factory will also provide enhanced sensitivity to subtle new physics effects and will cover a much larger range of possible phenomena than any other existing or currently proposed neutrino facility.



**$\mu$-to-$e$ conversion sensitivity**

**Comparison of the sensitivity to charged LFV of the MEG ($\mu \to e\gamma$) experiment at the Paul Scherrer Institute at a transition rate of $10^{-13}$ and the Mu2e experiment using the Fermilab Booster at the rate of $10^{-16}$ to $10^{-17}$.**

## Muon Physics

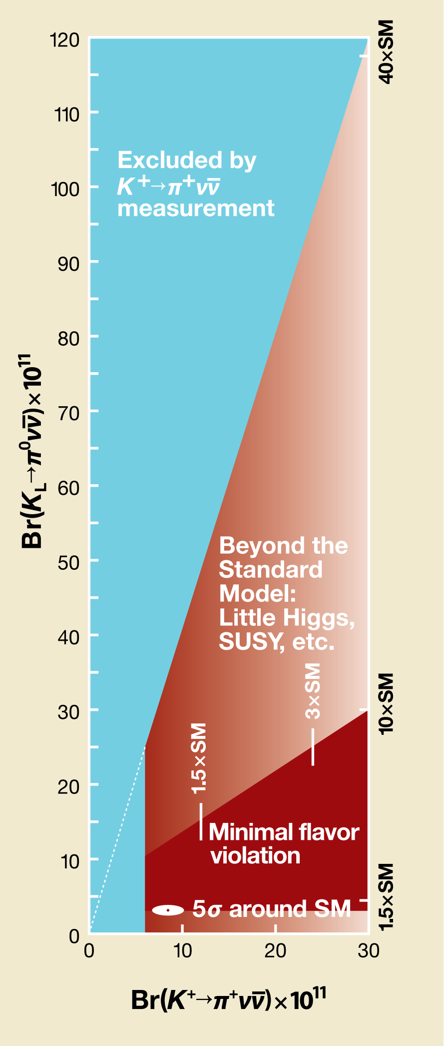
High-intensity sources of muons enable ultra-precise measurements of their fundamental physical parameters, as well as searches for new physics phenomena in rare processes involving muons. Such measurements could yield significant discoveries, such as the unexpected violation of lepton-flavor symmetries or subtle new physics entering at the quantum-loop level.

The anomalous magnetic moment of the muon, g-2, measured by the E821 experiment at Brookhaven National Laboratory with a precision of 0.54 parts per million, remains discrepant with the Standard Model and is a possible indication of new physics. A new Muon g-2 experiment at Fermilab, which will reuse the Brookhaven muon storage ring with the former Fermilab antiproton source, will achieve a fourfold improvement in precision. Combined with improved theoretical analysis, the new g-2 measurement will provide an important constraint on new physics phenomena.

The observation of an electric dipole moment for any elementary particle would constitute a major discovery of a new source of CP violation. The current 95% CL muon EDM limit is $10^{-19}$. The Muon g-2 experiment will also search for a muon EDM with a sensitivity 100 times better than current experiments. A next-generation experiment with Project X could further improve the sensitivity by another three orders of magnitude.

Rare decays of muons, if observed, could be harbingers of new physics phenomena. Starting late this decade the Mu2e experiment will search for one such rare-decay process, the conversion of a muon to an electron. This process, known as charged lepton flavor violation, is predicted by many theories that include new physics to occur at rates that could be within reach of Mu2e. Such studies provide sensitivity to mass scales of new physics phenomena that may lie at thousands of TeV for certain scenarios, significantly beyond the reach of the LHC.

Mu2e will use the 8 GeV proton beam from Fermilab's Booster and the beamline from the former antiproton source to search for the muon-to-electron conversion process with sensitivity at the $10^{-16}$ to $10^{-17}$ level, 1,000 to 10,000 times better than previous experiments. Project X would increase the beam power to the experiment by more than a factor of 10, further improving the sensitivity to the $10^{-19}$ level if the first phase of the Mu2e experiment does not discover charged lepton flavor violation. If a discovery is made in the first phase, a Project X-era experiment would offer the unique capability of distinguishing the underlying new physics by measuring the muon-to-electron conversion rate using a variety of nuclear targets.



**$K \to \pi\nu\bar{\nu}$ sensitivity**

**Project X experiments based on 1000 Standard Model events can probe new physics phenomena with greater than $5\sigma$ sensitivity.**

## Kaon Physics

A global suite of experiments seeks to measure ultra-rare decays of kaons, either to test the Standard Model with uniquely high precision or to discover new physics phenomena at the $10^3$ TeV scale. The Project X era at Fermilab will offer unmatched sensitivity to ultra-rare decays of kaons.

The rare kaon decay processes, $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$, provide physicists with the opportunity to test the Standard Model with high precision or discover new physics, since both modes are extremely suppressed in the Standard Model. The $K_L \to \pi^0 \nu\bar{\nu}$ is a purely CP-violating process, with a hadronic matrix element that is known theoretically at the one percent level of precision. The observation and precise measurement of this rare process will constitute a major triumph in kaon physics.

Fully exploiting the opportunities of kaon physics requires experiments capable of detecting about 1000 decays in each mode, thus achieving a statistical error that approaches the theoretical uncertainty. The high-intensity proton beam of Project X would readily enable experiments at the 1000-event level. The continuous-wave linac technology proposed for Project X would provide ideal conditions for these experiments, which would yield simplifications of the experimental apparatus and reduced technical risks. Both neutral and charged kaon-decay measurements would reach precisions of a few percent, comparable to the uncertainty on the Standard Model prediction, thus offering greatly increased sensitivity for new physics phenomena in these processes. Kaon experiments at Project X would also be sensitive to a variety of other rare decays involving possible exotic final states.

## Search for New Physics with Heavy Nuclei

Project X can be used to produce large quantities of heavy short-lived nuclei, such as radon, radium, americium and francium, which offer significantly amplified sensitivity to the electron EDM. The current 90% CL limit on the electron EDM of $10^{-27}$ e-cm already rules out generic models of supersymmetry. Project X-era experiments using heavy nuclei and a combination of nuclear shape and relativistic effects could approach limits of $10^{-31}$ e-cm, or discover a new type of CP violation in the strong interaction.

The target station of a facility to produce heavy nuclei with Project X could also include an ultra-cold neutron capability, the development of isotope-production techniques for beta-beams, biological studies with radiotherapeutic (alpha-emitting) isotopes, and materials-science studies with implanted radioisotopes.

## Clean Nuclear Energy Applications of Project X

In addition to its broad program in fundamental science, Project X could support R&D towards the destruction of spent fuel from conventional nuclear reactors, and the development of accelerator-driven subcritical systems for safe and abundant nuclear energy production.

The issue of high radio-toxicity and the long lifetime of conventional spent nuclear fuel is a global challenge. Accelerator-driven systems can be used to transmute spent nuclear fuel, significantly reducing the lifetime and toxicity of nuclear waste. Accelerators can also drive fission reactors that incorporate advanced fuels, such as those based on thorium. This has advantages over conventional reactor fuels, including a fuel supply that can meet global demand for 100 to 1000 times longer; less long-lived nuclear waste; reduced possibility of nuclear weapons production; and relatively safer operation. Fermilab will not establish a full-scale accelerator-driven nuclear reactor development program, but key elements for the future of accelerator-driven nuclear energy can be studied and developed with Project X.

# Chapter 4
# The Energy Frontier

Energy frontier colliders are the most powerful microscopes we have. They convert energy into new forms of matter, whose interplay with conventional matter can reveal unknown forces of nature and new physical principles. At the close of the Tevatron era and the opening of the Large Hadron Collider era, scientists have begun to directly examine physics up to multi-TeV energies. No one knows what the experiments at the LHC will find. These experiments aim to discover what generates mass for elementary particles. While both theory and Fermilab data hint at a relatively light Higgs boson, the LHC may reveal a more complex picture with unexpected twists and turns. The ultimate story of the origin of mass may well involve new forces of nature, new energy regimes and a connection to dark matter. Whatever discoveries are made will inspire deeper questions about the organizing principles that give rise to these new phenomena. Discoveries at the LHC will also define the future of physics at the Energy Frontier, guiding the choice of the optimal new accelerator for the next major advance, including a possible Muon Collider at Fermilab.

Fermilab, in partnership with its users, will fully exploit the large datasets collected by the Tevatron experiments. Over the next two decades the laboratory will use its scientific, computing and technical leadership to maximize the discovery potential of the CMS experiment. It will play key roles in planned upgrades to the LHC detectors and accelerator, with significant CMS upgrade activities being carried out on the laboratory site. Fermilab's accelerator and detector R&D programs will create technologies that will enable the next generation of particle colliders.

## Theoretical Physics at the Energy Frontier

Fermilab's strong theory group plays a critical role in supporting the national and international high-energy physics program. The group played a central part in conceiving the experimental program for the Tevatron and the Large Hadron Collider and creating theoretical tools for the analysis of collider data, as well as developing ideas being tested experimentally. Members of Fermilab's theory group are closely engaged in today's experiments at the Tevatron and LHC while also assessing the scientific promise of future lepton and hadron colliders.

## The Tevatron Collider

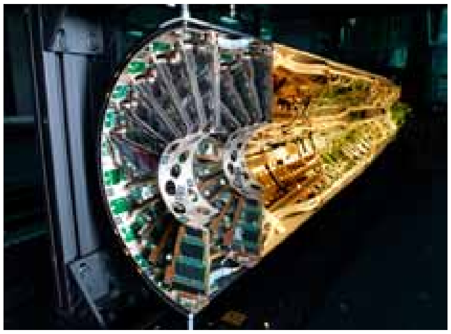
The Tevatron collider shut down in September 2011 after 26 years of operation at the Energy Frontier of particle physics. The CDF and DØ experiments will continue analyzing the full data set for several years. Each experiment expects to publish an additional 40 to 50 peer-reviewed journal articles following the end of data taking.

Of particular importance will be the experiments' final results on the search for the Standard-Model Higgs boson. The search should be sensitive at the 95% CL exclusion level or better over the mass range 110–180 GeV and should be complete by the end of 2012. At masses below about 140 GeV, search channels using the $b\bar{b}$ decay mode contribute significantly to the Tevatron's sensitivity. This is the dominant decay mode at low masses and offers information complementary to the LHC experiments' searches, which rely for now on $W^+W^-$ or $\gamma\gamma$ decays in the same mass region.

The top quark was discovered in 1995 by the Tevatron experiments, and the collaborations will complete their measurements of top-quark properties and a precision measurement of the top-quark mass within the next year. Other high-priority analyses that should be complete by the end of 2012 include measurements of diboson cross sections and kinematic distributions, searches for flavor-changing neutral-current decays of heavy-flavor mesons, and measurements of CP asymmetries in $B$-meson decays. Top-quark and heavy-flavor measurements take advantage of unique capabilities offered by the Tevatron's CP-symmetric initial state. Some additional measurements, such as a precision determination of the $W$-boson mass using the full data set, are expected to take a few additional years to complete.

**The Tevatron collider**

**The Tevatron was the world's highest-energy proton-antiproton collider from 1985 until 2011. The Tevatron enabled some of the most important fundamental discoveries of our time, including the existence of the top quark and five baryons, which helped to test and refine the Standard Model of particle physics and shape our understanding of matter, energy, space and time.**



**The CMS forward pixel detector**

**Fermilab contributed major components to the CMS detector and is involved in upgrades to the detector and computing systems.**

## The Large Hadron Collider

Fermilab is making major contributions to Energy Frontier physics through its strong participation in the CMS experiment at the Large Hadron Collider at CERN, and through its contributions to upgrades of the CMS and ATLAS detectors and the LHC accelerator.

With more than 5 $fb^{-1}$ of data recorded at collision energies of 7 TeV, and with at least two times more data expected by the end of 2012, the CMS and ATLAS experiments are poised to conclusively test the Standard Model and to search for indications of physics beyond it. Fermilab's participation in the CMS experiment includes the activities of its own research group and the critical supporting role the laboratory plays for the collaboration of more than 600 scientists and students from 49 institutions across the United States.

As the host national laboratory for the U.S. CMS collaboration, Fermilab operates a Tier-1 computing center for the CMS experiment, a Remote Operations Center from which U.S. scientists monitor CMS data quality, and hosts the LHC Physics Center. The LPC is a world-leading analysis center for CMS, providing office space, computing resources, software support and U.S. CMS administrative services to an expanding population of users and visitors, as well as hosting numerous schools, seminars and workshops.

The Fermilab CMS group is directly pursuing several research goals, including discovery or exclusion of the Standard-Model Higgs boson for any allowed mass, searches for supersymmetry well above the TeV mass scale, and searches for new dijet resonances or quark compositeness up to several TeV in mass. The group also fulfills essential responsibilities in detector operations and maintenance and provides a large part of the CMS computing services.

The current LHC run plan will conclude 7 TeV collisions at the end of 2012, and then shut down for 18 months for accelerator upgrades, which will allow for 14 TeV collisions in 2014. Taking advantage of Fermilab's experience in detector construction and microelectronics, the laboratory is directly involved in CMS upgrades for operation at higher luminosities and 14 TeV running. Planned activities include instrumenting the outer hadron calorimeter with silicon-based photomultipliers and extensive retooling in software and computing. Fermilab is also heavily involved in CMS upgrades to be deployed in later periods, particularly a new pixel detector, silicon-based photomultiplier instrumentation throughout the hadron calorimeter, and a new silicon tracker.

In collaboration with the University of Chicago and Argonne National Laboratory, a small group of Fermilab scientists and engineers is involved in the upgrade of the trigger system for the ATLAS experiment.

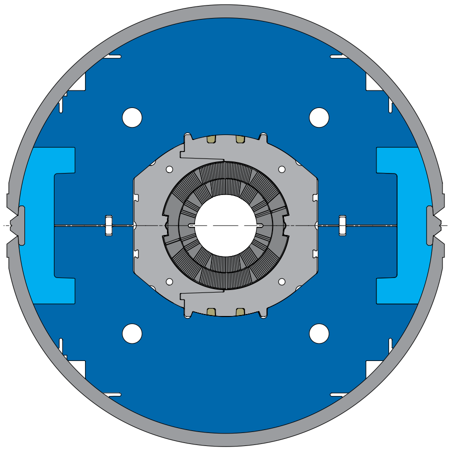
**The Remote Operations Center**

**Fermilab plays a critical supporting role for U.S. participation in the CMS experiment at the Large Hadron Collider. Scientists monitor CMS data quality from Fermilab's Remote Operations Center.**

Fermilab's major contribution to LHC accelerator upgrades will come from its work in high-field magnet technology. The development of high-field superconducting magnets has been central to achieving higher and higher energies in the Tevatron and LHC. Building on the niobium-titanium superconductor technology developed for the Tevatron, Fermilab and collaborating U.S. institutions contributed to the construction of the final-focus magnets for the LHC. This established technology is limited to dipole magnetic fields of 8 to 10 Tesla, however, and plans for an LHC luminosity upgrade in the 2020s require dipole fields of 14 to 16 Tesla. Recognizing this limitation, Fermilab initiated a program to develop magnets based on $Nb_3Sn$ superconductor. In the context of the LHC Accelerator Research Program and in collaboration with Brookhaven and Berkeley national laboratories, Fermilab has achieved a major breakthrough in the construction of reliable, accelerator-quality, long $Nb_3Sn$ magnets. The technology has advanced beyond the R&D stage and now will be ready for production for the LHC luminosity upgrade.

## Computing Support for Tevatron and LHC Experiments

The Fermilab Scientific Computing Division stewards the petabytes of data collected by the CDF and DØ experiments and a significant fraction of the multi-petabyte datasets from the CMS experiment. Because the life cycle of these experiments extends over several decades, data preservation to enable a variety of future physics analyses is an important challenge. Data processing and analysis is done using Fermilab facilities in concert with computing centers around the world connected through grid technologies. Fermilab is a founding member of the Open Science Grid and a collaborator on the Worldwide LHC Computing Grid. The distributed computing enabled by these consortia is essential for providing computing for simulations of physics processes, for processing the large distributed datasets, and for making these datasets available to the U.S. and global scientific communities.



**Dipole magnet for LHC upgrades**

**Cross section of a demonstrator magnet for an 11-Tesla dipole magnet using $Nb_3Sn$ technology. Plans for an LHC luminosity upgrade in the 2020s require dipole fields of 14 to 16 Tesla, while established niobium-titanium technology is limited to 10 Tesla.**

## R&D for Future Colliders

Over the next decade, experiments at the Large Hadron Collider will explore a new energy regime and uncover the mechanism that distinguishes the weak interactions from electromagnetism. The answer might be the Standard-Model Higgs boson or a more elaborate form of new physics—new forces of nature, new symmetries, new particles or new dimensions of space. Highly sensitive experiments at the Intensity Frontier that aim to detect extremely rare processes will study neutrino oscillations and transitions among different quark and lepton flavors. These experiments will indirectly probe energies beyond those explored directly at the LHC. Discoveries from these experiments will settle some of our most urgent questions, bring others into sharper focus and raise fresh challenges. A diverse and extended experimental campaign beyond the LHC will be needed to address remaining questions and challenges. Future colliders will establish what determines the quark and lepton masses, mixings and degree of CP violation. They may also be needed to tease out the detailed nature of particle dark matter and to give a systematic account of the spectrum, dynamics and symmetries that characterize new phenomena. Fermilab has a strong program in accelerator and detector technology development and fundamental accelerator science for future lepton and hadron colliders, including a superconducting linear collider, a Muon Collider and a high-energy upgrade to the LHC.

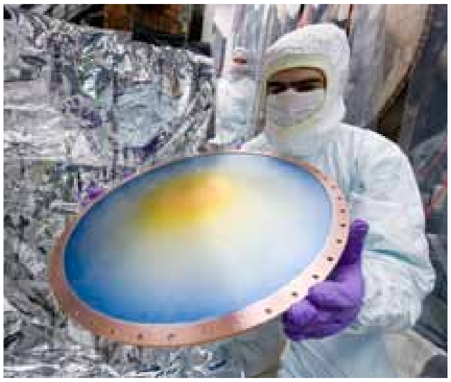
## The International Linear Collider

To prepare to capitalize on discoveries from the LHC and Intensity Frontier experiments, Fermilab is part of the international effort to develop linear electron colliders, notably the International Linear Collider at 500 GeV. Fermilab has become a world leader in the engineering and technology of superconducting radio-frequency accelerating structures and systems, such as would be required to construct Project X and the ILC. Substantial infrastructure and test facilities have been built at Fermilab to enable development, production and testing of superconducting linear accelerator components and systems. National laboratories, universities, international partners and industry, all coordinating dedicated development activity through the ILC's Global Design Effort, are obtaining accelerating gradients that reach the ILC performance specification with a greater than 50 percent yield, steadily increasing toward the final R&D goal of 90 percent. Through close coordination with the national and international program, they will continue their efforts to achieve ILC beam quality parameters in Fermilab's superconducting test accelerator and will continue to develop and refine processing techniques for achieving a high yield of high-gradient superconducting radio-frequency cavities in a cost-effective manner.

Fermilab and its collaborators work to develop detector systems that are designed to fully exploit the ILC environment to make precision measurements of particle decays. Fermilab has led the development of 3D electronics that can enable the construction of vertex detectors that are 10 times less massive and have position resolution three times better than the current generation. Novel calorimetry techniques are being developed to provide the necessary resolution for hadron showers. An integral part of this work is the design and testing of the low-mass mechanical supports, cooling systems, power-delivery systems and infrastructure essential to the fabrication and operation of linear-collider detectors.

## Muon Collider

Fermilab scientists are also exploring the feasibility of a multi-TeV Muon Collider, which could be a very attractive complement to the LHC at the Energy Frontier. The Fermilab community is leading physics and detector studies to map out the physics potential of a Muon Collider in terms of the machine's energy and luminosity. Muon Collider detectors would have to withstand large backgrounds from decays of the muon beams. Simulations of this complex environment are currently being performed that will define the detector technologies necessary for the never-before-tested environment of a Muon Collider. Initial studies have shown that tracking detectors and calorimeters with nanosecond timing can reject much of the beam-related background. Once detector performance is understood, the group will begin detailed simulations of the physics to be addressed by a multi-TeV Muon Collider, such as the full spectrum of larger-mass-scale supersymmetry or strong dynamics.



**Components in the MuCool Test Area**

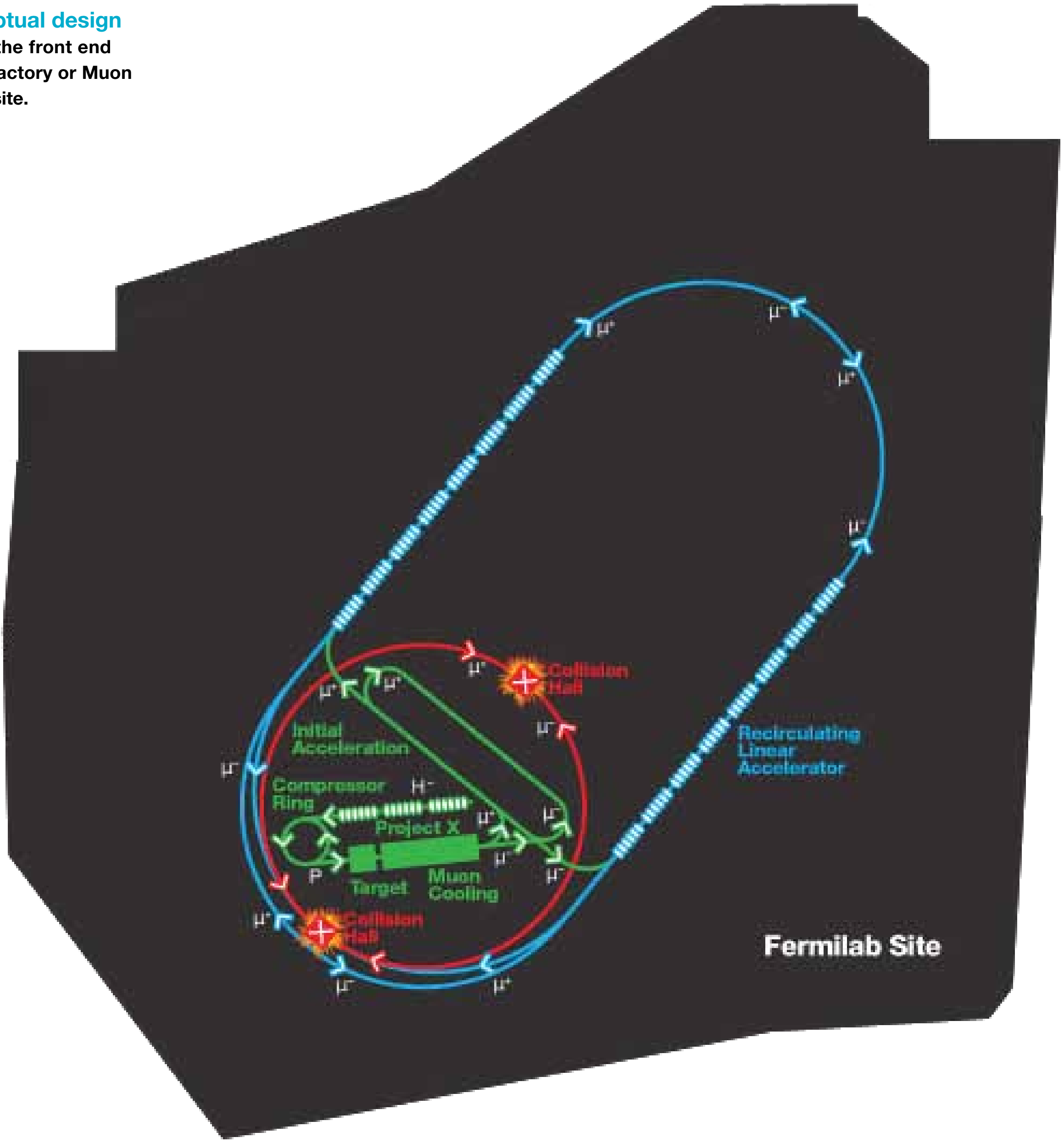
**An international collaboration of about 200 scientists is working on R&D for a Muon Collider. At Fermilab's MuCool Test Area, scientists test equipment for muon cooling.**

A multi-TeV Muon Collider has many potential accelerator physics advantages over electron colliders, most of which arise from the lack of synchrotron radiation emission by muons, which allows a compact circular design. These advantages include multi-pass acceleration and multi-pass collisions, which could make for a cost-effective approach to reaching high energies with leptons, and a very narrow energy spread. Fermilab leads the national Muon Accelerator Program aimed at developing and demonstrating the concepts and critical technologies required to produce, capture, condition, accelerate and store intense beams of muons. MAP's goal is to deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider following a focused five-year R&D program. Under study are critical technologies including the MICE experiment's demonstration of transverse muon cooling; RF cavity performance in the presence of high magnetic fields required for muon cooling; and very-high-field solenoids. MAP is also conducting advanced beam dynamics simulations of the muon production, capture, cooling, acceleration and collision processes. The initial application of these new technologies might be in a Neutrino Factory based on a muon storage ring. Project X, under development at Fermilab as part of its Intensity Frontier program, could serve as the front end of a Neutrino Factory or Muon Collider.

Fermilab's expertise in high-field superconducting magnets will also be critical to a Muon Collider or high-energy LHC upgrade, which both benefit from magnets capable of achieving the highest possible fields. For example, one design for a muon collider requires 50 Tesla focusing solenoids, while a high-energy LHC upgrade would demand 25 to 30 Tesla dipole fields. Such magnets could be based on high-temperature superconductors operating at low temperatures, where they can carry high currents in high magnetic fields. Fermilab is engaged in R&D leading to the construction of the first high-temperature superconductor-based magnets for future Energy Frontier accelerators.

**Muon Collider conceptual design**

**Project X could provide the front end for a possible Neutrino Factory or Muon Collider on the Fermilab site.**



# Chapter 5

# The Cosmic Frontier

**SDSS image of Galaxy n4753**

**In the universe's vast web of galaxies, black holes grab matter at the speed of light into cataclysmic space-time vortices and fling off particles at energies millions of times greater than any laboratory accelerator. Particles of invisible dark matter are a critical element in the formation of galaxies. A mysterious dark energy accelerates the expansion of space between galaxies. Such extraordinary things never happen in a laboratory, but they can reveal deeply hidden details of fundamental physics beyond the Standard Model.**

At the Cosmic Frontier, scientists investigate the relationship of matter with gravity and spacetime and search for new physics beyond the reach of particle accelerators. Fermilab pioneered particle physics at the Cosmic Frontier and has continued to develop the connection between the very large and the very small for almost 30 years. Cosmic Frontier experiments make use of Fermilab's world-leading technical capabilities, such as high-precision, low-noise silicon detector technology, large and ultra-clean vacuum and cryogenic systems, fast electronics, and large-scale data management, analysis and simulation tools. Fermilab serves as the host institution for global Cosmic Frontier experiments, providing scientific, technical and administrative support for widely distributed international scientific collaborations.

Over the next two decades, Fermilab will lead the Dark Energy Survey and participate in the Large Synoptic Survey Telescope as they explore the nature of dark energy; support the search to directly detect dark matter particles by playing a major role in four experiments using different technologies; study the highest-energy cosmic rays with the Pierre Auger Observatory; and take experimental physics to the Planck scale with the Fermilab Holometer.

## Theoretical Physics at the Cosmic Frontier

Fermilab theorists explore the connections between new ideas in fundamental physics and experiments at the Cosmic Frontier. They compute the interactions of particle dark matter in accelerators and experiments; estimate the measurable effects of various possible forms of dark energy in Dark Energy Survey data; and calculate how the properties of the modern universe, such as cosmic background radiation, depend on theories of the inflationary beginnings of the Big Bang. Close collaboration with theorists is important in all stages of experiments, from first conceptualization to the final analysis and interpretation of data. The synergy between Cosmic Frontier and the Energy and Intensity Frontiers, and the various theorists who work in these areas, has never been stronger at Fermilab than it is today.

## Dark Energy

Measurements of the distant cosmos reveal a new force that appears to accelerate the expansion of the universe and makes up most of its total energy content. This mysterious dark energy can be studied through large-scale precision measurements of the expansion and structure of the universe using massive surveys—maps of the cosmos extending far into space and back in time.

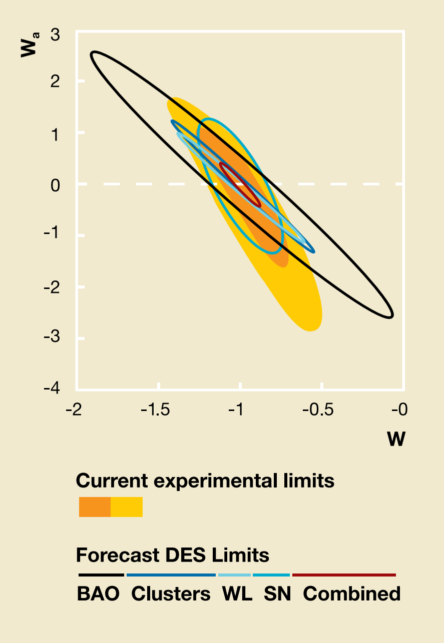
Fermilab's connection to dark-energy research began with its role as the anchor laboratory for the Sloan Digital Sky Survey. The SDSS, the highest-impact astronomy facility of the 2000s, was the world's first large, deep digital survey of the universe. The SDSS pioneered precision cosmology and made many important contributions to dark energy measurements. Fermilab now leads a survey with SDSS that is setting new standards for precision and error calibration in the use of supernovae to measure very large cosmic distances.

In this decade, Fermilab's dark-energy research program is focused on the Dark Energy Survey, a deeper, more precise successor to the SDSS. Fermilab leads the international DES collaboration, which is deploying a powerful new instrument called the Dark Energy Camera on the 4-meter telescope at the Cerro Tololo Interamerican Observatory in the Chilean Andes. Starting in 2012, and over the course of 525 nights through 2017, the DES will map about 5,000 square degrees of the sky. The final petabyte-scale survey database will comprise approximately 300 million galaxies and will look back in time over more than half of the age of the universe.

The DES will probe dark energy using a variety of complementary techniques: galaxy clustering, weak gravitational lensing, baryon acoustic oscillations and supernovae. Together they will provide unprecedented probes of the dark-energy equation of state and its effects

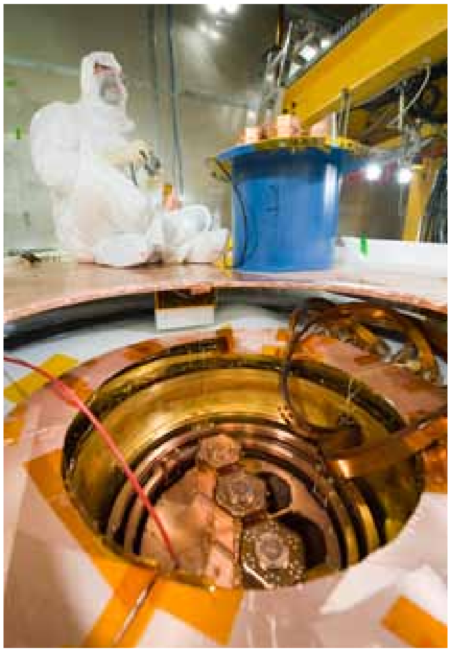
**Dark Energy Camera telescope simulator**

**Fermilab leads the international Dark Energy Survey collaboration, which is deploying the 570-megapixel Dark Energy Camera on the 4-meter telescope at the Cerro Tololo Inter-american Observatory in Chile.**



**Measurement uncertainties in dark energy behavior**

**Sensitivity of the Dark Energy Survey to equation-of-state parameters of dark energy: w denotes the ratio of mean dark energy pressure to density of the cosmic vaccuum state and $w_a$ is the derivative of w with respect to cosmic scale factor. DES will use a variety of complementary techniques to study dark energy, including baryon acoustic oscillations (BAO), galaxy clustering, weak gravitational lensing (WL) and supernovae (SN).**



**Cryogenic Dark Matter Search**

**Assembly of the CDMS detector in its cryostat in Minnesota's Soudan Mine. The next-generation SuperCDMS experiment will be deployed in Canada's SNOLAB.**

on the expansion of the universe and on the growth of cosmic structure. These probes will allow scientists to distinguish the effects of various possible forms of dark energy from each other. For example, they will test whether cosmic acceleration is due to the energy of the vacuum or a more exotic form of dark energy, or if it is due to a new theory of gravity.

The deep DES sky survey will be even more powerful if it obtains spectra of many of its galaxies, providing velocity and 3D position information. Fermilab and its collaborators are developing the technology to create a catalog of 10 to 100 million spectra that will provide an exquisitely sensitive probe of dark energy's effects on structure growth over time.

The next step in cosmic surveys after the DES is the Large Synoptic Survey Telescope, which should start its survey in the early 2020s. Now in the final stages of planning and design, this project proposes to create a dedicated telescope and camera system that will survey the universe significantly wider, deeper and faster than the DES. LSST will combine a larger mirror (8 meters), a bigger field of view (3 gigapixels over 10 square degrees) and a faster cadence to make a dedicated survey of the universe. Fermilab brings its decades of experience in digital surveys to the large consortium of institutions developing this project.

## Dark Matter

Since the 1930s astronomers have accumulated evidence that the mass that holds galaxies and clusters together with its gravity far exceeds the amount of mass in normal atoms in any detectable form. Scientists suspect that this gravity comes from an invisible "dark matter" made of some new kind of elementary particle left over from the early universe. A leading postulate, based on Big Bang cosmology and natural extensions of Standard Model physics, is that the dark matter is made of Weakly Interacting Massive Particles. WIMPs would weigh more than atomic nuclei but would interact only by the weak force and gravity. There is hope that some of them might one day be produced in accelerators, but they have never been directly detected.

Fermilab is a leader in the worldwide hunt for dark matter particles. In collaboration with international partners, the laboratory plays a major role in four kinds of experimental searches. These experiments, which are based on a variety of technologies, all seek to detect the very rare interactions of dark-matter particles from the Galaxy's halo with nuclei of ordinary matter using very low-background detectors placed deep underground.

Fermilab is a lead laboratory in the Cryogenic Dark Matter Search, which uses ultra-cold silicon and germanium crystals to achieve a high level of control over unwanted backgrounds. The experiment is entering a new phase with the deployment of 10 kilograms of advanced detectors in its existing facility at the Soudan Underground Laboratory in Minnesota. The 10-kg SuperCDMS experiment will take data until about 2013. A next-generation 100-kg experiment is planned for Canada's SNOLAB, with the goal of improving sensitivity to dark-matter particles by a factor of 100 without any backgrounds generated by normal-matter particles.

The Chicagoland Observatory for Underground Particle Physics uses bubble-chamber technology, allowing for relatively inexpensive scaling to larger volumes and flexibility in target material. A 4-kg COUPP chamber is operating at SNOLAB, and a 60-kg chamber being tested underground at Fermilab will be deployed in Canada in 2012. Designs for a 500-kg system are underway.

Fermilab contributes key technology for the DarkSide project that is based on a liquid-argon detector similar to that being developed for Fermilab's long-baseline neutrino experiments. A 50-kg chamber is now under construction that will start operations in 2013 at the Gran Sasso National Laboratory in Italy. Larger follow-up experiments are planned. A new Fermilab project called DAMIC is based on the same CCD detectors used to build the Dark Energy Camera. In the DAMIC technology, very fine-grain imaging of particle

**Pierre Auger Observatory**

**Seventeen countries contributed to the construction of Auger, which uses 1,600 water tanks and 24 fluorescence telescopes to study the highest-energy cosmic rays.**

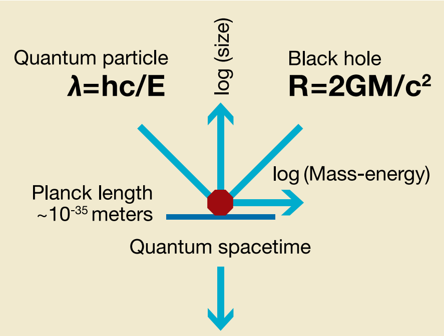
tracks allows efficient diagnosis of unwanted particle backgrounds and an extended sensitivity to low WIMP masses. An experimental system is currently under development underground at Fermilab, and will be deployed to the much deeper SNOLAB site in 2012.

Over the next few years, the next generation of experiments will be able to either detect these particles for the first time—revealing a new kind of matter and opening a new way to study the universe—or to exclude many of the theoretical ideas that lead to the WIMP hypothesis. In the next decade, based on the results of those experiments, some of these technologies will be deployed with a ton or more of detector mass, leading to a conclusive test.

## High-Energy Cosmic Particles

The universe accelerates particles to energies far greater than human-made accelerators can, reaching collision energies nearly 100 times greater than those achieved at the Large Hadron Collider. Although the highest-energy particles are extremely rare, they can be studied by large arrays of ground-based detectors. Their composition, interactions and natural history provide a unique window into high-energy particle interactions and the extreme sources in the universe that accelerate them.

Fermilab is the lead laboratory supporting the Pierre Auger Observatory in Argentina, the world's premier facility for studying the highest-energy cosmic rays. Auger's international collaboration has published many groundbreaking results on the composition, interactions, anisotropy and spectrum of ultra-high-energy cosmic rays. The highest-energy events can be statistically traced back to their sources in the sky, the nuclei of distant galaxies.



**The Planck scale**

**Experiments beyond the Planck scale probe a deeper level of quantum spacetime. In this diagram, log of length is plotted against log of mass-energy. At upper left, the equation relating wavelength and energy for a quantum particle, Einstein's photoelectric formula. At upper right, the equation relating the radius and mass of a black hole, predicted by Einstein's theory of spacetime. These two realms cross at the Planck scale.**

## Quantum Spacetime

A new experiment called the Fermilab Holometer will study physics at the Planck scale, the deepest layer of reality we can explore with the tools of conventional physics. The Planck scale defines the intersection of two realms of physics: the quantum world, which describes the fundamental particle/wave behavior of all forms of mass and energy; and spacetime physics or relativity, which describes the large-scale space and time within which the mass and energy move and transform.

Planck-energy particles are impossible to study at particle accelerators because they have such high energies—about $10^{16}$ TeV. The Fermilab Holometer will study Planck-scale physics indirectly by detecting directionally coherent quantum noise in spacetime position. With collaborators from the gravitational-wave community, Fermilab is developing this new experimental capability using intense, ultra-stable laser cavities and interferometers. The Holometer will start taking data in late 2012 and will run for several years.

The target precision of the Holometer is set by the Planckian amplitude of predicted "holographic noise" in spacetime. If holographic noise exists, it causes the difference of position compared in two different directions to wander randomly, by about a Planck length every Planck time. Although the Planck length itself is far too small to see directly, the effect of the accumulated wandering over the light crossing time of the 40-meter apparatus—a few attometers in a fraction of a microsecond—can be detected. The holometer will find out whether or not such noise exists in nature. If it does, it will be our first experimental glimpse beyond spacetime as we know it.

# Chapter 6

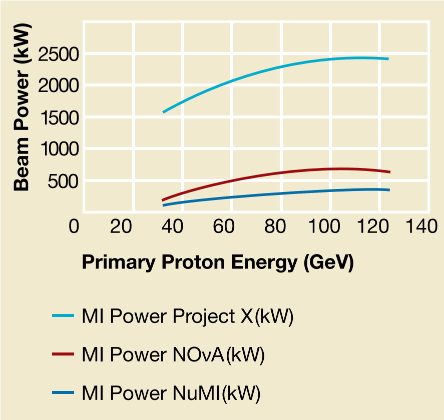
# Fermilab Accelerator Facilities for the Intensity Frontier

Fermilab is transforming its accelerator facilities to meet the challenges of the Intensity Frontier era and support science at the Energy and Cosmic Frontiers. Project X is the centerpiece of the Fermilab strategy to develop a world-leading Intensity Frontier program and lay the groundwork for eventual construction of a Neutrino Factory or Muon Collider at Fermilab. The plan for the continuous evolution of the accelerator complex, as outlined below, supports discovery science at every stage. It makes the best use of assets freed up by the end of Tevatron collider operations, and provides a platform for even longer-term accelerator development. It features the following elements:

## Stage One

The existing Fermilab accelerator complex, including the Main Injector synchrotron, Recycler storage ring and NuMI neutrino beamline and target, will be upgraded in 2012 to supply 700 kW beams for NOνA, Fermilab's second-generation long-baseline neutrino experiment.

The Proton Improvement Plan will upgrade the existing proton facility to deliver 33 kW of proton-beam power at 8 GeV simultaneous with NOνA operations. The PIP, which will be completed in 2016, is designed to support the operation of Fermilab's suite of neutrino and muon experiments at the Intensity Frontier and the test-beam facility for detector R&D. The complex will operate in this configuration until Project X becomes operational.



**Proton beam power**

**Beam power from the Main Injector (MI) for three neutrino facilities: the existing NuMI beam, the planned upgrade for NOvA and Project X.**

## Stage Two

Fermilab and its national and international partners will build Project X, the world's most powerful proton facility. Project X could begin construction in 2016, and would deliver 5 MW of total beam power to the next stage of Intensity Frontier experiments with neutrinos, muons, kaons and nuclei. Based on a modern high-power $H^-$ linac, it would simultaneously deliver 2.9 MW at 3 GeV; 50–200 kW at 8 GeV and 2.3 MW at any energy between 60 and 120 GeV.

## Stage Three

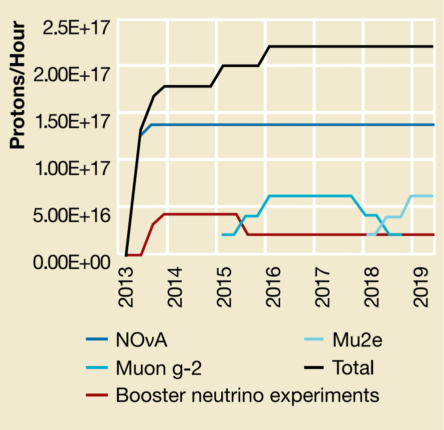
Starting in the 2020s Fermilab, together with its national and international partners, could be preparing to build the next major accelerator. Depending on the outcome of earlier experiments and international decisions, the next accelerator could be a Neutrino Factory or Muon Collider located at Fermilab. Project X could serve as the front end for either next-generation accelerator.

**Accelerator performance**

**Evolution of the performance of the Fermilab accelerator complex during stages one and two, from 2012 to 2022.**

| | During Tevatron Operation | NOvA | Proton Improvement Plan | Project X | |
|---|---|---|---|---|---|
| **Batch Intensity (8 GeV)** | $4.3\times10^{12}$ | $4.3\times10^{12}$ | $4.3\times10^{12}$ | $2.6\times10^{13}$ | protons per pulse |
| **Repetition Rate** | 7.5 | 9 | 15 | 10 | Hz |
| **Total Flux (8 GeV)** | $1.2\times10^{17}$ | $1.4\times10^{17}$ | $2.3\times10^{17}$ | $1.0\times10^{8}$ | protons per hour |
| **Total Flux (3 GeV)** | NA | NA | NA | $2.2 \times 10^{19}$ | protons per hour |
| **Main Injector (MI) Batches** | 11* | 12 | 12 | 6 | |
| **MI Cycle Time** | 2.2 | 1.33 | 1.33 | 1.3 | seconds |
| **MI Beam Power (120 GeV)** | 400 | 700 | 700 | 2300 | kW |
| **8 GeV Beam Power (available)** | 15 | 0 | 33 | 200 | kW |
| **3 GeV Beam Power (available)** | NA | NA | NA | 2900 | kW |

** 9 batches to NuMI target and 2 to antiproton production target*



**Proton demand**
**Total proton demand from Fermilab's experiments through 2020.**

## Stage One: Upgrades to Existing Facilities

Fermilab's existing proton facility consists of a 400 MeV linear accelerator, 8 GeV Booster accelerator and 120 GeV Main Injector synchrotron. The complex delivers beams to a variety of target stations including the MiniBooNE target at 8 GeV, the NuMI and antiproton targets at 120 GeV, and a test-beam facility. Two key components of the proton facility—the initial 181 MeV of the Linac and the Booster—have been operating for 40 years and rely on components that are either no longer commercially available or are at risk of being discontinued. The Linac and Booster have the potential to operate at up to 15 Hz, but limitations in the RF systems and the overall tolerance to beam loss currently limit beam cycles to 7.5 Hz. This rate will support the short- and long-baseline neutrino program through 2012.

Following the end of Tevatron operation portions of Fermilab's existing antiproton facility—the 8 GeV Recycler and Antiproton Rings—are being converted to enhance the Intensity Frontier program. Starting in 2013 the Recycler will accumulate protons in support of NOνA, and several years later the Antiproton Rings will accumulate and then resonantly extract protons for the muon complex.

### NOνA Upgrades

The NOνA experiment requires 700 kW of proton beam power delivered to the NuMI target, double the power produced in the Tevatron era. This power will be achieved by reducing the Main Injector cycle time and increasing the number of batches targeted, but without increasing the batch intensity. The cycle time is reduced by increasing the Main Injector acceleration rate and using the Recycler as a proton accumulation ring. Component fabrication to complete these upgrades is currently underway. Installation will start in spring 2012 and take 11 months to complete. Startup of the NOνA experimental program will begin in the spring of 2013, at which time the Booster will be able to deliver beams at 9 Hz.

### Proton Improvement Plan

Further upgrades to the proton facility are required to support the balance of the near-term Intensity Frontier program—the MicroBooNE, Mu2e, and Muon g-2 experiments—in parallel with NOνA. The PIP will also provide the initial beams required by LBNE. The

**The Fermilab accelerator complex in 2020**

**Legend**

🟥 Protons
🟧 Neutrinos
🟩 Muons
🟨 Electrons
⬛ Target

Proton Improvement Plan will enable the Linac and Booster to meet this program's total demands. The goals of the PIP are:

- Increase the beam repetition rate to 15 Hz.
- Eliminate major reliability vulnerabilities and maintain reliability at present levels (>85%) at the full repetition rate.
- Eliminate major obsolescence issues.
- Increase the proton throughput to more than $2 \times 10^{17}$ protons per hour.
- Ensure a useful operating life of the Linac and Booster through at least 2025.

The last goal is meant to ensure continuity of operations in the face of potential delays for Project X. The PIP is currently underway and will be completed in 2016.

## Stage Two: Project X

Project X will be unique in the world in its ability to deliver high-power proton beams with flexible beam formats to multiple users. A Project X reference design has been developed based on a 3 GeV continuous-wave superconducting linac operating at an average current of 1 mA followed by a 3–8 GeV pulsed linac operating with a duty factor of 4%. These facilities are further augmented by upgrades to the Main Injector/Recycler complex to support higher-power operations. A total of 5 MW of beam power will be available at Project X: 2.9 MW at 3 GeV; up to 200 kW at 8 GeV; and 2.3 MW at 60–120 GeV.

Project X is currently in the pre-conceptual design and development stage and a R&D program targeting the critical technical issues is underway in collaboration with 14 universities and laboratories. While no project schedule has been agreed to with DOE, Project X could be ready to begin construction as early as 2016.

### Project X Reference Design

The design of Project X is driven by four main research goals:

- Long-baseline neutrino experiments: Project X will deliver 2.3 MW of proton beam power onto a neutrino production target at any energy between 60 and 120 GeV.
- Rare-process experiments: Project X will provide megawatt-class, multi-GeV proton beams supporting multiple precision experiments with kaons, muons and neutrinos simultaneous with the long-baseline neutrino program.
- Muon facilities: Project X will provide a path toward a muon source for a possible future Neutrino Factory or Muon Collider.
- Nuclei and nuclear energy: Project X will provide opportunities for implementing a program of Standard Model tests with nuclei and possible research into technologies necessary for cleaner nuclear energy.

The first three goals were defined in the U.S. Department of Energy's long-range strategic plan for high-energy physics (P5 report), which also recommended the development of a high-intensity proton facility.[1] The fourth goal was developed in discussion with the broader scientific community.

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[1] U.S. Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years, May 2008, http://science.energy.gov/~/media/hep/pdf/files/pdfs/p5_report_06022008.pdf

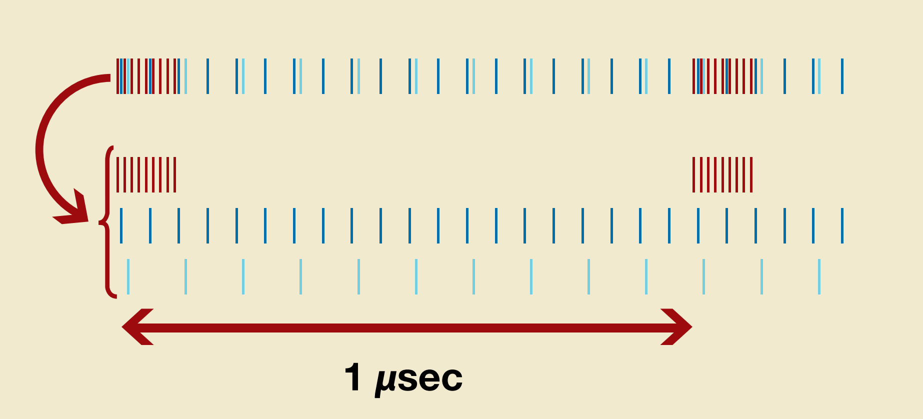
The Project X Reference Design meets the high-level design criteria listed above in an innovative and flexible manner.[2] The primary elements comprising the Reference Design are:

- An $H^-$ source consisting of a CW ion source, 2.1 MeV RFQ, and Medium-Energy Beam Transport line with an integrated wideband beam chopper capable of accepting or rejecting bunches in arbitrary patterns at 162.5 MHz.
- A 3 GeV superconducting linac operating in CW mode and capable of accelerating an average $H^-$ beam current of 1 mA, and a peak beam current of 10 mA.
- A 3-to-8 GeV pulsed linac capable of accelerating 1 mA of peak beam current at a duty factor of up to 4%.
- A pulsed dipole that can direct beam towards either the Main Injector/Recycler complex for neutrino experiments or the 3 GeV muon, kaon and nuclei experimental areas.
- An RF beam splitter that can deliver the 3 GeV beam to multiple experimental areas.
- Modifications necessary to support 2 MW operations in the Main Injector/Recycler complex.
- All interconnecting beamlines.

### Operating Scenarios

The CW linac primarily supports a program of precision experiments with muons, kaons and nuclei at 3 GeV. Key to the success of this program is the delivery of different bunch patterns to three experiments simultaneously. This is achieved by the coordinated utilization of a wideband chopper at the linac front end and a transverse deflecting RF separator at the exit. The power available to the 3 GeV experimental program is 2.9 MW when 4% of the CW linac beam is diverted to the pulsed linac.

The pulsed 8 GeV linac operates at 10 Hz and supports the long-baseline neutrino program in concert with the Main Injector and Recycler. The pulsed linac provides 350 kW of total beam power. The power is increased to 2.3 MW by accumulating six pulses from the linac in the Recycler. The accumulated beam is then delivered in a single turn to the Main Injector for subsequent acceleration to any energy between 60 and 120 GeV. Since 60–120 GeV beams do not use every available beam pulse, there is 200 kW of extra power available to support an 8 GeV experimental program when the Main Injector is operating at 120 GeV, and 50 kW available at 60 GeV.



**Project X linac loading pattern**

Example linac loading pattern (top line) providing independent bunch patterns to three experiments (red, blue, teal lines) simultaneously. The red experiment receives bunches with a 1 MHz macrostructure and a 80 MHz micro-structure; blue at 20 MHz; and teal at 10 MHz. For a peak current of 4.2 mA the average current is 1 mA, and the red, blue and teal areas receive 700, 1540, and 770 kW, respectively.

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[2] Project X Reference Design Report, November 2010, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=776

### Project X R&D Program

The Project X R&D program is well underway and consists of facility design and systems optimization studies and development of the critical underlying technologies. Foremost among the latter are the wideband chopper that provides the required bunch patterns, the system for providing multi-turn injection of $H^-$ into the Recycler, and superconducting RF development at four different frequencies. The Project X R&D program is being undertaken by a collaboration consisting of ten U.S. laboratories and universities and four laboratories in India.

Development of the wideband chopper is a key element of the R&D program. The chopper consists of a set of four kickers and a corresponding set of kicker drivers. The system is required to deliver one nanosecond rise and fall time with a one nanosecond flattop. Kicker voltages in excess of ±200 V are required and a repetition rate of 60 MHz must be supported. Helical transmission line structures have been developed that meet the kicker requirements, while MOSFET-based wideband amplifiers are being investigated for the driver.

Another key element is the system to deliver $H^-$ beam in six 4.3 msec pulses. The $H^-$ are stripped during a multi-turn injection into the Recycler, representing a 400-turn injection. Simulations indicate that 400 turns is roughly the maximum number that can be tolerated when taking into account foil heating, emittance growth, and reasonable foil survival times. However, there would be advantages to injecting the full current directly into the Main Injector in a single 26 msec-long pulse—something that is not possible with the standard foil techniques. Alternative techniques that include moving/rotating foils and laser-assisted stripping are currently under development.

**SRF development**

**Superconducting radiofrequency technology is being developed at Fermilab for future accelerators, in partnership with laboratories around the world.**

A very significant superconducting radiofrequency development program has been underway for several years, utilizing resources at Fermilab and partner laboratories. For the CW linac, the emphasis is on developing high-$Q_0$ cavities with gradients of approximately 15 MV/m at frequencies of 162.5, 325 and 650 MHz. Two 325-MHz cavities have been built and tested, both achieving 15 MV/m with $Q_0$ of $1.5\times10^{10}$. At 650 MHz, a number of elliptical shapes are currently being investigated in single-cell tests. For the pulsed linac, cavities with $Q_0$ of $1\times10^{10}$ and gradients of 25 MV/m are required. The development of these 1300 MHz cavities is at a more advanced stage, due to strong overlap with the International Linear Collider development program. A complete cryomodule is currently under RF testing and a second cryomodule is under construction.

Significant effort is also going into the development of RF sources. The CW linac cavities will be driven by individual sources, with up to 30 kW per source required in the 650 MHz section. Solid-state sources have been identified as the preferred technology at 325 MHz, and both solid-state and inductive output tubes are being investigated at 650 MHz.

## Stage Three: Project X as a Platform for Future Facilities

The high-power linacs in Project X share many fundamental characteristics that would be required from the front end of a Neutrino Factory or Muon Collider, including approximately 4 MW of proton-beam power at an energy of 5 to 15 GeV. Unlike Project X, however, a Muon Collider requires a very low-duty-factor beam with very short, but intense, bunches. The Muon Collider under study at Fermilab requires beam to be delivered in a single bunch, with a bunch length of 2–3 nsec, at a 15 Hz repetition rate. A Neutrino Factory would have slightly less stringent requirements.

Meeting the Muon Collider's beam-power and bunch-structure requirements would call for a power upgrade to Project X's 8 GeV beam and additional facilities to reformat the high-duty-factor beam from Project X. A task force, jointly sponsored by Project X and the U.S. Muon Accelerator Program, has been launched to develop a feasible concept that will be fed back into Project X planning activities. This task force will report by the end of 2011; however, a number of concepts that could provide the required beam power, repetition rate and bunch formatting are already under investigation.

# Chapter 7
# Milestones in a New Era of Particle Physics

The decades ahead will bring great scientific opportunities and difficult challenges. As the only national laboratory dedicated to particle physics, Fermilab has a responsibility to keep the United States at the forefront of physics research by providing the scientific community with powerful tools for cutting-edge experiments, supporting advanced accelerator and detector R&D, and maintaining a vibrant experimental and theoretical particle physics community. Fermilab's twenty-year scientific plan makes the best possible use of the laboratory's unique facilities and capabilities, evolves over time to meet changing scientific and societal imperatives, strengthens ties with university scientists and other laboratories, and provides scientific training and education for the next generation of particle physicists. The plan offers many paths to possible discoveries at the Intensity, Energy and Cosmic Frontiers.

**Here are its major milestones:**

## 2011–2020

- **The MINOS+ and NOvA long-baseline neutrino experiments will measure neutrino mixings with greater sensitivity and investigate the ordering of neutrino masses.**
- **Fermilab's short-baseline neutrino program will study the cross sections and kinematics of neutrino processes with higher accuracy.**
- **The Muon g-2 experiment will seek to measure the anomalous magnetic moment of the muon four times better than previous experiments, setting important limits on new physics.**
- **The Mu2e experiment will begin searching for the rare conversion of a muon to an electron, a process predicted by many theories that include new physics, with a sensitivity 1,000 times better than previous experiments.**
- **The experiments at the Large Hadron Collider will test the Standard Model and search for indications of new physics with 14 TeV collisions.**
- **The next steps will be taken in the quest to understand the phenomenon of dark energy and directly detect dark matter, with the completion of the Dark Energy Survey and the operation of 10—100 kilogram dark-matter detectors.**
- **The Fermilab Holometer will study Planck-scale physics, exploring the quantum behavior of space and time in a laboratory experiment.**

## 2021–2030

- **The Long-Baseline Neutrino Experiment will be taking data, with the goal of measuring CP violation with neutrinos for the first time.**
- **Project X will become the world's most powerful and flexible proton accelerator facility.**
- **Project X experiments with kaons, muons, neutrinos and nuclei will begin operating, opening a window on a 1000 TeV energy scale inaccessible at the LHC and possibly leading to indirect discoveries of new physics.**
- **Fermilab will contribute key technologies to the high-luminosity upgrades of the LHC accelerator and detector.**
- **A third generation of dark-matter experiments may use one-ton-scale detectors to raise the stakes in the hunt to directly detect these elusive particles.**
- **The Large Synoptic Survey Telescope could be well underway in its more than ten-year program to record the widest and deepest survey of the sky.**
- **Depending on the scientific developments of the previous decade, Fermilab could be leading the effort to construct an electron-positron linear collider, a Neutrino Factory or a Muon Collider.**

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