About Fermilab

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

Fermilab's 1,925 employees and 2,300 scientific users carry out a world-leading program of discovery at the three interrelated frontiers of particle physics: the Energy, Intensity and Cosmic Frontiers.

At the Energy Frontier, particle accelerators produce high-energy collisions that signal new phenomena. Fermilab supports the continuing analysis of data collected by the experiments at the Tevatron collider, enables more than 1,000 U.S. scientists to engage in research at the Large Hadron Collider, and carries out R&D on accelerator and detectors for future colliders.

At the Intensity Frontier, scientists use intense beams from particle accelerators to explore neutrino interactions and ultra-rare processes in nature. Fermilab's accelerator complex produces the world's most intense high-energy beam of neutrinos, whose unique properties appear to be at the crux of many questions about the universe. Ongoing R&D prepares Fermilab to break new ground in research on revelatory rare phenomena with the muon-to-electron conversion, or Mu2e, and g-2 experiments.

At the Cosmic Frontier, scientists use the cosmos as a laboratory to investigate the fundamental laws of physics. Fermilab scientists bring the perspectives and techniques of particle physics to the search for dark matter and dark energy, and to the construction and operation of large-scale ground and space telescopes.

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. Fermilab is constructing the most advanced R&D center for SRF technology in the United States, which will be used to test components for future accelerators and will be a unique user facility for advanced accelerator R&D. At the Illinois Accelerator Research Center, which will begin construction in the fall of 2012, scientists and engineers from national laboratories, universities and industry will work side by side to develop breakthroughs in accelerator technology and apply them to energy and environment, medicine, industry, national security and discovery science.

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

Fermi Research Alliance manages Fermilab for the Department of Energy. 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.

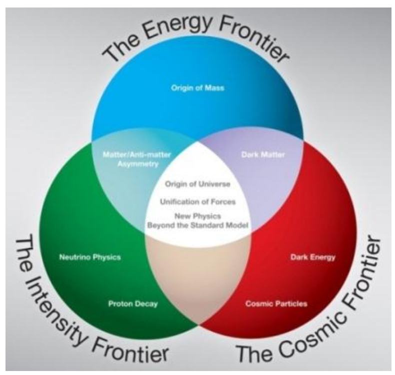
About the Plan for Fermilab

This Plan for Fermilab has its roots in the 2007 Fermilab Steering Group Report. Fermilab Director Pier Oddone convened the Fermilab Steering Group in early 2007 to obtain input from a broad spectrum of the U.S. particle and accelerator physics communities, and to prepare a report that would serve as input to the Fermilab Director, Particle Physics Project Prioritization Panel, 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, delay in timeline for key decisions regarding the International Linear Collider, and the decision in January 2011 to shut down the Tevatron Collider. These events have guided Fermilab in its implementation of the recommendations of the Steering Group Report, and have led to the development of this updated Plan for Fermilab. This plan maintains the national's leadership in particle physics, and keeps the laboratory and the United States on the path to discovery at the frontiers of particle physics.

Chapter 1. Executive Summary: A Plan for Fermilab

As the national particle physics laboratory, Fermilab's mission is to enable the U.S. scientific community to tackle the most fundamental physics questions of our era, and to integrate universities and other laboratories fully into national and international particle physics programs. Fermilab provides the only accelerator facilities in the United States for particle physics research. Particle physics is a central component of the physical sciences, focused on the fundamental nature of matter, energy, space and time. Discoveries in particle physics change our basic understanding of nature. For the U.S. to remain among the leaders in this field of science, it must maintain a laboratory that builds and exploits new facilities in partnership with universities and other national and international laboratories. Facilities for particle physics are global and ever more challenging to design, build and operate. A laboratory with a singular focus and consolidated particle physics facilities will give the U.S. a competitive advantage in the future.

The Standard Model of particle physics provides a remarkably accurate description of elementary particles and their interactions. However, experiment and observation strongly point to a deeper and more fundamental theory that breakthroughs in the coming decade will begin to reveal. To address the central questions of particle physics and thus to deliver on the missions of the Department of Energy's Office of High Energy Physics, Fermilab uses a range of tools and techniques at the three interrelated frontiers of particle physics:



- **The Energy Frontier**, where high-energy particle colliders are used to discover new particles and directly probe the architecture of the fundamental forces of nature.

- **The Intensity Frontier**, where intense particle beams are used to uncover properties of neutrinos and observe rare processes that will tell us about new physics beyond the Standard Model.

- **The Cosmic Frontier**, where underground experiments and ground-based telescopes are used to reveal the natures of dark matter and dark energy, and high-energy particles from space are used to probe new physics phenomena.

These three approaches ask different questions and use different techniques, but answers to challenging questions about the fundamental physics of the universe will come from combining powerful insights and discoveries at each of the three frontiers. Fermilab's scientific program supports the U.S. scientific community with world-leading research at all three interrelated frontiers of particle physics.

At the Energy Frontier**,** after a very successful 26 year program, Fermilab's Tevatron collider and the CDF and DØ experiments will end data taking in September 2011. Fermilab's accelerator, detector, computing and physics facilities support the ongoing LHC program. Fermilab is the principal U.S. contributor to the LHC accelerator and the CMS detector, and is the headquarters of the U.S. CMS collaboration. Fermilab's Remote Operations Center and LHC Physics Center make the participation of U.S. institutions in the LHC and in CMS more effective, enhancing U.S. leadership in LHC science. Fermilab is a world-leading institution in the development of accelerator technologies for future lepton colliders such as the International Linear Collider and the Muon Collider.

In designing the laboratory strategy for the post-Tevatron era we need to meet the following criteria:

- Address timely, exciting questions
- Be bold and establish world leadership in at least one domain

- Attract partners to leverage our investments through international collaboration
- Fit within a global strategy for the field and within a realistic profile for U.S. funding
- Be robust enough to adapt to both physics discoveries and funding fluctuations

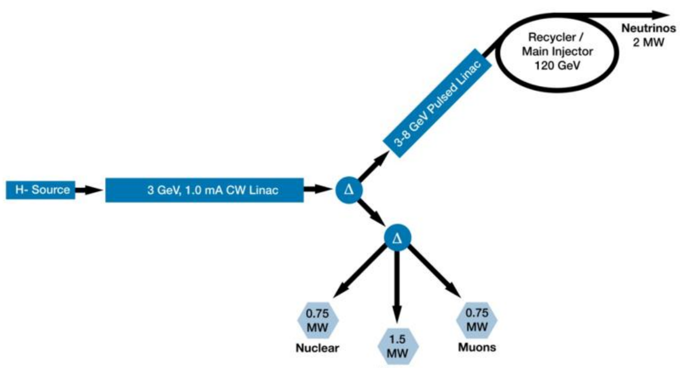
An analysis of the world's particle physics program leads us to the conclusion that the greatest opportunity for U.S. leadership lies in experiments driven by high intensity proton beams at the Intensity Frontier. In this area we are sensitive to physics beyond the Standard Model up to energies much greater than the direct reach of the LHC. The most intense proton source enables the best set of neutrino experiments. The discovery of neutrino oscillations was the first experimentally observed phenomenon that departed from the very successful Standard Model of particle physics. This discovery strongly suggests a connection between neutrino physics and physics on a very high mass scale and identifies a number of key questions that could open a path to new discovery. These neutrino experiments would greatly increase our understanding of this still mysterious sector. Whether the LHC is physics "rich" or physics "poor" we need to connect the interpretation of the LHC results to lower energy quark and lepton processes where the same effects are visible as very rare transitions. These rare processes and precision measurements would be enabled by high intensity proton beams.

The Fermilab strategy is to fully exploit and expand the capabilities of the existing accelerator complex to enable world-leading experiments at the intensity frontier, including precision muon and neutrino experiments. Central to this strategy is a coordinated attack on some of the most important questions neutrino physics. Upgrades to the Main Injector complex, which already delivers the world's most powerful high-energy neutrino beam to the MINOS and MINERvA experiments, will double the available beam power for the NOvA experiment, currently under construction. The flagship of this program will be the Long-Baseline Neutrino Experiment (LBNE), which will have unrivaled capability to search for and measure CP violating effects in neutrino oscillations. LBNE will be designed to able to take advantage of even higher beam power, when it becomes available -- up to an order of magnitude larger than currently available.

To increase the beam intensity further, Fermilab will build a high intensity continuous wave superconducting linac and to couple it to the rest of the existing Fermilab accelerator complex. We call it *Project X*. The design and construction of *Project X* will take at least the rest of the decade. When completed it will drive LBNE with ten times the flux of the present Fermilab NuMI beam, short baseline neutrino experiments with ten times current fluxes, and kaon, muon and EDM experiments with fluxes that are two orders of magnitude greater than the current capabilities. To get there we need to manage the transition from 26 years of Tevatron Collider operations to the world's leading program at the Intensity FrontierDuring the *Project X* era the beam intensity up to 3 GeV would be a factor of a hundred greater than the present complex.

Project X would substantially re-use existing facilities such as the Main Injector and Recycler Ring, infrastructure that would be very costly to reproduce elsewhere. We have aligned the technology of *Project X* to the ILC superconducting technologies so that the project benefits from the advances developed by the ILC community. We have also placed a requirement that it should be usable with well understood improvements as the front end of a neutrino factory or a muon collider, thus allowing for the very long range development of the complex. The alignment of technology with the ILC also means that by developing *Project X* we will be in a position to take a leadership role if the ILC is eventually built.

Design of *Project X*, a multi-megawatt high-power proton facility. With unique capabilities and flexibility, *Project X* would support multiple world-leading experiments simultaneously at the Intensity Frontier.



At the Cosmic Frontier, Fermilab has been the anchor laboratory for world-leading experiments. They include the Sloan Digital Sky Survey (SDSS) and the Dark Energy Survey (DES) that probe the properties of dark energy; the Cryogenic Dark Matter Search (CDMS) and the Chicago land Observatory for Underground Particle Physics (COUPP) that search for particles of dark matter; and the Pierre Auger Observatory that studies the source and nature of ultra-high-energy cosmic particles. Fermilab plans to continue a leading role for the following generation of experiments at the cosmic frontier.

Theoretical work in particle physics and particle astrophysics are an essential part of the laboratory. Theorists guide the development of experiments and elucidate their results, emphasizing the connection between theory and experiment to advance cutting-edge science.

As Fermilab addresses the defining questions in particle physics and delivers the DOE's high energy physics mission, it pays special attention to educating future generations of scientists. Fermilab trains about 250 postdoctoral fellows and 540 graduate students each year, resulting in more than 100 Ph.D. degrees awarded each year based on research performed at laboratory facilities. Fermilab contributes to science, technology, engineering and mathematics (STEM) education with a broad program for undergraduate university students and K-12 students and teachers.

Chapter 2. Fermilab and the Quantum Universe

Particle physicists are on a 21st-century quest to answer profound questions about the universe. Powerful new scientific tools for particle physics and astrophysics now bring the answers to these compelling questions within reach. Along with astrophysical observations, particle accelerators offer different paths to the exploration of the physics of the Quantum Universe.

- **What are the origins of mass?**
- **What are the origins of matter?**
- **How did the universe come to be?**

At the energy frontier, experiments at the Large Hadron Collider are probing a new energy region for whatever discoveries it holds. These discoveries could include contact with new phenomena that generate mass for elementary particles: perhaps the Higgs with its related particles and forces, or perhaps a new strong force that mimics how nucleons obtain mass from quantum chromodynamics. Precision measurements, at the Tevatron and elsewhere, of the quantum consistency of the Standard Model hint at a relatively light Higgs boson, but the LHC may reveal a more complex picture with unexpected twists and turns. Over the next two decades or more, the story of the origin of mass is likely to involve new forces of nature, new energy regimes, and fundamental symmetries beyond the Standard Model.

At the intensity frontier, experiments at Fermilab and other laboratories have recently discovered many surprising properties of neutrinos, the most mysterious elementary particles yet observed. Neutrinos have tiny masses at least a million times smaller than the next lightest particle. Neutrinos are the only known elementary particles that morph from one flavor to another as they travel over long distances; this quantum process may also connect them to even more exotic "sterile" particles that are immune to Standard Model forces. The novel properties of neutrinos dramatize the larger question of the origins of matter: there are 45 known "elementary" matter particles, whose quantum properties show a bewildering variety but also suggest unified origins. Ideas about the unified origins of matter can be tested in new experiments at the intensity frontier. The Mu2e experiment at Fermilab may show that charged leptons morph in flavor, like their neutral cousins the neutrinos.

This new phenomenon, in turn, has a natural quantum connection to effects that could be detected in a Fermilab g-2 experiment, or in experiments detecting tiny electric dipole moments. Observing rare decays of kaons at Fermilab would give a unique window on the properties of quarks, and anomalies seen there could be tied to new physics at the energy scale of the LHC or beyond. Just as key observations in chemistry and spectroscopy led from the periodic table to the quantum basis of atomic structure, the next decades may yield the clues to the unified origins of matter at a more fundamental level.

Neutrinos have the unique potential to explain our cosmic beginnings from a process called leptogenesis. As part of Fermilab's world-class program in neutrino science, the laboratory has already embarked on the NOνA experiment. providing the first chance at determining the ordering of neutrino masses, a key piece of information for understanding the role of neutrinos in unification. The joint power of the Japanese T2K (Tokai to Kamioka) experiment and NOνA will be the first step toward detecting the matter-antimatter properties of neutrinos that leptogenesis requires. Neutrino discoveries could link up with LHC discoveries of phenomena such as supersymmetry and with charged-lepton-flavor-violation if discovered in the Mu2e experiment.

Do we all come from neutrinos?

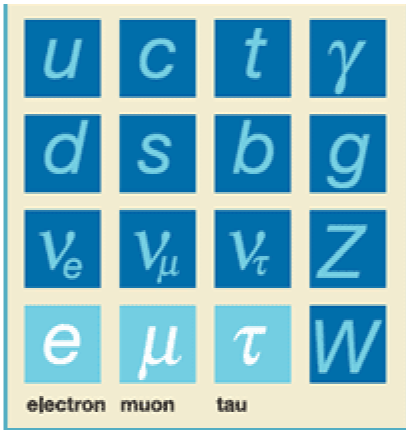
Leptogenesis, from the Greek for "delicate origins," is the theory that all visible matter (stars, planets, people) comes from neutrinos. The Big Bang produced matter and antimatter directly, but in nearly equal amounts. The cosmic annihilation of matter and antimatter should have been almost complete, leaving not nearly enough leftover matter to form the billions of stars that we see today. Where did all this matter come from? Leptogenesis could be the answer.

The theory of leptogenesis starts with the observation that neutrinos are very different from other kinds of matter, and may be the only matter particles that are their own antiparticles. If so, it means that they obey a different set of rules with respect to the symmetry between matter and antimatter, or CP symmetry. Neutrinos also have superlight masses; to physicists this suggests that the origin of neutrino mass involves both the Higgs and an additional shorter-range interaction with hypothesized superheavy neutrinos. This "see-saw" with superheavy partner neutrinos could provide an experimental window to leptogenesis.

When theorists rerun the tape of the Big Bang introducing superheavy partner neutrinos with nonstandard CP symmetry, the result is leptogenesis. The heavy neutrinos fall apart into light neutrinos, producing an excess of matter over antimatter. In the hot environment of the early universe, this excess is quickly passed along to all the particles that we are made of. If the theory of leptogenesis is correct, we owe our existence to neutrinos from the big bang.

At the cosmic frontier, Fermilab is already leading searches with CDMS and COUPP aimed at finding the identity of dark matter. Once direct detection of dark matter particles is confirmed, it will be an even greater challenge to link this discovery to the formation of structure in the cosmos, to the possibility of producing dark matter in LHC collisions, or to possible signals of dark matter annihilation in our galaxy. The effects of dark matter on the evolution of the expanding universe is entwined with the even more mysterious role of dark energy, but here again Fermilab is already at the forefront with the Dark Energy Survey.

Throughout Fermilab's history, the heart of the laboratory's scientific research has been the quest to solve the mysteries of the universe using particle accelerators. For U.S. particle physics, the decade ahead will bring great scientific opportunity and difficult challenges. Our questions for the universe could not be more profound or more compelling, especially because the means to address them are at last within reach. In this context, Fermilab has a unique responsibility as the nation's primary particle physics user facility. The Fermilab strategic plan is pragmatic and flexible enough to meet the challenges of a still-unfolding future, but most importantly it will provide Fermilab's users with the greatest possible opportunities for scientific discovery.



The charged leptons

Unification and LFV

In the Standard Model, the weak interactions connect the three kinds of neutrinos to the three particles known as charged leptons: electron, muon and tau. Since experiments have discovered that neutrinos change from one kind to another, physicists wonder if the charged leptons do too. By producing huge numbers of muons in a controlled environment, experimenters hope to observe the direct conversion of a muon into an electron. This would be the first observation of lepton flavor violation outside the world of neutrinos.

Aleardy hints from data point toward matter unification, the idea that all of the charged leptons, neutrinos and quarks arose from a single kind of superparticle in the first instant of the big bang. Theorists find that when they put the ideas of unification and supersymmetry together, their models predict LFV for charged leptons at a rate that next-generation experiments could detect.

In models of unification, LFV is related to the process of leptogenesis. LFV with charged leptons is sensitive to different parts of the mechanism of leptogenesis from those accessible by neutrino experiments. An experimental program combining neutrino science with muon-to-electron conversion experiments and energy-frontier searches for supersymmetry would be a powerful probe of our unified origins.

Chapter 3. the Energy Frontier

The Tevatron Collider

The Tevatron experiments, CDF and D0, stop taking data at the end of 2011. They will then focus their efforts on publishing an array of legacy measurements utilizing the full Run II data set. Of particular importance will be the final Tevatron result on the search for the standard-model Higgs boson, which should be sensitive at the 95% CL exclusion level or better over the mass range 110-180 GeV. 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 will offer complementary information relative to the LHC searches, which rely for now on W^+W^- or $\gamma\gamma$ decays in the same mass region.

CDF and D0 will also pursue other results with high priority including measurements of top-quark properties, precision measurement of the top-quark mass, measurements of diboson cross sections and kinematic distributions, search for flavor-changing neutral-current decays of heavy flavor mesons, and measurements of CP asymmetries in B-meson decays. It is expected that most of these analyses will be finished within about a year of final data taking. Some measurements, such as a precision determination of the W-boson mass using the full Run II data set, are expected to take a few additional years to complete. Since the Tevatron has a CP symmetric initial state, it offers some unique capabilities in top-quark physics and in heavy flavor samples collected by the CDF SVT trigger. The Tevatron experiments each expect to publish an additional 40 to 50 peer-reviewed journal articles beyond 2011.

The Compact Muon Solenoid at CERN's Large Hadron Collider

The Fermilab CMS group will continue to exploit the very successful startup of the LHC, fulfill several major physics research goals, and prepare the CMS experiment for future operations at higher beam energies and luminosities. With over 2 fb-1 recorded at collision energies of 7 TeV, and with at least five times more data expected by the end of 2012, the CMS experiment is poised to conclusively test the standard model and to search for indications of physics beyond the standard model. The Fermilab group is directly pursuing several 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 will also fulfill its essential operational responsibilities to the experiment for the duration of the 2010–2012 run, including operating, maintaining, and improving components of the CMS detector; providing a large part of the computing services to the experiment; monitoring data quality via the Remote Operations Center at Fermilab, and hosting the LHC Physics Center (LPC). Fermilab will continue to be a world-leading analysis center, providing office space, computing resources, software support, and US CMS administrative services to an expanding population of users and visitors, as well as hosting numerous schools, seminars, and workshops. (add the ROC where the US CMS collaborators can take shifts….)

The current LHC run plan is to conclude 7-TeV collisions at the end of 2012, and then shut down for eighteen months for accelerator upgrades, which will allow for 14-TeV collisions in 2014. Taking advantage of Fermilab's experience in detector construction and microelectronics, we are 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 (SiPM) 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 and SiPM instrumentation throughout the hadron calorimeter and a new silicon tracker.

Computing Support for Collider Experiments

The Fermilab Scientific Computing Division stewards the petabytes of data collected by the CDF and D0 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 the Fermilab computing facilities in concert with computing centers around the world connected through grid technologies. Fermilab is a founding member of the Open Science Grid (OSG) and a collaborator on the Worldwide LHC Computing Grid (WLCG). 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 global user community.

Lepton Collider Physics

Over the next decade, experiments at the Large Hadron Collider will explore the Terascale and uncover the mechanism that distinguishes the weak interactions from electromagnetism. The answer might be the Higgs boson of the standard model or a more elaborate form of new physics—new forces of nature, new symmetries, new particles, or new dimensions of space. Highly sensitive experiments that study neutrino oscillations, transitions among different quark and lepton flavors, and aim to detect exquisitely rare processes will probe indirectly to the Terascale and beyond. What we discover will settle some of our most urgent questions and bring others into sharper focus. We expect that a diverse and extended experimental campaign will be needed to establish what determines the quark and lepton masses, mixings, and degree of CP violation. Fresh challenges are sure to arise. These might include teasing out the detailed nature of particle dark matter and giving a systematic account of the spectrum, dynamics, and symmetries that characterize new phenomena.

To prepare to capitalize on discoveries at the LHC and intensity-frontier experiments, Fermilab has joined in the development of linear electron colliders (notably the ILC at 500 GeV) and is exploring the feasibility of a multi-TeV muon collider. A multi-TeV lepton collider could be a very attractive complement to the LHC on 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. These studies will set benchmarks for various standard-model processes and new physics, and to understand how experiments could be carried out in the unusual environment of a muon collider

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 in creating theoretical tools for the analysis of collider data, as well as developing ideas being put to experimental test. 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.

Accelerator Technology for the Energy Frontier

Fermilab has a strong program in technology development and fundamental accelerator science for future lepton colliders. 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 the International Linear Collider. Substantial infrastructure and test facilities have been built to enable development, production, and testing of superconducting linac components and systems. Through a dedicated development activity involving national laboratories, universities, international partners and industry, all coordinated through the Global Design Effort, accelerating gradients that reach the ILC performance specification are obtained now with a greater than 50% yield, steadily increasing toward the final R&D goal of 90%. Efforts will continue, through close coordination with the national and international program, on demonstration of ILC beam quality parameters in Fermilab's superconducting test accelerator, and continued development and refinement of processing techniques for achieving a high yield of high-gradient superconducting radio-frequency cavities in a cost-effective manner.

A multi-TeV muon collider has many potential advantages, 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 energy, and a very narrow energy spread. Fermilab leads the national Muon Accelerator Program (MAP) aimed at developing and demonstrating the concepts and critical technologies required to produce, capture, condition, accelerate, and store intense beams of muons. The goal of MAP 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. Critical technologies are under study, including the demonstration of transverse cooling in the MICE experiment, the study of RF cavity performance in the presence of high magnetic fields, as is required in a muon cooling channel, and the study of very high field solenoids, together with advanced beam dynamics simulations of the 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.

Magnet Technology for the Energy Frontier

The development of high-field superconducting magnets has been central to achieving higher and higher energies in the Tevatron and Large Hadron Collider. Building on the niobium–titanium superconductor technology developed for the Tevatron, Fermilab and collaborating U.S. institutions have contributed to the construction of the LHC focusing triplets. This established technology is limited to dipole magnetic fields of 8 to 10 teslas. Recognizing this limitation, Fermilab initiated a program to develop magnets based on niobium-3–tin superconductor, with the aim of achieving dipole fields of 14 to 16 teslas. In the context of the LHC Accelerator Research Program, Fermilab (together with Brookhaven and Berkeley Lab) has achieved a major breakthrough in the construction of reliable, accelerator-quality, long niobium-3–tin magnets. bringing the technology from the R&D lab to being "production-ready" for the immediate-future LHC luminosity upgrade planned for the 2020s decade.

A future muon collider or Very Large Hadron Collider will 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 40-TeV VLHC in the LHC tunnel would demand 25 to 30-tesla dipole fields. Such magnets could be based on high-temperature superconductors (HTS) 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 HTS-based magnets for the future energy-frontier accelerators.

Chapter 4. Physics at the Intensity Frontier

The Standard Model has successfully described the physical world over an enormous energy range, up to hundreds of GeV, or equivalently, down to short-distance scales of 10^{-16} cm. Fermilab has played a central role in the elucidation of the Standard Model, with the discovery of the top-quark, b-quark, the τ-neutrino, the measurement of many key properties of charm- and b-quark heavy mesons, such as D-meson weak decays and B_S mixing, and foundational explorations of numerous other processes in QCD and electroweak physics.

At the close of the Tevatron era at Fermilab and the opening of the LHC era at CERN, we have begun to directly examine physics well beyond these scales, to multi-TeV energies and approaching distances ten thousand times smaller than the size of a proton. At these ultra short distance scales, we don't know what we'll find, since the Standard Model leaves open many questions, mainly revolving around the central theme, "what is the origin of mass?" or equivalently "what is the origin of electroweak symmetry breaking?" Despite a myriad of theories addressing these questions, only experiment is the ultimate arbiter that can unveil what is really happening in nature, deep within the fabric of matter.

The LHC is now operating at 7 TeV cms, and has achieved an integrated luminosity exceeding 1 fb^{-1}. Plans are underway to aggressively increase its luminosity and energy. New discoveries are expected soon at the LHC that will define the future of our field, particularly at the energy frontier, perhaps dictating what new high energy machines may be optimal for the next leap to still shorter distance scales, machines such as a lepton collider, e.g., CLIC, or a Muon Collider. New discoveries will inspire deeper questions as to "what organizing principles give rise to the new physics?" Old questions, such as "why do we observe a given pattern of masses and mixing angles among the quarks and leptons?" will be cast into a new light. And, there will still be long standing questions as well, "What new physics lies beyond the energy frontier of the LHC?"

There is a time-honored and synergistic method for probing much deeper into the shortest distances scales of nature, beyond the direct energy frontier. This method is to search for and study *rare processes*, using *intense beams* of known particles, such as *neutrinos, muons, and kaons.* We call this the "Intensity Frontier."

Rare processes are powerful probes of new physics happening on deep high-energy or short-distance scales many orders of magnitude beyond the reach of energy frontier machines. Indeed, the weak interactions were first witnessed in rare β-decays in the late 19th and early 20th century. This was codified into the first theory by Fermi in 1935, and led to the Standard Model which is today the bread-and-butter of studies at the Energy Frontier of the LHC. Experiments at the Intensity Frontier are thus essential and provide critical and unique tools to address some central questions in particle physics that will not be accessible for many years, if ever, by the Energy Frontier.

Future plans for the Intensity Frontier at Fermilab provide a major domestic program in particle physics with rich and diverse, world-class experiments. Fermilab will continue to operate the current neutrino program, including NOνA and MicroBooNE, for the next several years while upgrading the accelerator complex. This allows concurrently the development of a next generation neutrino experiment, LBNE (Long Baseline Neutrino Experiment), and the commencing of a new program involving muons, with the two experiments "g-2" and "Mu2e".

Fermilab, in collaboration with its partner institutions and nations, is pursuing the design and eventual construction of a multi-Megawatt proton accelerator, *Project X*, providing more powerful and flexible beams for neutrino, muon, and kaon experiments. Project X also permits a program in accelerator driven nuclear fission that may offer an abundant, safe, and clean solution to the worldwide energy demand. Project X can produce copious quantities of muons that can ultimately be used in a muon storage ring to provide intense beams of both electron and muon neutrinos, a *"Neutrino Factory,"* which will permit the ultimate exploration of neutrino physics. This also provides a pathway to an eventual Muon Collider and a return to the energy frontier in the U.S.

There have been many recent developments in Intensity Frontier physics that make this program compelling. In the past two decades, we have learned that neutrinos have miniscule masses, and large mixing angles. Neutrino physics likely includes a new form of CP-violation, the discovery goal of future high intensity long-baseline experiments. Neutrino CP-violation is of profound importance as it may play a key role in the generation of the matter anti-matter excess observed in the universe. Kaons have historically provided a deep window on the structure of quark families. Through kaon physics, theorists were able to predict the mass of the charm quark several years before its discovery at BNL and SLAC, and today CP-violation in kaon physics probes the top quark, previously discovered at the energy frontier with the Fermilab Tevatron.

We are now poised to carry out the ultimate kaon experiments that will profoundly challenge or confirm the consistency of the CKM picture of quark CP-violation. Muons, in the measurement of their detailed electromagnetic properties and through searches for new family-changing rare processes, may also be the key to revealing a new stratum of physics. Intensity Frontier experiments are essential to complete our understanding of nature as LHC probes the Energy Frontier, and will provide new windows into the short distance scales of nature, approaching 10^{-20} cm, equivalently many thousands of TeV, for many years to come.

Neutrino Physics

Fermilab's future program centrally involves the physics of neutrinos. Enormous progress has been made over the past two decades, beginning with the stunning discovery of non-zero neutrino masses and the advancement of our knowledge of the subtle mixing angle structure of the system of known neutrinos. However, many fundamental questions remain to be answered and Fermilab neutrino experiments are poised to play a leading role in the worldwide effort to resolve them.

The most fundamental open issue in neutrino physics, and possibly the one with the most far-reaching consequences, is whether neutrinos and antineutrinos behave differently. Observation of CP-violating effects in a future neutrino oscillation experiment (the most striking of which would be an asymmetry between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation rates) would provide a direct pathway to understanding the observed asymmetry between matter and antimatter throughout the universe. Resolving the neutrino mass hierarchy ambiguity will also have dramatic implications, both for other experimental programs such as the search for neutrinoless double beta decay as well as for our basic understanding of fermion masses and mixing.

Our present knowledge about the masses and mixing angles of elementary particles already hints at a tantalizing underlying but unknown physics. The situation is reminiscent of the status of chemistry when Mendeleev's Periodic Table was empirically known, but before the underlying physics of the atom was understood. Quantum theory allowed us to understand the atom, which explained chemical properties of elements, why chemical bonds form, the properties of solid state materials, and the atomic nucleus, etc. Similarly, one of the greatest goals of modern elementary particle physics is to discover the deeper physics underlying the empirical flavor structure observed in nature, i.e., the masses and mixing angles, of the particles in the Standard Model. More precise measurements of particle masses and mixing angles are crucial in this endeavor, since they may point to new underlying flavor symmetries. For instance, it is known that one of the neutrino mixing angles is very close to zero, while another one is close to the maximal allowed value of 45^{o}. To determine whether this is merely a numerical coincidence or if it is the "smoking gun" of a more fundamental physical mechanism at work, precise measurement of all neutrino masses and mixing parameters are mandatory.

Fermilab, with its long-baseline neutrino program, is ideally poised for such precision measurements. The existing MINOS experiment, the upcoming NOvA detectors, and future projects such as LBNE and a

Neutrino Factory provide a step-by-step improvement in sensitivity, with the ultimate goal of reaching and surpassing the accuracy to which the quark mixing matrix has been determined. Indeed, results from neutrino physics have astonished physicists in the past, and this may likely happen again in the future. New and unexpected phenomena, such as the existence of sterile neutrinos, non-unitarity of the neutrino mixing matrix, or new neutrino interactions beyond the Standard Model, could be discovered in the future. Long-baseline oscillation experiments with neutrino beams from pion decay, such as MINOS, NOvA, and LBNE, are most sensitive to relatively large new effects, whereas the low-background environment of a Neutrino Factory could provide sensitivity to subtle effects at the sub-per cent level and would cover a much larger variety of possible phenomena than any other proposed neutrino facility.

Complementary to the long-baseline neutrino program is a rich variety of short-baseline experiments such as MiniBooNE, MINERνA, and MicroBooNE. These experiments measure the cross sections and kinematics of neutrino reactions to a supreme accuracy, and they will therefore greatly advance our understanding of the underlying dynamics of neutrino-nucleus interactions. Short-baseline experiments also have a unique discovery potential for new phenomena, in particular neutrino interactions beyond the Standard Model and sterile neutrinos. Indeed short-baseline experiments, such as LSND at Los Alamos and MiniBooNE at Fermilab, have already provided hints, albeit inconclusive, for possible new physics. If these hints strengthen, then a future short-baseline program at Fermilab could be mounted to definitively address these indications.

Current and Mid-Term Program

The Fermilab MINOS experiment has already provided the world's most precise measurement of Δm_{23}^2, as well as important and highly competitive constraints on many other standard and non-standard phenomena in the neutrino sector. This successful program will be continued and enhanced with the upcoming NOvA experiment, which consists of two detectors, one located at Fermilab and the other at 810km from the neutrino source in Ash River, Minnesota. NOvA will measure θ_{23} and $|\Delta m_{23}^2|$ with greatly increased precision, and will in addition be able to measure θ_{13} and the sign of Δm_{23}^2 (the neutrino mass hierarchy), provided θ_{13} is relatively large. Indeed, a first hint that θ_{13} may be sizable has been recently reported by the T2K and MINOS experiments.

Parallel to the NOvA program, the MINERνA experiment in the NuMI beam, and MiniBooNE and MicroBooNE in the Booster Neutrino beam, will continue to provide high-precision measurements of neutrino interaction cross sections for a variety of target materials over a broad energy range, and will search for short-baseline oscillations and other indications of new physics in the neutrino sector.

As a sequential step after NOvA, LBNE --- a much longer baseline experiment between Fermilab and a proposed far detector site at the Homestake mine in South Dakota --- will significantly enhance the sensitivity to θ_{23}, Δm_{23}^2, and θ_{13}. Most importantly, as its main goal, LBNE will search for a Standard-Model-like CP-violating asymmetry in the oscillation of muon neutrinos (and antineutrinos) to electron neutrinos (and antineutrinos). As designed, LBNE will be the first experiment capable of discovering CP-violation in the neutrino sector over a large range of possible θ_{13} values. Even for small θ_{13}, LBNE's capabilities of measuring θ_{13} and determining the mass hierarchy will greatly exceed those of NOvA.

An important aspect of LBNE will be its versatile and massive detector(s), either a water Cherenkov detector with a mass of several 100 ktons or a liquid argon time projection chamber of several 10's of ktons with superb background suppression capabilities, at a distant location. Such massive and capable detectors are crucial for detecting neutrino oscillations and collecting sufficient event samples over such unprecedentedly long distances. In addition, both water Cherenkov and liquid argon detectors allow for a rich physics program beyond long-baseline neutrino oscillation studies, in particular, searches for proton decay signatures and studies of neutrino bursts from supernovae in our galaxy and nearby.

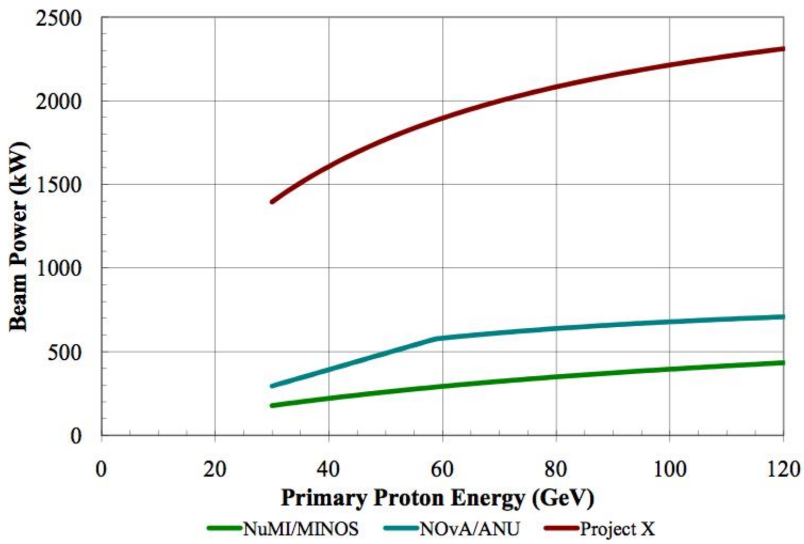
While the water Cherenkov technology is already very mature, liquid argon detectors have not yet been realized on such large scales. With the already completed ArgoNeuT detector and the upcoming MicroBooNE experiment, Fermilab is playing a very active role in this development. This technology is especially interesting because liquid argon-based time-projection chambers are also under active study as dark matter detectors and as detectors for neutrinoless double beta decay, a rare decay process that could shed light on the mechanism of neutrino mass generation (Majorana vs. Dirac masses).

The Fermilab Neutrino Program in the Project X Era

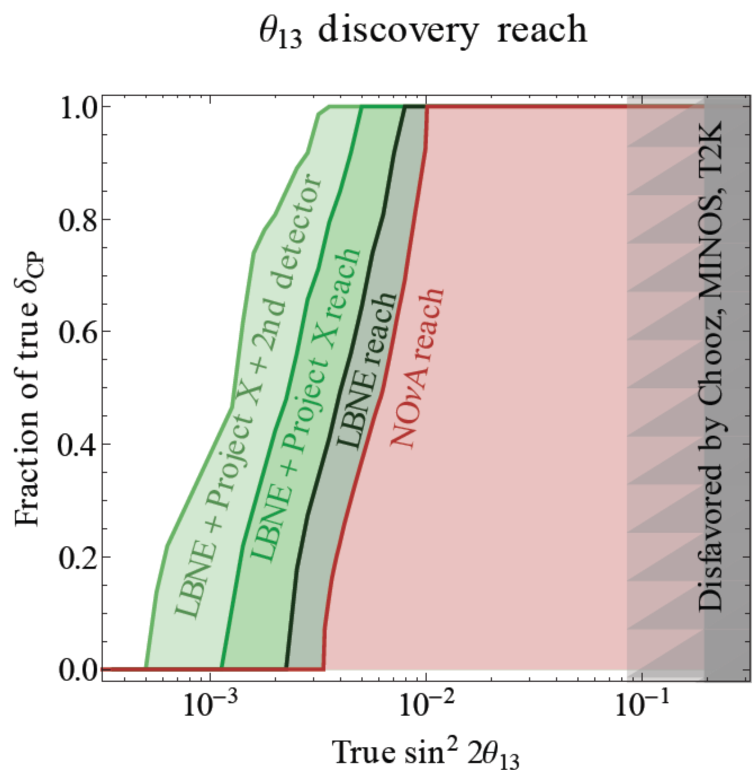
After the next generation of mid-term long and short baseline neutrino experiments, the construction of a multi-MW source of high-intensity proton beams (Project X) provides a very interesting and fruitful upgrade path. Compared to the planned beam for NOvA, Project X would supply more than a factor of three higher beam power (see Figure 1). Project X's flexible beam energy and higher power would especially enhance the sensitivity of LBNE, particularly boosting its sensitivity to leptonic CP violation. Figures 2-4 demonstrate the program's ability to resolve the three most important questions currently facing neutrino physics: is θ_{13} non-zero, what is the neutrino mass hierarchy, and is CP violated in the neutrino sector? The reach of the Fermilab neutrino program spans several orders of magnitude in parameter space and is significantly advanced with Project X. The physics achievable in 10 years with Project X would take 30 years without!

Similarly, a neutrino beam driven by Project X would allow for a new short-baseline program to study the nuclear physics of neutrino interactions with superior precision. Also, if the current and mid-term experiments provide hints for the existence of sterile neutrinos or new types of neutrino interactions, short-baseline detectors driven by a Project X beam could be turned into discovery machines for physics beyond the Standard Model.

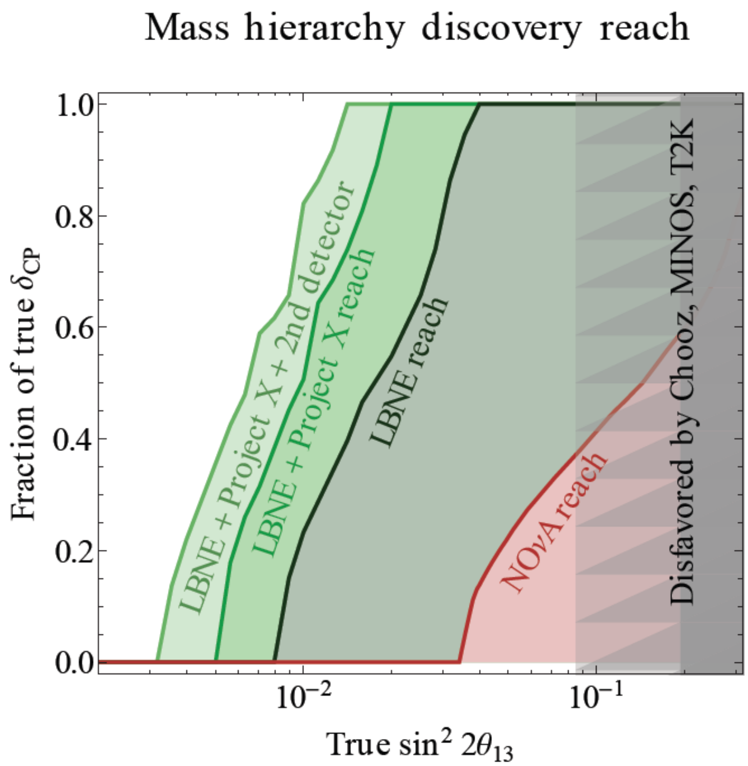
Project X would allow for the production of a wide variety of proton beams, with energies between 3 GeV and 120 GeV, and thus the facility would provide the necessary flexibility to fine-tune Fermilab's physics program in the future.



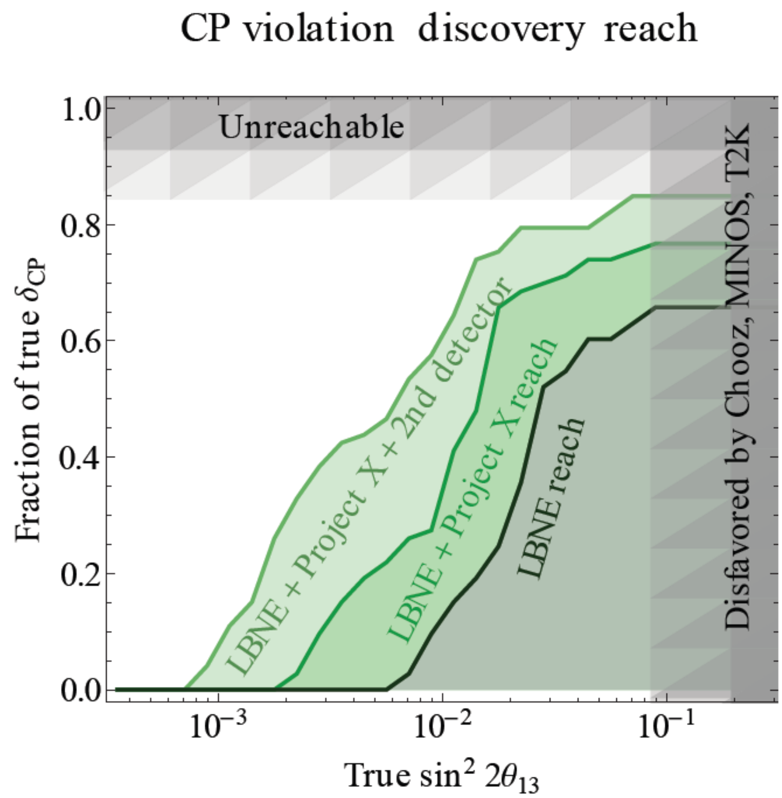
(Figure 1) Proton Beam Power: Beam power as a function of proton beam energy for three neutrino facilities: the existing NuMI beam which currently supplies neutrinos to the MINOS and MINERνA experiments (shown in green), the planned upgrade for NOvA (shown in blue), and Project X (shown in red).



(Figure 2) Sensitivity to Non-Zero θ_{13}: Evolution of the sensitivity of the Fermilab neutrino program in determining whether or not $\sin^2 2\theta_{13}$ is non-zero. The colored bands show the 3σ discovery potential for NOvA and LBNE as a function of $\sin^2 2\theta_{13}$ and the fraction of CP-violating phases for which the measurement can be made assuming a normal mass hierarchy. The NOvA projections assume 5+5 years of neutrino+antineutrino running and a 25 kton far detector operating in the 700kW NOvA beam. The nominal LBNE sensitivity assumes 5+5 years of neutrino+antineutrino running with a 200 kton water Cerenkov (or equivalently 34 kton liquid argon) detector in a 700 kW LBNE beam. Also shown are possible sensitivity reaches for 5+5 years of LBNE running with Project X or 5+5 years of LBNE running with Project X and a second far detector. While not shown, a Neutrino Factory can cover all of the accessible parameter region shown and has a sensitivity extending down to $\sin^2 2\theta_{13}$ values of a few x 10^{-5}.



(Figure 3) Sensitivity to the Neutrino Mass Hierarchy: Sensitivity of the Fermilab neutrino program in resolving the neutrino mass hierarchy (i.e., whether the mass ordering is normal or inverted) at 3σ confidence. Same convention as Figure 1. While not shown, a Neutrino Factory can cover all of the accessible parameter region shown and has a sensitivity extending down to $\sin^2 2\theta_{13}$ values of a few x 10^{-5}.



(Figure 4) Sensitivity to CP Violation: Sensitivity of the Fermilab neutrino program for detecting CP violation in the neutrino sector at 3σ confidence. Same convention as Figure 1. NOvA is unable to detect CP violation at this level of significance over the plotted range of θ_{13} and hence is not shown. A Neutrino Factory can cover all the accessible parameter region shown and has a sensitivity extending down to $\sin^2 2\theta_{13}$ values of a few x 10^{-5}.

Long Term Prospects: The Neutrino Factory

Even though short- and mid-term experiments will be able to answer many of the open questions in neutrino physics, the final stage of the overall phased program is the construction of a Neutrino Factory. Its target station would use a high-intensity proton beam from Project X to copiously produce muons. These muons will be collected to form a high-quality muon beam that can be accelerated and circulated in a storage ring. The muons decay within fractions of a second, yielding a high-quality, background-free neutrino beam. Neutrino detectors would be located at distances of up to several thousand kilometers, making the Neutrino Factory an ideal tool to study the perturbations of the oscillation pattern induced by the matter through which the neutrinos travel.

Depending on the value of θ_{13}, which will be measured or tightly constrained by prior experiments, both a high energy Neutrino Factory with a 25 GeV muon beam and a low energy option with a 5 GeV muon beam are under consideration. Small values of θ_{13} require a high energy Neutrino Factory whereas for large θ_{13}, a low energy Neutrino Factory is more optimal as the high energy facility would suffer from larger backgrounds due to CP-conserving electron <-> muon oscillations. In both cases, a Neutrino Factory with suitable detectors could study up to 12 of the 18 known three-flavor oscillation channels together, thus thoroughly covering the landscape of standard and non-standard neutrino physics.

Finally, many components of the Neutrino Factory accelerator complex are identical to those ultimately required for a Muon Collider. Thus, a Neutrino Factory would not only consolidate the strength of the U.S. intensity frontier program, but would also pave the way to the Muon Collider thereby enabling the U.S. to once again host experiments at the Energy Frontier.

Muon Physics

High-intensity sources of muons enable experiments that can make ultra-precise measurements of the fundamental physical parameters of the muon and search for new physics in rare processes. These new processes carry the potential of yielding significant discoveries, such as the unexpected violation of lepton flavor symmetries that are part of the Standard Model. These experiments complement the rest of the worldwide particle physics program by looking for effects that the LHC, the heavy flavor factories in Italy and Japan, the neutrino program, and cosmic frontier experiments cannot detect. Results from these muon experiments are important in formulating a more complete and deeper description of nature and addressing fundamental open questions of particle physics.

Precision Measurements

The goal of precision measurements is to probe nature at the "quantum loop level," by comparing the precise experimental results to comparably precise theoretical predictions derived in the Standard Model. A significant discrepancy between the measurement and prediction indicates that the theory is incomplete and requires new physical ingredients beyond the Standard Model.

An possible example of such a measurement is the anomalous magnetic moment of the muon, "g-2", which was measured by the E821 experiment at Brookhaven with a precision of 0.54 parts per million. This measurement is currently moderately discrepant with the Standard Model prediction and could indicate the existence of new particles or interactions. The Brookhaven measurement is statistics limited, which suggests that significantly improved precision is possible. A new g-2 experiment using the Fermilab complex of proton accelerators to produce high-intensity bunches of muons can achieve a fourfold improvement in precision. By including improved theoretical analysis, involving possibly input from lattice gauge theory, the discrepancy with the Standard Model prediction could persist, and even widen. This would constitute a major failure of the Standard Model and provide an important constraint for any proposed new beyond-Standard-Model theories.

The required muon beam would be produced reusing the Fermilab Booster and the Accumulator/Debuncher rings that were used to manage antiprotons in the Tevatron era. The experiment would also reuse the Brookhaven muon storage ring. It would employ the same measurement strategy, but using an upgraded and improved experimental apparatus. This apparatus can also be used to search for a possible permanent electric dipole moment (EDM) of the muon with sensitivity 100 times better than the current world's best limits. The muon EDM is predicted to be vanishingly small in the Standard Model and its observation would constitute a major discovery. A dedicated muon EDM experiment using Project-X to produce an intense source of muons could further improve the sensitivity by another three orders of magnitude.

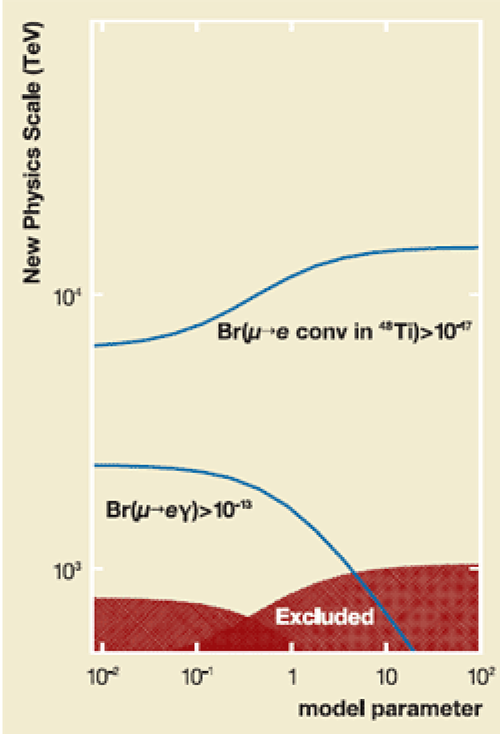
Rare Processes with Muons

Rare decay processes of muons, if observed, could be harbingers of new physics. In the Standard Model rare processes are probes of quantum loops and precise predictions can be made. The observation of a rare decay process at a rate significantly different than predicted by the Standard Model would signal the discovery of beyond-Standard-Model physics. Lepton flavor violation (LFV) is an example of a rare decay process, such as a μ –> e transition known as "charged LFV," and offers just such a window to new physics and the potential of a major discovery.

The Standard Model predicts that charged LFV is un-observably small. Many theoretical models, however, predict charged LFV at rates that could be within reach of the experiments being proposed at Fermilab. These theories incorporate ideas such as grand unification, extra space-time dimensions, supersymmetry, or exotic heavy-neutrino mixing. Combined with neutrino and LHC results, these experiments could elucidate new previously unidentified sectors of physics. In general, searches for charged LFV using muons are amongst the most powerful and promising probes of new physics at the Intensity Frontier and to scales well above the TeV scale.

There are several promising experimental possibilities for discovering charged LFV. Two of the most promising are $\mu\rightarrow e\gamma$ decay, and μ-to-e conversion. These experiments have sensitivity to very high energy scales, orders of magnitude beyond the direct reach of the LHC. Other possibilities to search for charged LFV use tau leptons but are not expected to have comparable sensitivity due to the available tau flux, which is much less than that of muons, and to the greater cleanliness of the muon experiments.

The Muon-to-Electron-Gamma (MEG) experiment at the Paul Scherrer Institute has begun collecting data and will search for the LFV process $\mu\rightarrow e\gamma$ with a predicted sensitivity at the 10^{-13} level. As demonstrated in the figure above, this offers sensitivity to mass scales of thousands of TeV for certain new physics scenarios (model parameter <<1).



***μ*-to-*e* conversion sensitivity**

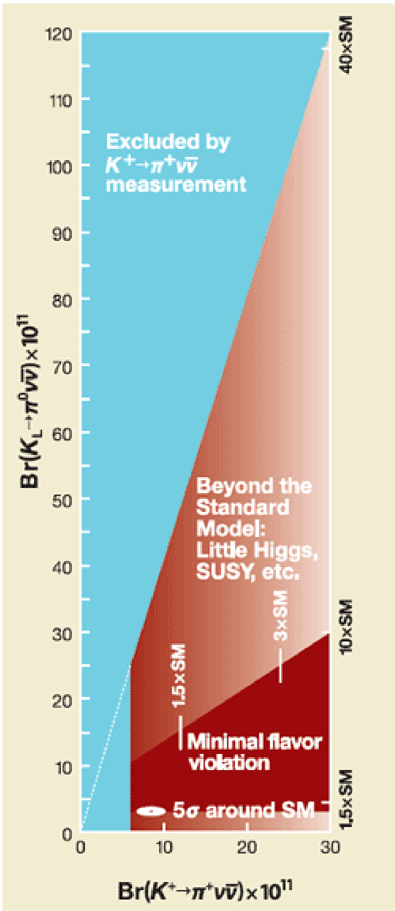
Figure 5: Comparison of the sensitivity to charged lepton flavor violation of the MEG ($\mu \to e\gamma$) experiment at a transition rate of 10^{-13} and a μ-to-e conversion experiment using the Fermilab Booster at the rate of 10^{-17}. The comparison is made as a function of a model parameter which controls the type of processes that generate the LFV effects. For values <<1 magnetic dipole type interactions dominate, while for values >>1 four fermion type interactions dominate. The range of the model parameter considered was chosen to qualitatively capture the predictions of most new physics scenarios generating charged LFV effects. The figure demonstrates that the Fermilab Mu2e experiment offers superior sensitivity for all physics scenarios.

The Mu2e experiment at Fermilab will use the 8 GeV proton beam from the Booster to search for the μ-to-e conversion process with sensitivity at the 10^{-17} level, 10,000 times more sensitive than previous experiments. The required proton intensity can be delivered in parallel with that required for the NOvA experiment discussed in the previous section. The Mu2e beam line will re-purpose the Accumulator and Debuncher rings from the Tevatron complex once the Run II program is completed. As demonstrated in the figure above, sensitivity at the 10^{-17} level will enable this experiment to probe mass scales that exceed the capabilities of the MEG experiment independent of new physics scenario, achieving sensitivity up to 10,000 TeV, significantly beyond the reach of the LHC. This level of sensitivity gives the Mu2e experiment impressive discovery potential that covers a wide range of beyond the Standard Model theories. Project X offers the possibility of increasing the beam power to the experiment by another factor of 10 or more. This increased intensity could be used together with improvements to the muon beam to reach sensitivity at the 10^{-18} - 10^{-19} level. If the Mu2e experiment discovers charged LFV by observing a signal, the Project X era experiment would offer the unique capability of distinguishing the underlying new physics by measuring the μ-to-e conversion rate using different nuclear targets.

Kaon Physics

Theories of beyond-Standard-Model physics often predict new flavor-violating processes involving quarks. Experiments at the flavor factories, the Tevatron, and elsewhere have unexpectedly found no clear signals of such contributions. This suggests a strategy of concentrating on rare processes that are as theoretically and experimentally clean as possible in order to maximize the sensitivity.

The ultra-rare kaon decay process $K \rightarrow \pi\nu\bar{\nu}$ is one of the most promising opportunities for implementing this strategy. Both the charged $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and the neutral $K_L \rightarrow \pi^0\nu\bar{\nu}$ decays are extremely suppressed in the Standard Model. The charged mode has been studied by the Brookhaven E787/949 experiment using a high intensity stopped-kaon technique to yield a total of seven candidate signal events. The NA62 experiment at CERN is pursuing a new in-flight technique with the aim of achieving a 100-event sensitivity at the Standard Model level.



***K→πνν* sensitivity**

Figure 6: Project X experiments based on 1000 Standard Model events could probe beyond TeV physics with greater than five sigma sensitivity.

The $K_L \to \pi^0 \nu\bar{\nu}$ decay has not yet been observed. An upper limit a factor of 1000 away from the Standard Model prediction was established by the KEK E391a experiment. The KOTO experiment at J-PARC is pursuing a staged approach to reach single event sensitivity, with an ultimate goal of reaching 100-event sensitivity, at the Standard Model level. The $K_L \to \pi^0 \nu\bar{\nu}$ decay is a purely CP-violating process, with a predicted Standard Model theoretical uncertainty no larger than two percent, since the transition matrix element is controlled by an approximately conserved vector current. The theoretical uncertainty for the $K^+ \to \pi^+ \nu\bar{\nu}$ decay is also at the level of a few percent. To fully probe for possible new physics contributions requires experiments capable of detecting about 1000 of each of these decays, achieving a statistical error that approaches the theoretical uncertainty.

Such experiments would be sensitive to new sources of CP violation involving quarks. Rare kaon decays offer a historic and unique window on these phenomena, having provided powerful constraints on the Standard Model over the past 40 years. They would provide a complete determination of the CKM matrix of the Standard Model independent of b-physics, and this in turn offers the tantalizing prospect of emergence of tension within the Standard Model framework. Rare kaons are sensitive to effects from new particles or new interactions in nature. For example, if superpartner particles are discovered at the LHC, kaon experiments could address such fundamental questions as distinguishing among different mechanisms for the breaking of supersymmetry. Or, if electroweak symmetry breaking involves new strong dynamics, again the rare kaon decays would reveal departures from Standard Model predictions.

Other rare kaon-decay modes offer opportunities for major surprises. They include possible detection of the lepton-flavor-violating decays such as $K \to \pi\mu e$ or $K \to \mu e$, and exotic decays of kaons, e.g., into axions or gravitons in certain models of extra dimensions.

The high intensity proton beam of Project X would enable experiments at the 1000 event level for both the charged and neutral $K \to \pi\nu\bar{\nu}$ decays. The continuous-wave-linac technology proposed for Project X creates ideal conditions for these experiments, which could yield simplifications of the experimental apparatus and reduced technical risks. The two experiments would be conducted using a common production target and could form flagship elements of the initial Project X physics program. Each experiment would build upon proven and well studied experimental techniques. Both measurements would reach precisions of a few %, comparable to the uncertainty on the Standard Model prediction, thus offering the ultimate sensitivity for new physics contributions to these processes. The two experiments would additionally offer world class sensitivity to a variety of other rare kaon decays.

Rare Processes with Nuclei

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Energy Applications

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Summary

We have described a program exploring the “Intensity Frontier” and consisting of a suite of challenging and compelling experiments that Fermilab is beginning now, continuing into the future, and eventually becoming the focus of Project X. This program is rich and diverse. It probes the highest energy scales, or shortest distance scales, achievable with present human capability. It searches for well-motivated, subtle and rare phenomena well beyond the reach of energy frontier machines, and can reshape the focus of our field, just as the discovery of the weak force in the early 1900’s became the mainstay of energy frontier physics today.

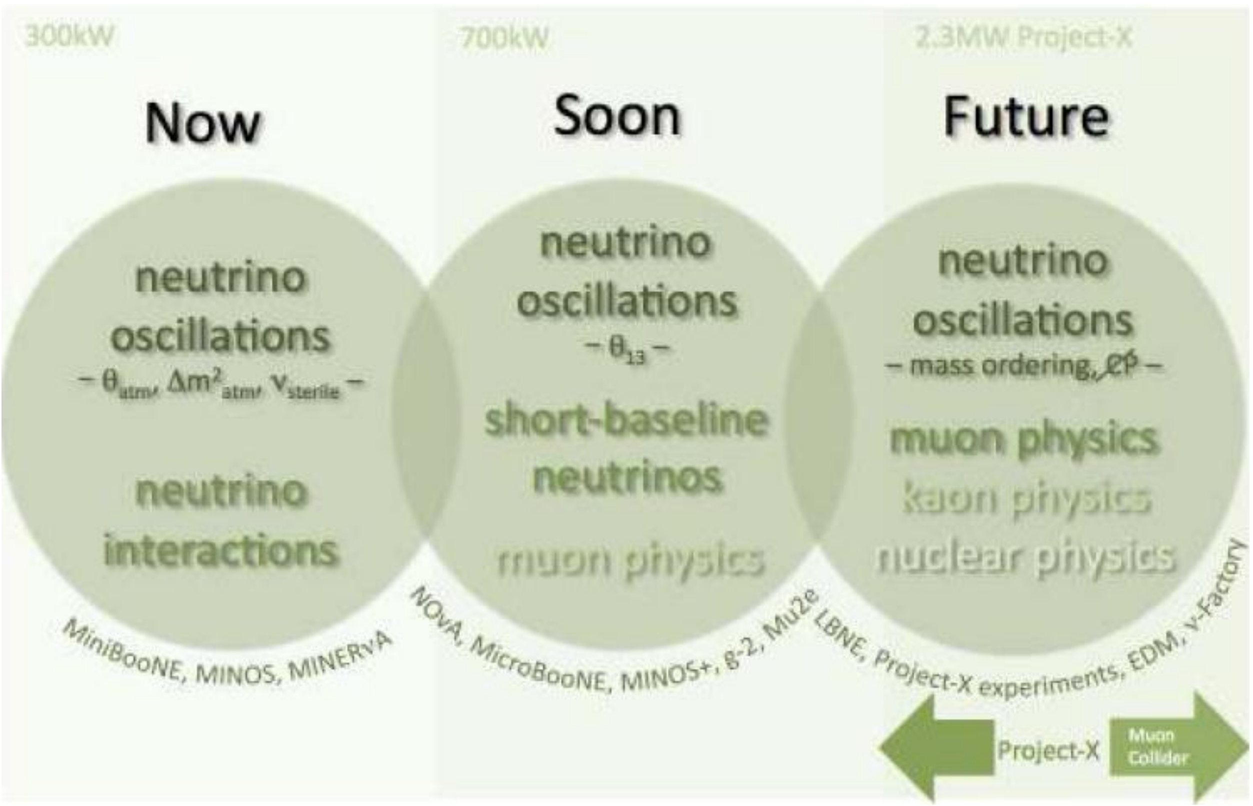


Figure 7: Overview of the physics topics and experiments that will address important questions in particle physics at the intensity frontier now, soon, and in the near future. The Fermilab program evolves from the use of existing upgradable neutrino beams to the advent of intense particle sources available with Project X. Combined, this diverse plan allows a robust and unparalleled program in neutrino, muon, kaon, and nuclear physics ultimately leading to the transition back to the energy frontier with a Muon Collider.

The Intensity Frontier program consists of experiments that address in detail the properties of neutrinos, muons and kaons. It ultimately puts these particles under the most powerful "microscope," the intense beam of Project X, which provides copious data and allows us to study new physics down to distances that are millions of times smaller than the proton. As Project X evolves, it will provide a Neutrino Factory that derives from a storage ring of muons.

Project X enables the possibility of eventually building a Muon Collider, one of the most complex devices ever created by humans, which produces and accelerates beams of muons and antimuons, colliding them at high energies of order 4 TeV, and allowing direct probes of energy and distance scales, and new processes, beyond the reach of the LHC. The Muon Collider would allow the U.S. to again host physics experiments at the energy frontier.

Chapter 5. Facilities at the Intensity Frontier

The Steering Group considered a variety of accelerator facilities and reconfigurations of the Fermilab accelerator complex utilizing the following criteria:

- Support a forefront Intensity Frontier physics research program,
- Potential for realization over the coming decade,
- Effectively utilize accelerator assets freed up at the end of Tevatron operations,
- Provide a long term platform for development of the Fermilab complex.

Since the original Steering Committee report was issued in 2007 a plan for evolution of the accelerator complex in has been developed consistent with these criteria. The plan features the following elements:

NOvA Upgrade: Upgrade the Recycler/Main Injector complex and NuMI beamline/target to 700 kW capability in support of the second generation long baseline neutrino experiment, NOvA.

Proton Improvement Plan: Upgrade the Proton Source to support beam operations at 15 Hz in support of elements of the Intensity Frontier program based on 8 GeV protons, in parallel with NOvA.

Project X: Construct a new facility to deliver 5 MW of beam power, including 3 MW beams at 3 GeV and 2 MW beams at 60-120 GeV simultaneously, in support of future rare processes and long baseline neutrino programs.

Longer Term Facilities: Prepare for the ultimate construction of either a Neutrino Factory or Muon Collider.

The evolution of the accelerator complex takes place in two stages. The first stage takes place over the next five years and is aimed at supporting a the intermediate program: MiniBoone, MicroBoone, Minerva, MINOS, NOvA, LBNE, Seaquest, mu2e, and g-2 experiments in addition to Test Beam facility in the Meson Lab. This stage is based on improvements to the existing complex implemented through the NOvA accelerator upgrades and the Proton Improvement Plan (PIP). The total demand for protons over the coming decade is shown in Figure 5.1. The total steady state demand beyond 2016, about 2.2 $\times 10^{17}$/hour, represents about a factor of two beyond the current. Thus, this stage targets the delivery of 700 kW of beam power to the long baseline production target simultaneous with roughly 30 kW to the 8 GeV program.

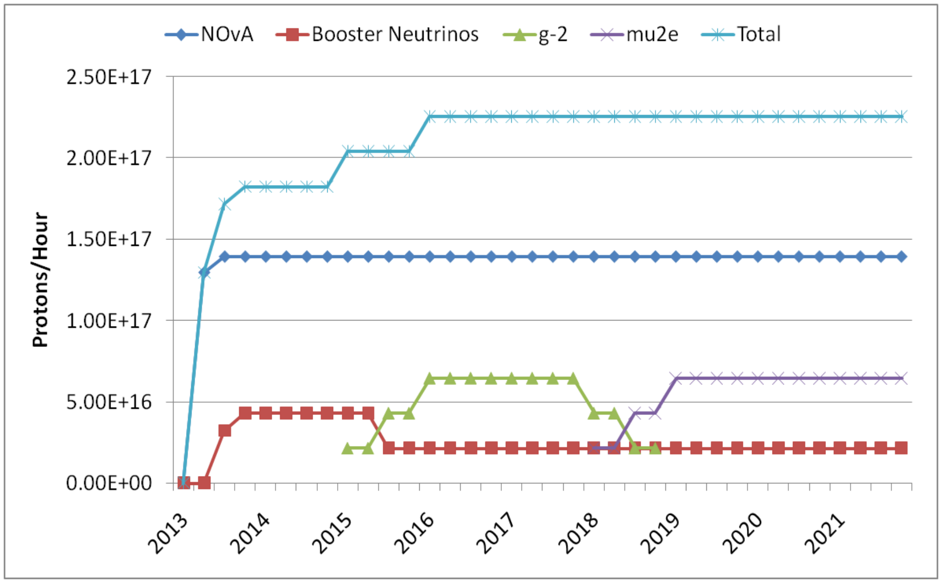


Figure 5.1: Total proton demand (protons/hour) over the coming decade.

In the second stage the existing proton source facility is replaced by a modern high power H- linac, named Project X. Project X will greatly enhance the capabilities of the complex by allowing the simultaneous delivery of 2 MW at 60-120 GeV, 200 kW, at 8 GeV, and 3 MW at 3 GeV. The total number of delivered protons is a factor of one hundred beyond what is achieved following the PIP. The performance parameters associated with this evolution of the accelerator complex are summarized in Table 5.1. The first three columns represent current performance and improvements now underway. The last two column list the Project X parameters. All columns are based on injecting beam from the existing 8 GeV Booster, except for Project X, which eliminates the need for the Booster. While the table does not explicitly list beam power at 60 GeV from the Main Injector, 2 MW can be supported at this energy at the expense of decreasing the available beam power at 8 GeV to 70 kW.

	Present	**NOvA**	**PIP**	**Project X**	
Batch Intensity	4.3×10^{12}	4.1×10^{12}	4.1×10^{12}	2.6×10^{13}	protons per pulse
Repetition Rate	7.5	9	15	10	Hz
Total Flux (8 GeV)	1.2×10^{17}	1.3×10^{17}	2.2×10^{17}	9.5×10^{17}	protons per hour

Total Flux (3 GeV)	NA	NA	NA	2.2×10^{19}	protons per hour
Main Injector Batches	11*	12	12	6	
MI Cycle Time	2.2	1.33	1.33	1.33	seconds
MI Beam Power (120 GeV)	400	700	700	2300	kW
8 GeV Beam Power (available)	15	0	30	200	kW
3 GeV Beam Power (available)	NA	NA	NA	2900	kW

Table 5.1: Planned evolution of proton availability at Fermilab

*Currently 9 batches are delivered to the NuMI target and 2 batches to the antiproton production target.

5.1 Existing Proton Facility

The existing Proton Facility consists of the 400 MeV linac, 8 GeV Booster, and the 120 GeV Main Injector. The complex delivers beams to a variety of target stations including the MiniBoone target at 8 GeV and the NuMI target at 120 GeV. In parallel the complex supports the Test Beam Facility in the Meson Lab. The upstream end of the Proton Facility is quite old – both the upstream 181 MeV of the linac and the Booster have been in operations for 40 years and are reliant on components that are either no longer commercially available or are at risk of being discontinued. The linac and Booster complex operate at up to 15 Hz. The Booster magnet system is a resonant circuit at 15 Hz and the magnets systems is continuously operating at this rate. However, the Booster cannot deliver beam at 15 Hz due to limitations in the rf systems and the overall tolerance to beam loss. At present the Booster delivers beam at 7.5 Hz – approximately 1.2×10^{17} protons/hour are currently available at this rate. This is sufficient to support NuMI/MINOS and antiproton production at about 400 kW, while leaving approximately 15 KW for the MiniBoone experiment.

The 8 GeV Recycler and Antiproton Rings currently play no role in the delivery of protons. However, following the cessation of Tevatron operations both will be converted to support of the ongoing program – the Recycler to accumulate protons in support of NOvA and the Antiproton Rings to accumulate and then resonantly extract protons to the mu2e experiment.

5.2 NOvA Upgrades

The NOvA experiment is based on the delivery of 700 kW of beam power onto the NuMI target. The neutrino beam generated will support the off-axis neutrino detector (NOvA) currently under construction in Ash River, MN. The goal of 700 kW beam power onto the target is achieved by increasing the number of batches targeted and reducing the Main Injector cycle time – there is no increase in the batch intensity. The cycle time will be reduced by utilizing the Recycler as a proton accumulation ring, thereby eliminating approximately 0.6 seconds of 8 GeV dwell time in the Main Injector, and by increasing the

Main Injector acceleration rate. The net result is reduction of the cycle time from 2.2 seconds to 1.333 seconds. In addition accumulation in the Recycler will accommodate 12 Booster batches, all of which are available for delivery to the NuMI target, thus increasing the number of targeted batches from 9 to 12. Modifications to the complex currently underway to support NOvA include:

- Implementation of slip-stacking into the Recycler Ring, with a capability of stacking 12 Booster batches.
- A new transfer lines for injection from the Booster to Recycler, and for transfers from the Recycler to Main Injector.
- Increasing the acceleration rate in the Main Injector through the addition of two rf cavities, an additional anode power supply, and upgrades to the quadrupole supplies.
- Modifications to the NuMI beamline.
- A new target design to support 700 kW
- A new target/horn configuration to provide the optimum neutrino spectrum.
- A variety of new fast kickers to support the above.

Component fabrication is currently underway and installation will take place during an 11 month shutdown to the accelerator complex scheduled to begin in March 2012. Startup of the NOvA program will begin in the spring of 2013.

5.3 Proton Improvement Plan

Without further upgrades to the proton source NOvA would utilize all protons generated by the Booster, leaving nothing to support the balance of the program – MicroBoone, mu2e, and g-2. The total demand is shown in Figure 5.1, and can be met by increasing the beam repetition rate in the Booster to 15 Hz while maintaining protons per batch at present levels. The Proton Improvement Plan (PIP) is being executed to implement this capability while dealing with a number of other issues in the 40 year old Linac/Booster complex. 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 source throughput to > 2×10^{17} protons/hour
- Ensure a useful operating life of the proton source through at least 2025

The last goal is meant to ensure continuity of operations in the face of potential delays in Project X. The major components of the PIP include:

- Replacing the Cockcroft-Walton ion sources with an RFQ
- Upgrades to the drift tube linac rf Power Systems
- Replacement of the Booster tube based power amplifiers with solid state amplifiers
- Modifications to Booster rf cavities, tuners, anode supplies, and bias supplies to allow operations at 15 Hz
- Enhanced beam instrumentation and controls
- Vacuum system upgrades
- Augmentation of the Booster gradient magnet spares pool

The PIP is currently underway and will be completed in 2016.

5.4 Project X

Project X is the centerpiece of the Fermilab long term strategy to develop a world leading Intensity Frontier program, and use this program as a stepping stone to a possible future Muon Collider at the Energy Frontier. Project X is a high intensity proton facility based on a 3 GeV continuous wave (CW) superconducting linac operating at an average current of 1 mA and a 3-8 GeV pulsed linac operating with a duty factor of 4%. These newly constructed facilities are augmented by upgrades to the Main Injector/Recycler complex to support higher power operations. A total of 5 MW beam power will be available at Project X: 3 MW at 3 GeV, 80-200 kW at 8 GeV, and 2 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.

5.4.1 Project X Mission Elements

Project X is a multi-MW proton facility being designed to support a multi-faceted Intensity Frontier program at Fermilab. Development of Project X was recommended as part of the long range strategic plan of the U.S. Department of Energy as described in the P5 report of May 2008 [1]. This report outlined a number of missions that would be supported by Project X. Three of these have been adopted as providing the primary mission elements for Project X. A fourth mission element has been developed in discussions with scientific communities outside of elementary particle physics.
The primary mission elements assigned to Project X include:

1) Long baseline neutrinos: deliver 2 MW of proton beam power onto a neutrino production target at any energy between 60 – 120 GeV;
2) Rare processes: provide MW-class, multi-GeV proton beams supporting multiple kaon, muon, and neutrino based precision experiments. Simultaneous operations of the rare processes and neutrino programs is required;
3) Muon facilities: provide a path toward a muon source for a possible future Neutrino Factory or Muon Collider;
4) Non-HEP applications: provide opportunities for implementing a program on Standard Model tests with nuclei and/or nuclear energy applications.

These mission elements establish the fundamental design criteria for Project X.

5.4.2 Project X Reference Design

The design concept for Project X has gone through several iterations, since the publication of the initial steering group report. These iterations have resulted in significant performance improvements at each step, culminating in a concept designated the Project X Reference Design [2]. The Reference Design, shown schematically in Figure 5.1, meets the high level design criteria listed above in an innovative and flexible manner. The Reference Design is based on a 3 GeV CW superconducting linac, a 3-8 GeV superconducting pulsed linac, and modifications to the existing Main Injector/Recycler complex at Fermilab. The Reference Design represents a facility that will be unique in the world in its ability to deliver high power proton beams with flexible beam formats to multiple users.

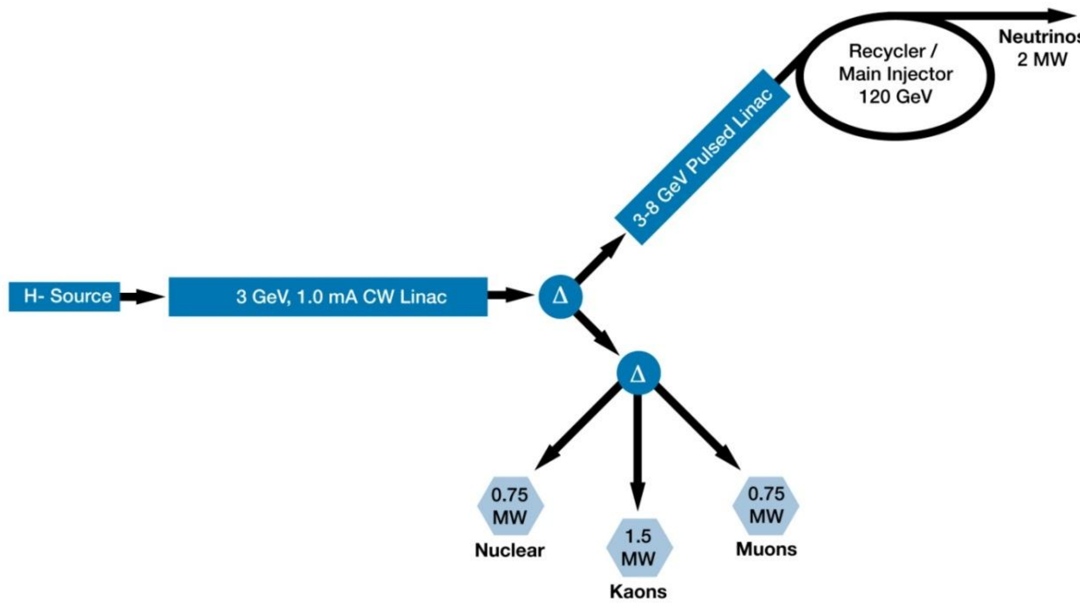


Figure 5.2: Project X Reference Design

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 (MEBT) 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 (averaged over >1 sec) H- beam current of 1 mA, and a peak beam current (averaged over < 1 sec) 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 or the 3 GeV 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.

Performance parameters associated with the Reference Design are given in Table 5.2.

CW Linac			
	Particle Type	H-	
	Beam Kinetic Energy	3.0	GeV
	Average Beam Current	1.0	mA
	Linac Pulse Rate	CW	
	Beam Power	3000	kW
	Beam Power to 3 GeV	2870	kW
Pulsed Linac			
	Particle Typ0e	H-	
	Beam Kinetic Energy	8.0	GeV
	Pulse Rate	10	Hz
	Pulse Width	4.33	msec
	Cycles to Main Injector	6	
	Particles per cycle to MI	2.6×10^{13}	
	Beam Power	347	kW
	Beam Power to 8 GeV	70-200	kW
	Upgraded Beam Power to 8	4	MW
Main			
	Beam Kinetic Energy	60-120	GeV
	Cycle Time	0.75-1.4	sec
	Particles per cycle	1.6×10^{14}	
	Beam Power	2000-2200	kW

Table 5.2: Project X Performance Goals

5.4.3 Operating Scenarios

The CW linac is primarily utilized to support a rare processes program at 3 GeV. A key element of the Reference Design concept is the coordinated utilization of a wideband chopper at the linac front end and a transverse deflecting rf separator at the exit of the 3 GeV linac to provide high duty factor bunch patterns to multiple users simultaneously. The transverse deflecting cavity operates at one fourth (or n+1/4) of the fundamental 162.5 MHz bunch frequency of Project X. Bunches are deflected to three distinct experimental areas by the transverse cavity depending upon the phase of their arrival. By accelerating bunched in an appropriate pattern, as determined by the wideband chopper, the requisite bunch patterns can be delivered to three experiments simultaneously.

The bunch structures delivered to three independently operating experiments are completely determined by the bunch pattern loaded into, and accelerated in, the 3 GeV linac. These bunch patterns are subject to two constraints: 1)the beam current when averaged over 1 μsec must be 1 mA or less; and 2)the instantaneous beam current at time scales less than 1 μsec cannot exceed the output of the ion source, nominally up to 10 mA. An example is shown in Figure 5.2. Buckets in the linac are color coded as red, green, or blue (R,G,B). In particular, the pattern of buckets in the linac is: R, G, R, B with the R buckets aligned at 0 and 180 degrees of phase with respect to the transverse deflector, and the G and B buckets at ±90 degrees respectively. In this manner any bunch occupying a red bucket will pass through the deflector without deflection, the green buckets will be deflected in one direction, and the blue buckets the opposite direction. Hence each bucket has a predetermined destination in one of the three experimental areas. In the particular example given ,the red area is receiving bunches with a 1 MHz macrostructure and a 80 MHz microstructure, the blue area is receiving bunches at 20 MHz, and the green area at 10 MHz. One can confirm that the average beam current in this example is 1 mA, the peak current is 4.2 mA, and the R, G, B areas are receiving 700, 770, and 1540 kW respectively.

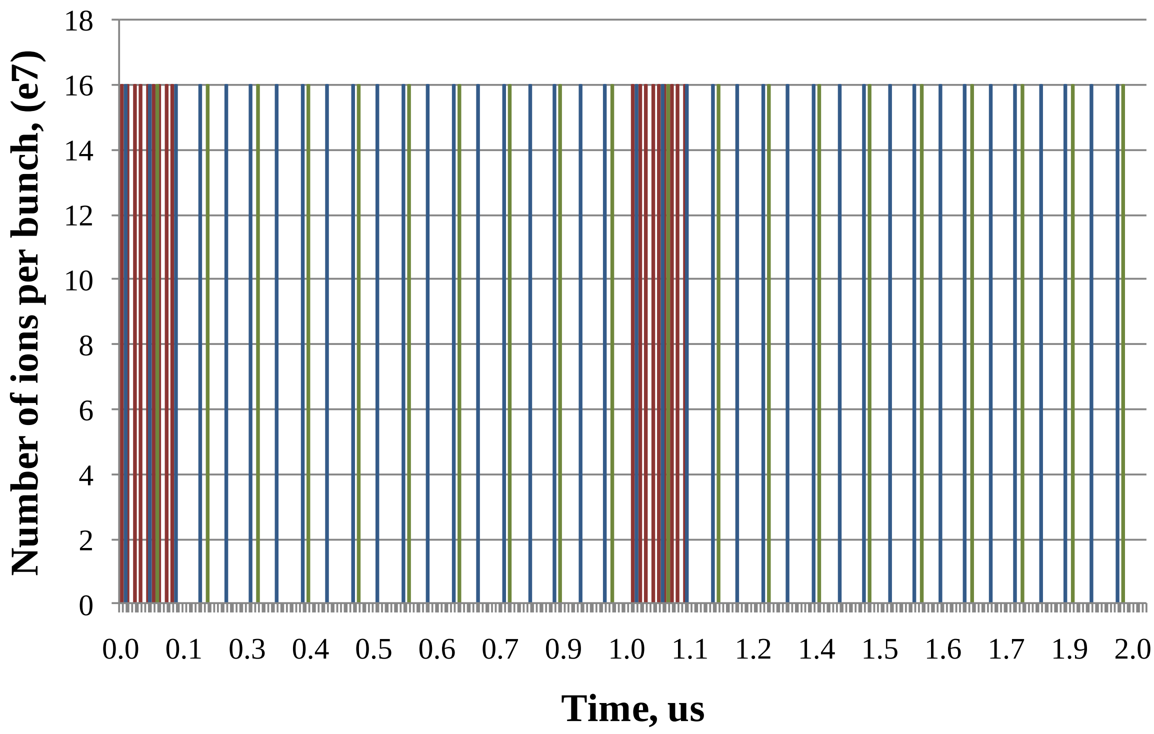


Figure 5.3: Example linac loading pattern providing independent bunch patterns to three experiments (labeled R, G, B) simultaneously

The pulsed linac operates at 10 Hz and is utilized to support the long baseline neutrino program in concert with the Main Injector and Recycler. In the Reference Design the beam pulse from the pulsed linac is 4.33 msec in length, thus the beam duty factor is 4.33%. Beam is diverted into the pulsed linac via a pulsed dipole with a rise/falltime of 0.5 msec and a 4.4 msec flattop. With a 1 mA beam current delivered from

the CW linac, the total beam power at the end of the 8 GeV linac is 350 kW. The diversion of 4.3% of the CW linac beam into the pulsed linac reduces the power available to the 3 GeV program to 2870 kW.
A total of >2 MW is generated for the neutrino program by accelerating 1.6×10^{14} protons to 60/120 GeV every 0.75/1.4 seconds. Generating the required number of protons requires 26 msec of 1 mA beam. This is achieved by delivering six 4.33 msec pulses into the Recycler where it is accumulated over six subsequent injections. This is then delivered in a single turn to the Main Injector for subsequent acceleration to either 60 or 120 GeV. The total cycle time depends on the beam energy: 2 MW at 60 GeV requires a 0.75 second cycle time, and 120 GeV requires a 1.4 second cycle time. Since neither cycle utilizes every available beam pulse in the linac there is extra power available to support an 8 GeV program amounting to about 200 kW if the Main Injector is operating at 120 GeV and 70 kW if operating at 60 GeV.

5.4.4 Project X R&D Program

The Project X R&D program been initiated and consists of facility design and systems optimization studies, and development of the critical underlying technologies of Project X. 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 Ring, and superconducting RF development at three 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.

<u>Facility Layout</u>

The Project X front end consists of a CW H- source capable of delivering up to 5 mA of beam current at 30 keV, a 2.1 MeV RFQ operating at 162.5 MHz, and a wideband chopper integrated into the MEBT and capable of removing bunches in arbitrary patterns while maintaining an average current of 1 mA. The beam from the MEBT enters directly into the CW linac which is entirely superconducting. The technology map for both the CW and pulsed linacs is shown in Figure 5.3 At total of six different cavity types operating at three different frequencies is imagined. The details of this layout (beta's, breakpoints, and technology) are still being optimized. However at present acceleration to 160 MeV is imagined as being provided by three families of spoke resonator cavities at 325 MHz, acceleration from 160 MeV to 3 GeV is via two families of elliptical cavities at 650 MHz, and acceleration from 3-8 GeV is via one family of 1300 MHz elliptical cavities. A total of approximately 500 superconducting cavities, contained in approximately 60 cryomodules are required.

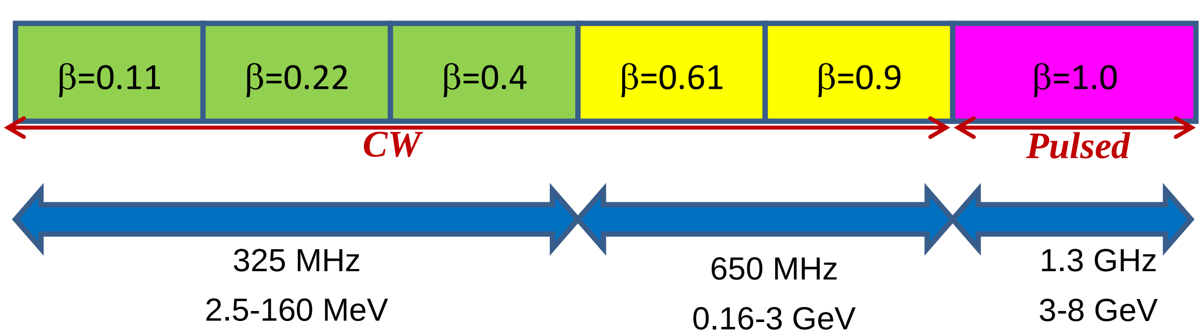


Figure 5.3: Technology map of the Project X linacs

Wideband Chopper

Development of the wideband chopper is a key element of the R&D program. The chopper consists of a set of four kickers, separated by 180 degrees of betatron phase in the MEBT, and a corresponding set of kicker drivers. The system is required to deliver a 1 nsec rise and fall time, with a 1 nsec flattop. Kicker voltages in excess of ±200 V are required and a repetition rate of 60 MHz must be supported. The criterion applied to bunch removal is that surviving H- particles in a bunch that is disposed of should be less that 1×10^{-4}. Helical transmission line structures have been developed that meet the kicker requirements, while MOSFET based wideband amplifiers are being investigated for the driver.

H- Injection

The pulsed linac is required to deliver 26 mA-msec of total beam charge to the Main Injector/Recycler complex each 0.75 seconds to support 2 MW of beam power at 60-120 GeV. In the Reference Design this is supplied via six 4.4 msec pulses of 1 mA H- current, repeating at 10 Hz. 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 of injecting the full current directly into the Main Injector in a single 26 msec long, 1 mA, pulse – something that is not possible with the standard foil techniques. Alternative techniques under investigation include moving/rotating foils and laser assisted stripping – a technique currently under development at the Spallation Neutron Source at Oak Ridge National Laboratory.

Superconducting RF Development

A very significant superconducting rf development program has been underway for several years, utilizing resources both at Fermilab and partner laboratories. As noted a total of six cavity shapes at three different frequencies are required for Project X. The emphasis within the program is on developing cavities with high Q_0 and modest gradients (typically 2×10^{10} and 15 MV/m) for the CW linac, and more modest Q_0 and higher gradients for the pulsed linac (typically 1×10^{10} and 25 MV/m). The pulsed linac development (1300 MHz) is most advanced at present, having strong overlap with the International Linear Collider (ILC) development program. A complete 1300 MHz cryomodule is currently under rf testing and a second cryomodule is under construction. Development at 325 MHz is concentrated on the β=0.22 single spoke resonator. Two cavities have been built and test, both achieving 15 MV/m with Q_0 of 1.5×10^{10} at 2 K. 650 MHz cavity development is currently investigating a number of elliptical shapes, and is concentrating on single cell tests. Preliminary indications are that Q_0 in excess of 2×10^{10} might be achievable. In parallel significant effort is going into development of rf sources. Within 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 (IOTs) are being investigated at 650 MHz.

5.5 Project X as a Platform for Future Facilities

The high power linacs in Project X share many fundamental characteristics of the Proton Driver required as the front end of intense muon based facilities, e.g. a Neutrino Factory or Muon Collider. The requirements are approximately 4 MW of proton beam power at an energy within the range 5-15 GeV. However, requirements are for a very low duty factor beam, with very short, but intense, bunches. These requirements cannot be met be Project X alone, but will require some sort of beam reformatting after the linac. Self-consistent concepts for utilizing Project X as a platform for a muon facility are currently under development.

The Muon Collider requires approximately 4 MW of beam power delivered onto a production target at an energy between 5 and 15 GeV. Furthermore, the beam should be delivered in a single bunch, with a bunch length of 2-3 nsec, at a 15 Hz repetition rate. Requirements are modestly relaxed for a Neutrino Factory. It is highly desirable that the Project X Reference Design include provisions for supporting such requirements in the longer term.

Providing the required beam power and bunch structure requirements for a Muon Collider will require both an upgrade of the Project X 8 GeV beam power and additional facilities to reformat the high duty factor beam from Project X. A Task Force has been jointly sponsored by Project X and the U.S. Muon Accelerator Program (MAP) to develop a feasible concept and feed back this concept into the Project X planning activities. This Task Force is asked to report by the end of 2011; however certain concepts are already being investigated.

Beam Power at 8 GeV

Project X naturally provides 350 kW of beam power at 8 GeV (8 GeV × 1 mA × 4.4 msec ×10 Hz). The strategy for providing 4 MW at 15 Hz, as required by the Muon Collider, is to increase the current to 5 mA, increase the pulse length to 6.7 msec, and increase the repetition rate to 15 Hz. The result is a 10% duty factor at 5 mA, or 4 MW of delivered from the pulsed linac at 8 GeV. The required 15 Hz repetition rate is provided.

Bunch Formatting at 8 GeV

The beam delivered at 8 GeV must be reformatted to provide the very low duty factor required for muon facilities. It is believed that two rings will be required: 1) an accumulation ring that collects the 6.7 msec long H- pulse and segregates it into roughly 4-8 bunches; and 2) a compressor ring that reduces the bunch to the required 2-3 nsec. This would be followed by a “trombone” beam line that utilizes varying times of flight to deliver multiple bunches onto the production target simultaneously. This concept needs further development to establish viability. In particular, space charge effects and beam stability are very serious issues in both rings.

Chapter 6. the Cosmic Frontier

Fermilab's quest to understand the fundamental nature of matter, energy, space and time explores far beyond the reach of even the most powerful particle accelerators--- from the smallest intervals of space and time, to the largest and most distant reaches of the universe.

Nature paradoxically connects the smallest inner space to the largest outer space. The cosmic expansion starts with a tiny speck of energy; quantum particles in the early universe lead to a vast cosmic web of galaxies today. Black holes suck matter into vortices at the speed of light, and spin off particles of unprecedented energy. Most of the total energy in the universe seems to reside in the "empty" space of vacuum between galaxies, and most of the mass that creates and binds galaxies together is made of particles that emit no light and have never been detected directly, except for their gravitational force on normal matter. All of these effects in the cosmic realm challenge us with new physics, beyond the Standard Model.

[if we are still using "quantum universe" questions in Joe's section, refer to them here]
For almost thirty years, Fermilab scientists have led the world in studies of such extraordinary phenomena of the cosmos as a laboratory for fundamental physics. Although these cosmic frontier experiments do not use accelerators, they do make use of the world leading technical capabilities of Fermilab, 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 an "anchor institution" for world-leading experiments, providing scientific, technical and managerial support for widely distributed international consortia of researchers. The cosmos presents some of the most profound mysteries facing physics today, and some of the greatest opportunities for future new discoveries at relatively modest cost.

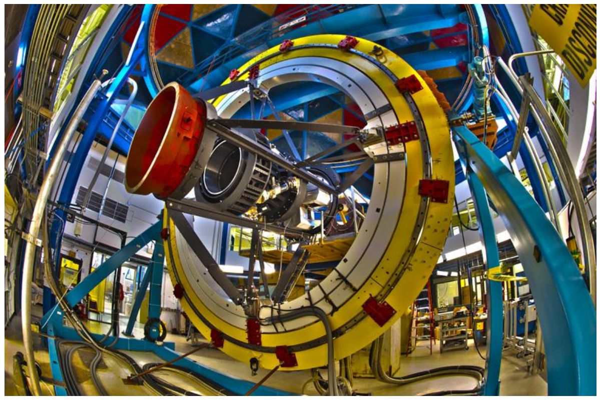
Dark Energy

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

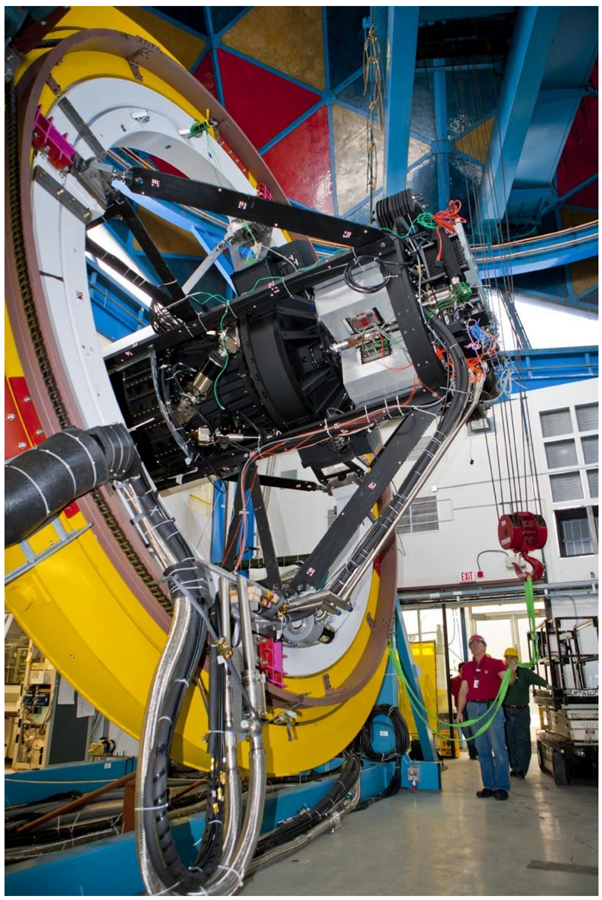
Fermilab's dark energy experiments began with its role as the anchor laboratory for the Sloan Digital Sky Survey (SDSS), the world's first large, deep digital survey of the universe, and the highest-impact astronomy facility of the last decade. SDSS pioneered precision cosmology and has made many important contributions to dark energy measurements, such as the discovery of "Baryon Acoustic Oscillations", a pattern in the galaxy distribution fossilized from primordial sound waves, that serves as a precise statistical length standard. Fermilab is currently leading a supernova survey with SDSS that is setting new standards of precision and error calibration in the use of supernovae to measure very large cosmic distances.

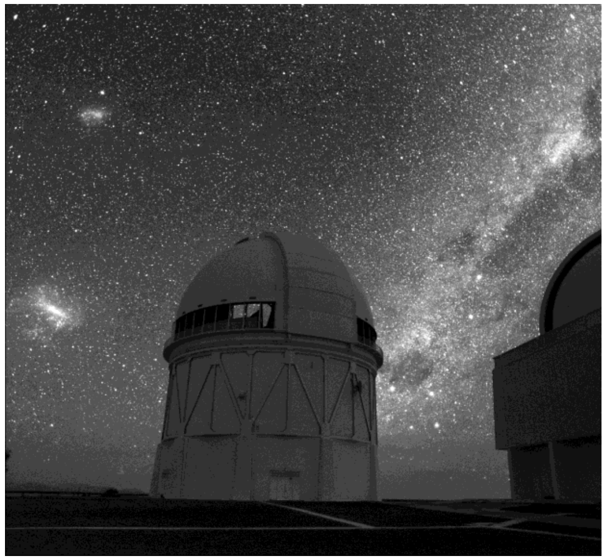
Fermilab is now leading an international collaboration in a new project: the Dark Energy Survey, a deeper, more precise successor to SDSS. A powerful new instrument called the Dark Energy Camera, capable of deep precision imaging over large patches of sky (3 square degrees), is being deployed on the 4-meter telescope at the Cerro Tololo Interamerican Observatory in the Chilean Andes. Starting in 2012, and in the course of about 525 nights over the next five years, DES will map about 5000 square degrees of the sky. The final petabyte-scale survey database will comprise about 300 million galaxies looking out into space, and back in time, more than half the age of the universe. It will reveal the growth of the large-scale "cosmic web" of galaxies with time, allowing us to distinguish the effects of various possible forms of Dark Energy from each other.

The Dark Energy Survey will probe dark energy using a variety of complementary techniques: galaxy clustering, weak gravitational lensing, baryon acoustic oscillations, and supernovae. Combined together they will provide unprecedented and powerful probes of the Dark Energy equation of state, and its effect on the growth of cosmic structure. These probes will sharpen our knowledge of dark energy's behavior. For example, they will test whether it acts like a uniform energy of the physical vacuum--- Einstein's "cosmological constant"--- or more like a modification of gravity, a fundamental overturning of Einstein's theory of space and time.

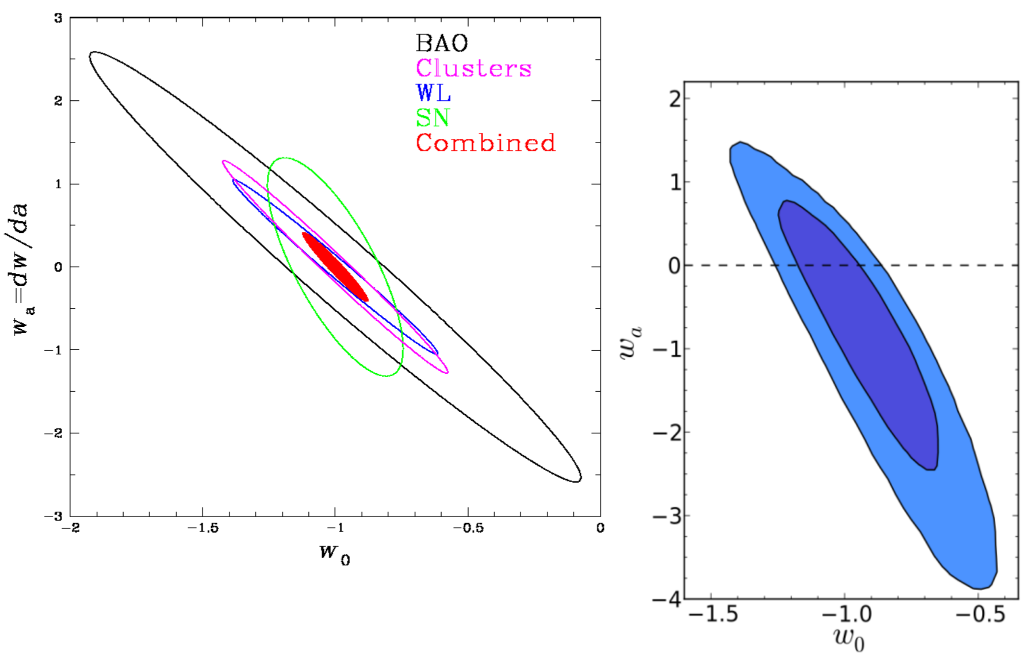


Above: Components of the Dark Energy Camera being tested at Fermilab in a full-scale simulator of the top end of the 4-meter-diameter Blanco telescope. Below: the back end of the camera, showing electronics and cryogenics systems surrounding the focal plane dewar.





Above: the 4-meter Blanco telescope at Cerro Tololo in Chile, where the Dark Energy Camera is being installed for the survey.



Above: Sensitivity of the Dark Energy Survey to equation-of-state parameters of Dark Energy: *w* denotes the ratio of mean pressure to density of the cosmic vacuum state, and w_a, its derivative with respect to cosmic scale factor. Left plot shows error contours predicted to be achieved by the various techniques used by the Dark Energy Survey, separately and together. Right plot shows current limits (2011) on the same scale, showing the much larger uncertainties. Planck Surveyor priors are assumed in both cases.

The deep DES sky survey will be even more powerful if spectra are obtained of many of its galaxies, providing precise velocity and 3D position information. Fermilab and collaborators are developing technology to build a system that will obtain thousands of spectra at once. The goal is to create a catalog of 10 to 100 million spectra, a high-fidelity 3-dimensional map of the cosmic web of galaxies over most of its history, and provide exquisitely sensitive probes of dark energy effects on structure growth over time.

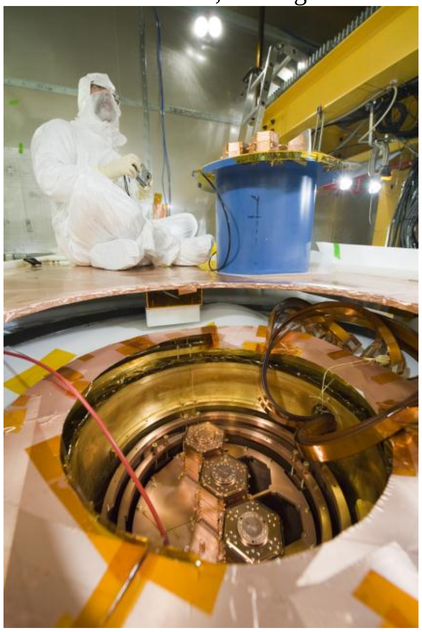
After DES, the next big upgrade in cosmic surveys is the Large Synoptic Survey Telescope. Now in the final stages of planning and design, this project proposes to create a dedicated telescope and camera system to survey the universe significantly wider, deeper and faster than DES. Fermilab is part of a consortium of institutions developing this project, which should start its survey near the start of the next decade.

Dark Matter

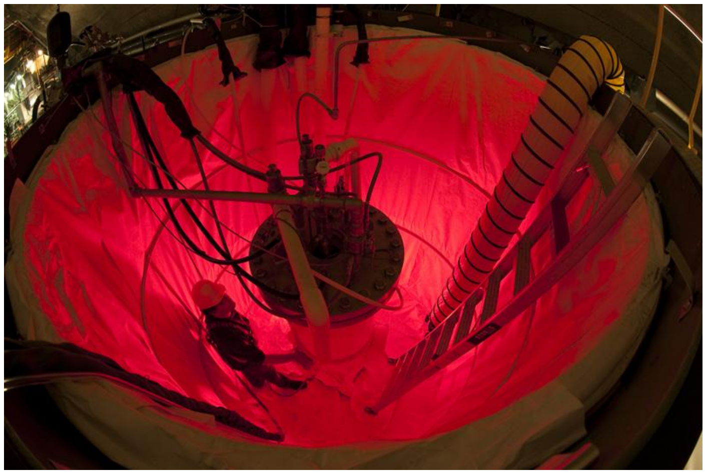
Astronomers established long ago that the mass whose gravity holds galaxies and clusters together far exceeds the amount of mass in normal atoms in any detectable, visible form, such as stars or gas. It has long been suspected that galaxies are bound by the gravity of invisible "dark matter", made of some new kind of elementary particle left over from the early universe. A leading theoretical hunch, based on Big Bang cosmology and natural extensions of Standard Model physics, is that the dark matter is made of Weakly Interacting Massive Particles, or WIMPs. These hypothetical particles weigh more than atomic nuclei but are dark because they do not interact with light at all; like neutrinos, they interact only by the weak force and gravity. They have never been detected directly.

Fermilab is helping to lead the worldwide hunt for these particles, and plays a major role in four kinds of experimental search. These experiments all seek to detect the very rare instances where dark matter particles interact with nuclei of ordinary matter, in deep underground, very low background detectors. Fermilab is a lead laboratory in the Cryogenic Cold Dark Matter Search (CDMS and SuperCDMS), using silicon and germanium crystals; the Chicagoland Observatory for Underground Particle Physics (COUPP), using bubble chambers; and Darkside, using a liquid Argon detector similar to that being developed for Fermilab's long baseline neutrino experiments. These experiments are deployed deep underground around the world, at the Soudan mine in Minnesota, SNOlab in Sudbury, Ontario, Canada, and Gran Sasso National Laboratory in Italy. In addition, a new technology based on CCD detectors (DAMIC), currently under development at Fermilab, aims to detect very low mass WIMPs.

So far, no experiment has made a confirmed detection of dark matter particles. The current generation of modest-scale experiments is already setting interesting limits on particles with properties favored by the favored theoretical extensions of Standard Model physics based on supersymmetry. In the near future, the next generation of experiments, with larger detector masses, and better control over particle backgrounds, 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. Eventually, some of these technologies will be deployed with about a ton or more of detector mass, leading to a conclusive test.



Fermilab scientist Dan Bauer during assembly of CDMS detector system in the cryostat at Soudan mine in Minnesota.



Fermilab scientist Andrew Sonnenschein with the COUPP 60-kg bubble chamber.

High Energy Cosmic Particles

The universe accelerates particles to energies far greater than human-made accelerators can. Although the highest energy particles are extremely rare, they can be studied by large arrays of detectors. Their composition, interactions, and natural history provide a unique window into high energy particle interactions, as well the exotic and extreme sources in the universe that accelerate them in the distant universe.

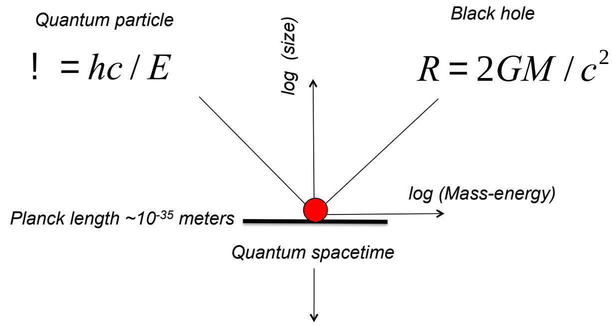
Fermilab is the anchor laboratory for the Pierre Auger Observatory in Argentina, the world's leading facility for studying the highest energy cosmic rays. When an ultra high energy cosmic ray enters the upper atmosphere, it collides with an atomic nucleus and generates a spray of many more particles, creating a cascade that can be seen as visible flash of fluorescent light in the night sky. PAO records these flashes, and also studies particles with a large array of ground detector tanks to detect electromagnetic particles of the showers that reach the ground. Auger's international collaboration has published many pathbreaking results on the composition, interactions, anisotropy, and spectrum of these extraordinarily energetic and rare particles. These particles have interactions in the center of mass frame with energy 100 times larger than those at CERN's Large Hadron Collider. The highest energy events can be statistically traced back to their sources on the sky, the nuclei of distant galaxies.

One of 1600 water tanks that are part of Pierre Auger Observatory.

Quantum Spacetime

Fermilab pursues laboratory experiments that search for effects of new physics beyond the energy reach of any accelerator, including new kinds of particles with ultra-weak interactions, and even the quantum behavior of space and time itself.

Fermilab's goal is to take experimental physics to the Planck scale, the deepest layer of reality we can talk about with the tools of conventional physics. The Planck scale is special because it defines the intersection of two realms of physics: the quantum world, which describes the particle/wave behavior of all forms of mass and energy, and spacetime physics or relativity, which describes the space and time within which the mass and energy move and transform.



[Above: A simple plot showing the meaning of the Planck scale. 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; experiments beyond the Planck scale probe a deeper level of quantum spacetime.]

Planck-energy particles are impossible to study by conventional and direct means, such as particle accelerators, because they have such a high energy--- about 10^{16} TeV. At Fermilab we are developing an experiment, called the Fermilab Holometer, that seeks to study new Planckian physics in a less direct way, 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, ultrastable laser cavities and interferometers. (Similar technologies can also be applied, together with Tevatron magnets, to search for certain new kinds of very weakly interacting "axion-like particles".)

The target precision of the Fermilab 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--- tens of 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.

Fermilab scientist James Volk aligns a 40-meter prototype laser cavity for the Fermilab Holometer.