

# **Fermilab Institutional Review**

**June 6 – 9, 2011**

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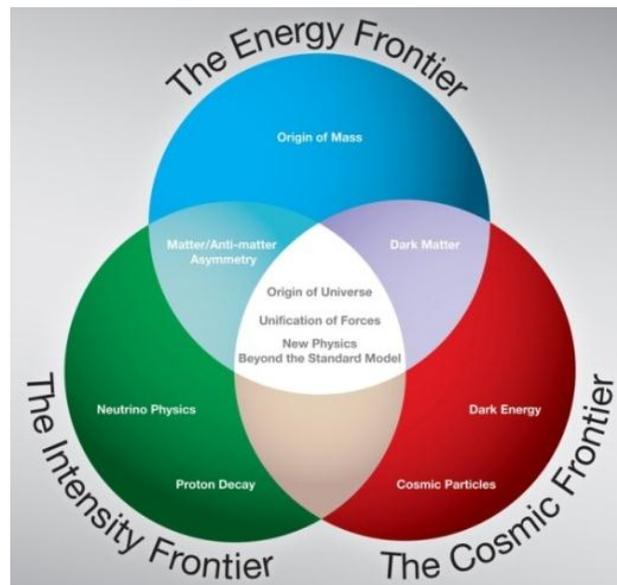
## Overview: Introduction

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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. Fermilab facilitates the U.S. physics community including universities and laboratories to participate in the national and international particle physics program.

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. 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 (SM).
- **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 1,925 employees and 2,300 scientific users carry out a world-leading program of discovery at the three interrelated frontiers of particle physics. Theoretical work in particle physics and particle astrophysics are an essential part of the laboratory. Theoretical physicists guide the development of experiments and elucidate their results, emphasizing the connection between theory and experiment to advance cutting-edge science.

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 the 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. Each year about 40,000 students and teachers either participated in activities at Fermilab or were visited in their classrooms by Fermilab staff.

## Overview: Science Strategy for the Future / Major Initiatives

Fermilab will continue its program of research at all three frontiers of particle physics and enable the U.S. particle physics community to tackle the most fundamental physics questions of our era. 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.

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

- Address critical and 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 reasonable U.S. funding
- Be broad enough to be resilient against physics discoveries and funding fluctuations

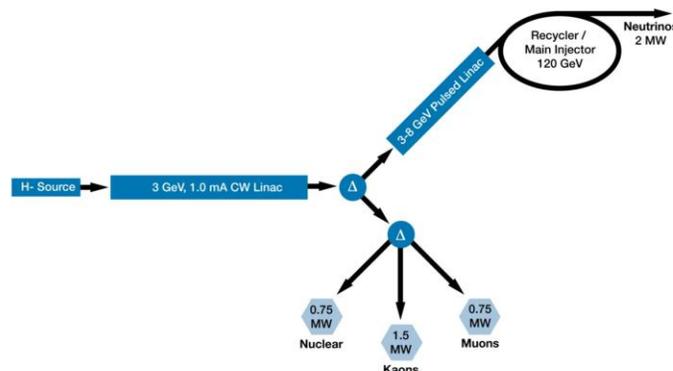
An analysis of the world's particle physics program leads us to the conclusion that the greatest opportunity for U.S. leadership lies in experiments driven by high intensity proton beams. In this area we are sensitive to physics beyond the Standard Model up to energies much greater than are reachable at the LHC directly. Whether the LHC is physics "rich" or physics "poor" we will want to connect the interpretation of those results to quark and lepton processes where those effects are visible, namely in very rare transitions. In addition, the most intense proton source will enable the best set of neutrino experiments both with short and long base-lines. These neutrino experiments should greatly increase our understanding of this still mysterious sector. Thus the centerpiece of the Fermilab strategy is to build a high intensity continuous wave superconducting linac, and to couple it to the rest of the existing Fermilab accelerator complex. We call this *Project X*.

The design and construction of *Project X* will take at least the rest of the decade. When completed it will drive a very long base-line neutrino experiment (LBNE) with ten times the flux of the present Fermilab MINOS beam, short base-line neutrino experiments with ten times current fluxes, and kaon, muon and EDM experiments with fluxes that are two orders of magnitude greater than have been possible up to now.

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 Frontier. An important element of the strategy is to exploit the present complex for a set of world-class experiments before *Project X* is available: MINOS, NOvA, MINERvA, g-2, Mu2e and MicroBooNE. The simultaneous running of these experiments requires us to improve the injection chain of the current complex to increase the particle flux by a factor of two. During the *Project X* era the flux of particles 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.



# Overview: Recent Achievements and Current Activities

## Accelerator Performance

The performance of the accelerator complex is captured in the table below, including the DOE OHEP goals for the Tevatron Collider and the NuMI neutrino beam driven by 120 GeV protons from the Main Injector, and what they have delivered in FY 2010 and FY 2011 up to now.

Accelerator	FY 2010 DOE Goal	Delivered in FY 2010	FY 2011 DOE Goal	Delivered so far in FY 2011
Tevatron Luminosity	1.9 fb <sup>-1</sup>	2.48 fb <sup>-1</sup>	2.0 fb <sup>-1</sup>	1.68 fb <sup>-1</sup>
NuMI Protons on Target	2.2 x 10 <sup>20</sup>	3.2 x 10 <sup>20</sup>	2.7x 10 <sup>20</sup>	1.5 x 10 <sup>20</sup>

The 8 GeV Proton Booster Ring has delivered the number of protons on target that has met the Fermilab goal in FY 2010 and would exceed the Fermilab goal by nearly a factor of two in FY 2011.

## Preliminary Schedule of Current and Future Experiments for the Next Five Years

The table below shows the preliminary run schedule of current experiments and the preliminary timeline for new projects in the next five years: R&D (yellow), construction / commissioning (red), operation (green), and MINOS and MiniBooNE running beyond the NOvA shutdown (light green – being considered). The shutdown of the entire accelerator complex is scheduled from March 2012 through February 2013 in order to complete the NOvA accelerator and detector construction. Note that NOvA will take date with a partial detector in FY 2013.

Accelerator	Experiment	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015
Tevatron	CDF			Dec./Ana.	Dec./Ana.	Analysis	Analysis
Tevatron	DØ			Dec./Ana.	Dec./Ana.	Dec./Ana.	Dec./Ana.
LHC	CMS						
Booster	MiniBooNE			Shut	down		
Booster	MicroBooNE	CD-1	CD-2	Shut	down		
Booster	Mu2e	CD-0	CD-1				
Booster	Muon g-2						
Main Injector	MINOS	350kW		Shut	down	700kW	
Main Injector	MINERvA	350kW		Shut	down	700kW	
Main Injector	NOvA			Shut	down	700kW	
Main Injector	LBNE	CD-0		CD-1	CD-2		
SY120	SeaQuest			Shut	down		
SY120	Testbeam			Shut	down		
SCRF Test Facility							
Project X	Experiments			CD-0	CD-1		CD-2
Non-Accelerator	CDMS (4kg)						
Non-Accelerator	CDMS (15kg)						
Non-Accelerator	COUPP (4kg)						
Non-Accelerator	COUPP (60kg)		Comm.				
Non-Accelerator	DES			Comm.			
Non-Accelerator	Pierre Auger						

# Overview: Recent Achievements and Current Activities

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## *The Energy Frontier*

The Tevatron: The CDF and DØ experiments provide a vital program in the next few years with physics analysis using the Tevatron Collider data taken through FY 2011. The Tevatron Collider has been the highest energy collider in the world for more than 25 years and it is the only proton-antiproton collider. Instantaneous luminosities greater than  $4 \times 10^{32} \text{ cm}^{-2}\text{sec}^{-1}$  have been achieved, and yearly integrated luminosities have been greater than  $2 \text{ fb}^{-1}$  in the recent years.

The CDF and DØ have published a total of over 500 refereed journal publications, and 520 students have obtained Ph.D.s, ~80 papers and ~60 Ph.D.s in 2010. Physics achievements in 2010 include: the exclusion of the SM Higgs boson in the mass range between 158 and 173 GeV, the first such result obtained at a hadron collider, reducing significantly the allowed region for the Higgs boson; the better than 1% measurement of the top quark mass; several tantalizing hints of new physics at or above the  $3\sigma$  level (the forward-backward asymmetry of pair-produced top quarks, the evidence for an anomalous charge asymmetry in like-sign muon pairs, and the excess of events with a dijet invariant mass around 150 GeV in  $W+2$  jet events).

While the data-taking phase is scheduled to end in 2011, the data analysis will continue for several years. The data analysis and computing support plan has been established. Future high-priority analyses include the search for the Higgs boson, the legacy measurements such as the top quark and  $W$  boson masses (achieving possibly precisions below 1 GeV and of 15 MeV on  $m_{\text{top}}$  and  $m_W$ , respectively), search for possible sources of CP violation in the neutral  $B$  and  $D$  meson systems with world's best sensitivities in some channels, and the investigation of the hints of new physics observed so far.

The LHC: Fermilab's accelerator, detector, computing and physics facilities support the ongoing Large Hadron Collider proton-proton collider program in Geneva, Switzerland. Fermilab is the principal U.S. contributor to the LHC accelerator and the CMS detector. Fermilab's Remote Operations Center and LHC Physics Center make the participation of U.S. institutions in the LHC and in CMS more effective.

The Fermilab group with 60 authoring scientists including 15 postdoctoral researchers is the largest CMS group in the U.S. and second only to the CERN group internationally. They are involved in most all aspects of detector operations, computing, and data analysis. Fermilab is one of the seven Tier 1 national computing sites in CMS. The Fermilab group occupies every corner of the CMS Physics Organization, including three current physics group conveners (QCD, Jet and Missing  $E_T$  reconstruction), and have recently contributed to publications of searches for the Higgs boson, supersymmetry, and dijet resonances, as well as conducting a host of new measurements in QCD, electroweak, and top physics. Fermilab is deeply involved in short and long term upgrades of LHC accelerators and CMS detectors.

Fermilab has a unique role as it hosts a number of services and facilities for use by U.S. and international CMS collaborators. The LHC Physics Center (LPC) was created to ensure that physicists who reside inside the U.S. contribute optimally to the CMS experiment and maximize their international impact. Presently, collaborators from 34 university groups reside at the LPC. The LPC Computing Analysis Facility (LPC CAF) sited at Fermilab provides computing power for analysis conducted locally. Fermilab staff is available for software and desktop support, and provides data analysis expertise. Fermilab is also home to the LHC@FNAL Remote Operations Center (ROC). The ROC was created to enable U.S. physicists to fully participate in LHC, CMS detector, and CMS computing operations while located in the U.S. Many operational shift responsibilities have been fulfilled at the ROC, and are recognized as creditable service by CMS.

Future Colliders: 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.

For the International Linear Collider, Fermilab contributes to work on Accelerator Physics & Machine Design, Conventional Facilities, Global Systems, and Superconducting Radio Frequency (SRF) R&D. The ILC SRF work is coordinated and well integrated with the larger FNAL SRF program that supports infrastructure and goals relevant for ILC, Project X, or other future U.S. SRF-based accelerator projects. The Fermilab Accelerator Science and Muon Accelerator Programs support developing the concepts and technologies that are critical to enabling future energy and intensity frontier accelerator facilities such as a muon storage ring based Neutrino Factory and a high energy (multi-TeV) Muon Collider.

# Overview: Recent Achievements and Current Activities

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## *The Intensity Frontier*

At the Intensity Frontier, experiments at Fermilab aim to uncover properties of neutrinos, such as their oscillation parameters, mass ordering, matter-antimatter asymmetry, and interactions with matter, and to probe new physics from rare processes in muons, kaons and nuclei.

Neutrinos: The NuMI neutrino beam is the most powerful in the world, serving the MINOS detector in Soudan, Minnesota and the MINERvA detector at Fermilab. Fermilab is currently upgrading the NuMI beam and constructing the NOvA detector. NOvA, located near Ash River, Minnesota, is a second-generation neutrino oscillation experiment. The construction of NOvA will be complete in 2013. A third-generation neutrino experiment, the Long Baseline Neutrino Experiment (CD-0 approval), is being developed by Fermilab in cooperation with the large national LBNE collaboration including other laboratories such as BNL, LANL and LBNL.

MINOS has published a total of 24 papers, 9 in the past year. A wide range of oscillation analyses have been carried out, including  $\nu_\mu$  disappearance (producing the world's most precise measurement of one of the oscillation parameters,  $\Delta M^2_{\text{atm}}$ ),  $\nu_\mu$  disappearance (observing an allowed region that is intriguingly inconsistent with their neutrino results at the  $2\sigma$  level),  $\nu_e$  appearance (setting limits on  $\theta_{13}$ , comparable to the world limit), active to sterile neutrino oscillations, and a search for violation of Lorentz and CPT invariance. ArgoNeUT (data taken in 2009 – 2010) is preparing its first publication addressing kinematic reconstruction and identification of muons and line-like tracks in a liquid argon time projection chamber (LAr TPC). This marks an important step in the development of LAr TPCs in the U.S., necessary for ensuring the success of proposed future large detectors. MINERvA completed their full detector installation March 2010 and has already presented first results on antineutrino quasi-elastic scattering, a topic that has been of much interest to the neutrino community.

The 8 GeV Proton Booster Ring drives a second beam of neutrinos to the MiniBooNE experiment, and will deliver neutrinos to the planned MicroBooNE experiment (CD-1 approval; CD-2 review Summer 2011) based on LAr TPC technology.

The MiniBooNE collaboration has produced 20 publications, 8 in the past year, including the observation of an intriguing excess of antineutrino electron-like events that appears consistent with LSND. Along with recent MINOS results, these findings hint at possible differences between the way neutrinos and antineutrinos behave and have been the subject of numerous articles in recent press. In addition to studying neutrino oscillations, MiniBooNE has published cross sections, many of which represent the first time such distributions have been reported. These cross section measurements have unearthed a new source of nuclear effects that has been the subject of intense theoretical work in recent months. In concert, SciBooNE has published measurements of four different neutrino interaction cross sections, made a measurement of the kaon flux in the Booster neutrino beamline, and has recently released a joint SciBooNE-MiniBooNE analysis of  $\nu_\mu$  disappearance. A joint SciBooNE-MiniBooNE analysis of  $\bar{\nu}_\mu$  disappearance is also underway.

Muons: The Booster Ring will also provide beams of muons for two future experiments: Mu2e (CD-0 approval; CD-1 review Summer 2011), a major new experiment that searches for the conversion of muons to electrons, a critical signature for any unified theory of particle physics; and the muon g-2 experiment, critical parts of which will be reused from a previous experiment at BNL.

The new g-2 experiment will determine the anomalous magnetic moment of the muon to 140 parts per billion precision by measuring the precession frequency of muons stored in a uniform magnetic field. A commissioning run is planned for FY15 and high statistics data runs are planned for FY16, FY17, and possibly beyond. In parallel, Fermilab scientists in the Theory Department plan to calculate QCD contributions to g-2 on the lattice. A similar muon storage ring technique can be used to search for a permanent electric dipole moment of the muon to  $10^{-24}$  e-cm using *Project X*.

Mu2e is an experiment designed to discover charged lepton flavor violation. The experiment will search for the spontaneous conversion of a muon into an electron in the field of a nucleus. Using protons from the Booster it will have sensitivity to a conversion rate  $3 \times 10^{-17}$  times smaller than the rate that muons are captured in the nucleus. Commissioning runs are planned for FY17 and the first high statistics run is planned in FY18. A follow up experiment using protons from Project X will have a sensitivity of  $3 \times 10^{-19}$ .

## Overview: Recent Achievements and Current Activities

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**Proton Plan:** Requested integrated proton flux for the near-term operating program, including NOvA, MicroBooNE, Mu2e and g-2, requires increasing the proton source throughput and repetition rate. The NOvA Project is upgrading the Recycler (new RF), Main Injector (more RF and increased magnet ramp rate) and NuMI beam line (new target and additional cooling) to increase the accelerator complex power from 350 kW to 700 kW of 120 GeV protons for the neutrino program. The Proton Improvement Plan aims to upgrade the 40-year old Linac and Booster systems to enable a doubling of proton flux for the additional users while maintaining acceptable availability and residual activation levels and ensuring a useful operating life of the Proton Source through 2025. Both the g-2 and Mu2e experiments will take advantage of a reconfiguration of the antiproton complex and they will use protons from the Booster during cycles when the Main Injector is accelerating particles to 120 GeV so that muon production has no effect on the NuMI program.

**Project X:** Fermilab is developing a multi-megawatt proton accelerator, *Project X*. This accelerator would provide a neutrino beam for the LBNE and beams of muons, kaons and nuclei for rare-process experiments, simultaneously. It will be the most powerful and flexible facility at the Intensity Frontier anywhere in the world.

*Project X* research program includes;

- ***Kaon, muon, nuclei & neutron precision experiments:*** These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (EDMs), and world-leading precision measurements of ultra-rare kaon decays.
- ***Neutrino oscillation experiments:*** A high-power proton source with proton energies between 8 and 120 GeV would produce intense neutrino beams directed toward near detectors on the Fermilab site and massive detectors at distant underground laboratories.
- ***Platform for evolution to a Neutrino Factory and Muon Collider:*** Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.
- ***Nuclear Energy Applications:*** Accelerator, spallation, target and transmutation technology demonstration which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems.

### ***The Cosmic Frontier***

**Dark Energy:** Fermilab was the anchor laboratory for the Sloan Digital Sky Survey (SDSS), measured to be the highest impact observatory in the world in the last decade. It set the standard for precision surveys in cosmology and made many new discoveries relevant to Dark Energy, such as the imprint of Baryon Acoustic Oscillations in the galaxy distribution. The database remains a unique resource for the world community. The next generation of the dark energy experiment is the Dark Energy Survey (DES), a deeper, more precise successor to SDSS. Fermilab has led the construction of a new Dark Energy Camera, and this year will deploy and commission it on the 4-meter telescope at the CTIO in the Chilean Andes.

**Dark Matter:** Fermilab is the anchor laboratory for two WIMP Dark Matter experiments, the Cryogenic Dark Matter Search (CDMS) and the Chicagoland Observatory for Underground Particle Physics (COUPP). For most of the last decade, these experiments have continuously been among the world leaders in detection sensitivity and led the world in background-free detection.

**Ultra-High-Energy Cosmic Particles:** Fermilab is the anchor laboratory for the Pierre Auger Observatory, the world's leading facility for studying the highest energy cosmic particles. The collaboration has over 500 members worldwide and has supported over 130 PhD theses. The unique data from the first few years of operation have led to discoveries and mysteries concerning the anisotropy, composition, and spectrum of the highest energy cosmic rays.

**Axion Searches and Other New Initiatives:** Fermilab's GammeV experiments have set the world's best limits on couplings of new axion-like particles and chameleon particles, using lasers interacting with strong fields produced by Tevatron magnets. The Fermilab Holometer uses advanced interferometer technology, developed with LIGO collaborators, to probe the quantum nature of space and time. It will be the first experiment able to detect Planckian fluctuations in position, or holographic noise, caused by a fundamental bandwidth or information capacity of spacetime.

## Overview: Summary of Activities for the Next Ten Years

Below is the table showing the vision for Fermilab for the next ten years. Not included are those facilities like the Tevatron or the MINOS and MiniBooNE detectors that will complete operations within a few years.

Activities	Leadership Areas	New Capabilities	Required Resources
<u>Energy Frontier:</u> Collider Physics	US-LHC; US-CMS; LHC accelerator and detector upgrades; Detector R&D for future lepton colliders	Ability to provide LHC remote operations and physics centers and establishment of a critical mass of expertise at Fermilab in all aspects of LHC and CMS in order to enhance the effectiveness of the US community. Development of radiation-hard electronics for the upgrade of CMS	Continuous upgrade of computational resources. Capital investments for LHC and CMS upgrades are determined nationally.
<u>Intensity Frontier:</u> Neutrinos, Rare Processes	<u>Neutrino:</u> The NOvA facility; MINERvA detector; MicroBooNE LAr TPC detector; LBNE beamline and detectors; <i>Project X</i> design and construction  <u>Rare Processes:</u> Mu2e experiment; Muon g-2 experiment; SeaQuest experiment; Rare K processes and other high rate experiments with <i>Project X</i>	Most powerful neutrino program in the world. <i>Project X</i> requires the ability to build high gradient, CW, superconducting linacs and the safe handling of very large beam power with the attendant induced radioactivity.  Unique rare process experiments in charged lepton-number violation, the decay of K mesons and other experiments require new capabilities in the design of high rate experiments, and improvement of the Proton Source	Capital over 10 years: NOvA (\$278M), <i>Project X</i> (~\$1.3-\$1.6B in FY11 dollars, not including experiments), and LBNE beamline and detectors (\$1.1B-\$1.6B cost range in FY11 dollars including underground laboratory infrastructure and operations during construction). These funds will be distributed to the national community. Part of the capital need offset by the termination of the Tevatron (\$60M/year). For rare process detectors, capital investments of ~\$200M over ten years
<u>Cosmic Frontier:</u> Dark Matter & Dark Energy	Dark Matter Searches (CDMS, COUPP, Darkside); Dark Energy Searches (DES, LSST); Ultra High Energy Cosmic Rays (Auger)	This suite of experiments extends the reach for dark energy and dark matter by an order of magnitude and requires new capabilities in the storing, organizing and serving of large data sets to the particle and astrophysics community	Capital needs determined by the national program.
Accelerator R&D	LHC Accelerator R&D (LARP); ILC superconducting RF lead; <i>Project X</i> R&D; Muon Collider R&D lead; Neutrino Factory R&D lead	Requires new capabilities to build niobium-tin magnets and crab cavities for LHC upgrades. <i>Project X</i> requires new capabilities in designing, building, processing and testing high gradient, high Q, RF cavities.	<i>Project X</i> requires an R&D investment of \$82M.
Computing	Computing for LQCD; High Throughput computing; Advanced Networking; Grids and Data Storage; Scientific Software; Accelerator Simulation	Optimized use of Grids and Clouds; very high bandwidth data movement and storage; advanced use of local and leadership computing facilities for science; new software frameworks	Capital investments in computing facilities; human capital; core and program-specific IT investments; access to R&D network infrastructure
Theory	Phenomenology and Model Building; Lattice Gauge Theory; Cosmology and Particle Astrophysics Theory	QCD is essential to extract new physics at the LHC. New models are required to interpret physics in quark and lepton sectors. The physics of rare muon interactions, neutrinos, and kaons, requires new model, lattice and phenomenological insights.	Requires continuous strengthening of the theory groups in particle and particle astrophysics

## Overview: Tevatron Decommissioning Plan

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With the decision to shut down the Tevatron at the end of FY2011 now firmly established, the planning for decommissioning has taken on a higher level of urgency. In past years, there have been various plans proposed to keep the Tevatron in a standby state for possible future use. This is no longer the case. The Tevatron will be permanently shut down and both CDF and DØ detectors will transition into a decommissioned state. The new, proposed decommissioning plan has two phases. Phase 1 consists of three distinct stages.

- Stage 1 - Secure and stabilize systems while eliminating or mitigating hazards
- Stage 2 - Clean out support areas and harvest components that will be reused
- Stage 3 - Configure both detectors and a small section of Tevatron tunnel for guided tours, to be incorporated into our overall visitor program

Under any scenario the first stage of Phase 1, "Secure & Stabilize" must be done. Even if the systems were moving straight to full decommissioning, the work would start by shutting down operations and eliminating potential hazards. Cryogenic, mechanical, electrical and radiological systems must be secured in order to remove unnecessary risks. In many ways this work is similar to what needs to be done in preparation for an extended shutdown; the hazards have to be removed or properly mitigated. In Stage 2, "Clean out & Reuse", work is driven by the expectation that future projects that will be centered at the CDF and DØ areas and will take advantage of the available infrastructure in those areas. Cleaning out and disposing of old equipment is warranted and clearly part of decommissioning. In some cases, there are collaborating institutions or future Fermilab experiments that want to reuse components. A list of equipment along with any possible reuse scenarios is being assembled. This will be managed closely to assure that potentially useful equipment is not inadvertently disposed of and that all interested parties are aware of what is available. Requests for large parts of either of the detectors will need approval from the appropriate level of management. For CDF, the interaction of Stage 2 with the construction of IARC is being closely integrated. The decommissioning schedule will incorporate major milestones from the IARC construction schedule. For DØ, the intended reuse of the building is to support development of future liquid argon experiments. This matches well with the current infrastructure of the DØ facility.

The implementation of the Stage 3 display concept has two parts. Initially, a more "basic" display will be established whereby the detectors will be available for viewing by tour groups along with a few areas of the existing experiment operations, such as a counting room and the detector control room. This will be done for both the CDF and DØ detectors. Since the detectors are quite special in technology and layout, they offer different experiences for the visitors. In the basic concept, there will be some small investment made in creating posters, videos, and targeted displays, which tell the story of the Collider Program as well as the Lab in general. The major anticipated education opportunity for these tours will be the ability to get close to and view the detectors and at least in one case, enter a small section of the Tevatron tunnel and see the accelerator hardware. It is likely that there will be strong interest in seeing first-hand the equipment used to make many important discoveries in the field of High Energy Physics. Numerous visitors have requested an opportunity to see inside the tunnel. The Education Office and the Office of Communication are working together to develop a detailed plan for exactly which areas the tours will visit and the amount of material needed for the display. The second part of this display concept will add additional displays and posters as well as "build-out" the tour areas to a full exhibit with a concentration on educating the tour group about future Fermilab projects. The full display concept would also add better accessibility.

It is expected that Phase 1 including the basic display can be completed within approximately one year. The full display concept would take more time to finish. The Lab will maintain these detectors in the Phase 1 configuration for several years (ten or more) depending on the success of and interests in the visitor program.

Phase 2 is defined as the full Decontamination and Decommissioning (D&D) of the Tevatron and the two detectors. This is the total effort to clean out all components from the tunnel and remove and dispose of both the CDF and DØ detectors. The Tevatron concrete tunnel sections are assumed to remain in place. Tevatron D&D is aided by the fact that Lab personnel have a great deal of experience with removing and installing Tevatron magnets. Therefore, the amount of work and the resources needed for removing tunnel components is well estimated. Both detectors have their specific challenges and the full D&D effort has a large degree of uncertainty and risk and therefore high contingency. As Phase 1 progresses additional effort will be directed at refining the plan and the cost estimate for Phase 2.

## Overview: Workforce Plan

Fermilab's current workforce consisting of

- Scientists – experimentalists and theorists in accelerator physics and particle / particle-astro physics (19%)
- Engineers (14%)
- Technicians (24%)
- Computing professionals (16%)
- Facilities management staff (10%)
- ES&H staff (3%)
- Administrative support, finance and business, and other laboratory support staff (14%)

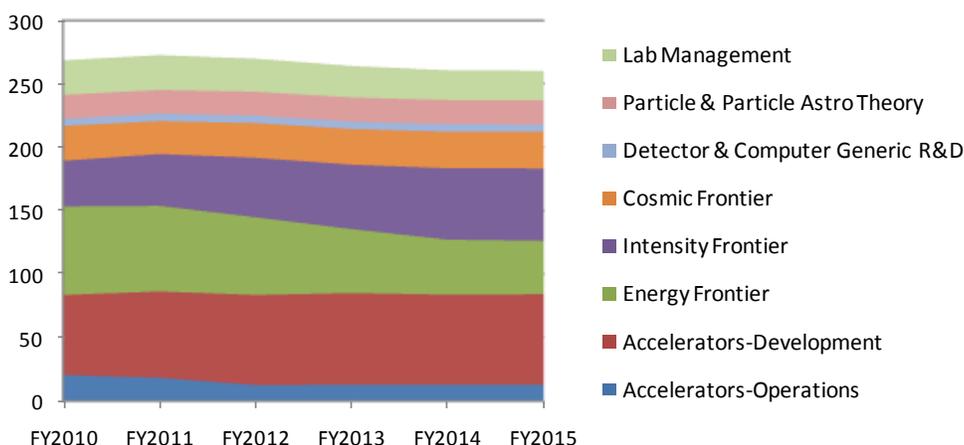
successfully maintains the core capabilities of the laboratory and accomplishes the present mission of the laboratory. However, the required skill mix varies with time, in particular with ending the Tevatron operation at the end of FY 2011 and starting and developing new accelerator and detector projects. For example, ~125 full time equivalent staff spread over approximately 200 individuals (6.5% of the current workforce), are exclusively engaged in accelerator / detector / computing operations and data analysis at the Tevatron. Although many of these employees possess skills that are required to support the computing and data analysis at the Tevatron, decommissioning of the Tevatron, and development, design, construction and operations of new projects at the Intensity Frontier, there will be some mismatch between the current workforce and workforce needed for the future mission of the laboratory.

Fermilab has a mechanism, OHAP (Organization and Human Asset Plan), to review the skills across the entire laboratory and guide the evolution of the workforce to carry out the Laboratory's future mission. The OHAP process combined with efforts of workforce optimization task forces:

- identifies the current people and skill sets (more than 200 skill sets are identified),
- reviews current and future programs and projects, and skills needed for them, and
- analyses the differences between current skill sets and skill sets needed for future programs and projects.

In FY 2009 and FY 2010, this process identified the gap in specific skill sets, such as mechanical and cryogenic engineers, drafters, and project support staff, and the laboratory handled the gap with a mixture of contractors and a small number of hires. The same process is currently being used to guide a realignment and potential reduction of the workforce beyond FY 2011. The figure below is one of the outcomes of the OHAP process showing scientists' past, current and intended activities between FY 2010 and FY 2015. The transition from the Tevatron to the Intensity Frontier projects is reasonably well aligned with the laboratory's strategy.

Number of current scientists at Fermilab in various activities between FY10 (past), FY11 (current), and FY15 (intended)



Our key challenges include:

- to provide the human resources needed to run the Tevatron and at the same time to staff the projects that will become the future of the laboratory
- to estimate future workforce needs accurately and to retain specialized skills not readily available in the labor market when the uncertainties on the timeline for new projects and programs are large.

## Particle and Particle-Astro Theory

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The Fermilab Theoretical Physics Group and Theoretical Astrophysics Group have an exceptionally strong effort in the Phenomenological, Lattice and Astrophysics Theoretical Thrusts and a modest effort in the Formal Thrust. A summary of the effort in all four Thrusts is given in the following paragraphs.

The Fermilab Theoretical Physics Group maintains a core effort in phenomenological aspects of theoretical physics. This naturally divides into three distinct sub-efforts: (i) Perturbative QCD, (ii) Beyond-the-Standard-Model (BSM) model-building and phenomenology, (iii) Neutrino Physics. These efforts, together with lattice gauge theory, are the central thrusts of the Fermilab Theoretical Physics Group. *These efforts are optimally aligned with the laboratory program, from the Tevatron through the LHC era, current and future Neutrino Program, Project X and its associated experimental program, and future lepton colliders.*

Historically the group has pioneered the challenging formulation and execution of practical calculations in perturbative QCD that are relevant to experimental HEP. It also maintains leading efforts in spectroscopy, flavor physics, Higgs physics, chiral dynamics, supersymmetry phenomenology, extra dimensions, and dynamical models of electroweak symmetry breaking. Members of the group also contribute to neutrino physics through their research, exposition, and participation in the planning and shaping of the future U.S. experimental neutrino program.

For 25 years Fermilab has been a leader both in developing hardware and software for lattice QCD and in applying lattice QCD to the Standard Model. Fermilab in fact builds and operates large clusters of computers for Lattice QCD as part of the national computational infrastructure for the Lattice QCD project established by DOE. The strongest interest of our lattice group is the application of lattice QCD to the broader program of particle physics, in particular the precise determination of the fundamental parameters of the Standard Model and the search for evidence of Beyond-the-Standard-Model effects in hadron data. In recent years, members of the group have worked very closely with the MILC Collaboration and occasionally with the HPQCD Collaboration. Their achievements include several of the first genuine predictions of lattice QCD, later confirmed by experiments. More recently, they have obtained, in concert with the B-factory experiments, the most precise determinations of the CKM matrix elements  $|V_{cb}|$  and  $|V_{ub}|$ , via exclusive decays of B mesons.

The Fermilab Theoretical Physics and Theoretical Astrophysics Groups have a continuing modest effort in formal aspects of theoretical physics to which many members make contributions from time to time. The groups *develop and apply formal concepts that have observable consequences in particle physics and astrophysics.*

Although the two groups are separate they share many common scientific goals and collaborate in a number of ways. The Theoretical Astrophysics Group focuses on theoretical studies connecting fundamental physics with astronomical observations. The interests and expertise of the Theoretical Astrophysics group range from the astrophysical implications of new theories beyond the Standard Model to high-resolution N-body simulations of structure formation to the development and refinement of new astrophysical probes of fundamental physics. This requires not only knowledge of the new physics but also a broad understanding of other astrophysical phenomena, statistical sophistication and understanding of astronomical techniques. Targets of this research include identification of a dark matter particle through “indirect detection”, understanding the nature of gravity, quantifying the dynamics of the cosmos at its very early stages by measuring the gravity waves and inhomogeneities produced, and constraining the properties of neutrinos and other (possibly exotic particles) through astronomical observation. The group also works closely with the KA13 programs at Fermilab.

## Experiments at the Energy Frontier: Tevatron

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The goal of experiments at the energy frontier is to directly probe the fundamental forces of nature. Over the last decade the energy frontier has been explored primarily by the two experiments at the Fermilab Tevatron proton-antiproton collider, CDF and DØ. The CDF and DØ Collaborations are constituted by a total of approximately 1000 scientists from over 100 institutions in 27 countries and have represented the largest community of users of Fermilab facilities ever. During Run II of the Tevatron, the two experiments have each collected data corresponding to an integrated luminosity of  $\sim 10 \text{ fb}^{-1}$  and extended the knowledge of particle physics beyond what had been achieved at previous colliders (LEP, SLAC, Hera, Run I of Tevatron). The highlights of the Run II physics program so far include the observation and precision measurement of the mixing of neutral  $B^0_s$  mesons, the observation of the electroweak (EW) production of single top quarks, achieving a precision of better than 1% on the measurement of the top quark mass, and the exclusion of the Standard Model (SM) Higgs boson in the mass range between 158 and 173 GeV, the first such result obtained at a hadron collider. This exclusion has reduced significantly the allowed region for the Higgs boson. While no conclusive sign of physics beyond the SM has been observed so far, tantalizing hints of new physics have been observed at or above the 3 standard deviations level in several processes: the forward-backward asymmetry of pair-produced top quarks, the evidence for an anomalous charge asymmetry in like-sign muon pairs, the excess of events with a dijet invariant mass around 150 GeV in  $W+2$  jet events. Further studies of these and related final states with the full Tevatron dataset will elucidate whether these are really the first signals of physics beyond the SM or statistical fluctuations in the data or shortcomings in the models and calculations used to model signals and backgrounds.

The CDF and DØ collaborations made many discoveries, including the top quark, the bottom quark, the tau neutrino, and the matter-antimatter transition in the  $B_s$  system, and numerous precision measurements. So far they have produced in total over 500 refereed journal publications and 520 students have obtained a Ph.D. degree with an analysis based on the data recorded in Run II. While the data-taking phase for the two collider experiments is scheduled to end in 2011, the data analysis is expected to continue for several years. The total analysis effort, especially computing requirements, is expected to increase since reaching this milestone will trigger data reprocessing and the completion of the final steps on many projects with the aim of attaining the ultimate analysis performance. The search for the Higgs boson will continue to be the main focus of the analyses following the shutdown of the Tevatron. Combining the data of the two experiments, there should be sufficient sensitivity to exclude the presence of a SM Higgs boson at the 95% C.L. over the entire mass range predicted by the precision fits to the EW model. This will either establish the non-SM nature of the EW symmetry breaking, or constrain the possible value of the SM Higgs mass into a tight window. The Tevatron experiments will have a unique opportunity to see hints or first evidence of the Higgs boson in the SM-favored region (masses in the 115-130 GeV region), but will also be complementary with the LHC experience by setting constraints on the Higgs boson branching ratio to  $b$  quarks, which will not be superseded by the LHC experiments until much later. The Tevatron constraints will be crucial in establishing the interpretation of a possible Higgs-like signal, or lack of signal, seen at LHC. The search for the low mass Higgs boson will benefit from improvements in algorithms, calibrations and alignments that will require a full (CDF) or partial (DØ) reprocessing of the raw data. This sets the timescale for the publication of the final Higgs results from the Tevatron experiments toward the Summer 2012. In parallel, the Tevatron experiments will keep improving the precision measurements of the top quark and  $W$  boson masses, search for possible sources of CP violation in the neutral  $B$  and  $D$  meson systems, with world's best sensitivities in some channels, and continue the investigation of the hints of new physics observed so far in the CDF and DØ data. Based on past experience, the final measurements of the top quark and  $W$  boson masses will be completed within 2 years from the end of the data taking. While both measurements are systematics limited, the increase in the datasets used for analysis and improved understanding of theoretical models will help in constraining these systematics and achieving possibly precisions below 1 GeV and of 15 MeV on  $m_{\text{top}}$  and  $m_W$ , respectively. Lastly, there are many SM tests that are important and unique to the Tevatron data. Each of the two Collaborations has the potential for publishing another 100 journal articles after the end of data taking and another 100 Ph.D. theses.

In addition to its role as host laboratory, members of the Fermilab groups have covered many leadership roles in both Collaborations. One of the two spokespersons on both CDF and DØ has been a member of the Fermilab group for the past 5 years and members of the Fermilab groups have covered important responsibilities not only on the detector and operations side of the experiments, but also leadership positions on data analysis.

## Experiments at the Energy Frontier: LHC

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In the past year, the LHC has established world record performance in both proton beam energy and colliding beam luminosity, and the experiments conducted at this new energy frontier have demonstrated outstanding performance in their first full year of colliding beam operations. The CMS experiment is now poised to make major discoveries in the next two years, including possible observation of the Standard Model Higgs boson, supersymmetry, or other new phenomena. Fermilab is well-positioned to play an integral role in this effort, through the activities of its own scientific staff and by hosting user facilities for the US and international CMS organizations.

Fermilab is the largest CMS collaborating group in the U.S. and second only to the CERN group internationally. Comprised of 60 authoring scientists including 15 postdoctoral researchers, they are involved in most all aspects of detector operations, computing, and data analysis. Fermilab physicists undertake operations responsibilities for the CMS hadron calorimeter, the silicon tracker, and forward pixel detectors, which they had previously helped construct and commission. Fermilab is one of the seven Tier 1 national computing sites in CMS and the host site for the US, and the supporting staff has international leadership roles in computing, data operations, and offline software development, including the current CMS Computing Coordinator. Fermilab CMS collaborators occupy every corner of the CMS Physics Organization, including three current physics group conveners (QCD, Jet and Missing ET reconstruction). They have recently contributed to CMS publications of ground-breaking searches for the Higgs boson, supersymmetry, and dijet resonances, as well as conducting a host of new measurements in QCD, electroweak, and top physics.

The Fermilab group is also deeply involved in short and long term upgrades of CMS detectors. As the LHC luminosity and energy are expected to increase in the future, the CMS Upgrade Program will be required to ensure continuing ability to produce physics results of the highest quality. Upgrade activities include engineering support for the design and fabrication of front end electronics, detector simulation software, production facilities for detectors, and beam facilities for testing prototypes. Detector components being developed include pixel detectors and forward muon cathode panels.

Fermilab has a unique role in the US CMS program, as it hosts a number of services and facilities for use by US and international CMS collaborators. The LHC Physics Center (LPC) was created to ensure that physicists who reside inside the US contribute optimally to the CMS experiment and maximize their international impact. Presently, collaborators from 34 university groups reside at the LPC. The LPC has a program to support both short term Guests and Visitors and longer terms via an LPC Fellowship Program. The LPC Computing Analysis Facility (LPC CAF) is sited at Fermilab and provides computing power for analysis conducted locally. In addition, Fermilab staff is available for software support, desktop support, and providing data analysis expertise. The LPC hosts workshops, data analysis schools, visiting theorists, a biweekly Physics Forum, and many other events.

Fermilab is also home to the LHC@FNAL Remote Operations Center (ROC). The ROC was created to enable US physicists to fully participate in LHC, CMS detector, and CMS computing operations while located in the US. Many operational shift responsibilities can be fulfilled at the ROC, and are recognized as creditable service by CMS. Fermilab staff provides training for US CMS shifters, is responsible for maintaining and operating the ROC. They also provide software support for data quality monitoring used by all of CMS.

Finally, Fermilab has a critical administrative role as the home of the US CMS Operations Program and its Manager. Fermilab supplies financial tracking and administrative support for the Program and prepares quarterly reports to DoE and NSF on the status of US CMS Operations. Fermilab also provides administrative support at CERN in order to provide liaison between CMS and CERN and US CMS visiting collaborators.

## Experiments at the Intensity Frontier: Recent and Current Neutrinos

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Fermilab's Intensity Frontier Neutrino Experiments address some of the most important questions faced by the particle physics community. The recently completed or on-going neutrino program has been extraordinarily successful, producing a wealth of neutrino interaction measurements and improving our understanding of neutrino oscillations. The entirety of the future neutrino program builds upon the knowledge already gained through operation of these experiments.

### Recent / Current Experiments: SciBooNE and ArogoNeuT / MiniBooNE, MINOS, and MINERvA

The Booster Neutrino Beamline has reliably provided neutrino and antineutrino beams to the MiniBooNE (2002—present) and SciBooNE (2007—2008) experiments. The MiniBooNE collaboration has produced 20 publications, 8 in the past year. These results include the observation of an intriguing excess of antineutrino electron-like events that appears consistent with LSND, although the experiment is currently collecting additional data to test this at higher significance. Along with recent results from MINOS, these findings hint at possible differences between the way neutrinos and antineutrinos behave and have been the subject of numerous articles in recent press. Fermilab hosted a short baseline workshop this May to discuss these results, their implications, and potential follow-ups, with over 100 scientists from multiple countries participating. In addition to studying neutrino oscillations, MiniBooNE has measured and published cross sections for roughly 90% of their data; many represent the first time such distributions have been reported. These cross section results have unearthed a new source of nuclear effects that has been the subject of intense theoretical work in recent months. In concert, SciBooNE has published measurements of four different neutrino interaction cross sections, made a measurement of the kaon flux in the Booster neutrino beamline, and has recently released a joint analysis of  $\bar{\nu}_\mu$  disappearance in the SciBooNE and MiniBooNE detectors. A joint SciBooNE-MiniBooNE analysis of  $\bar{\nu}_\mu$  disappearance is also underway.

The NuMI beamline has also hosted a wealth of productive neutrino experiments. MINOS (2005—present) has published a total of 24 papers, 9 in the past year. A wide range of oscillation analyses have been carried out, including  $\nu_\mu$  disappearance,  $\bar{\nu}_\mu$  disappearance,  $\nu_e$  appearance, active to sterile neutrino oscillations, and a search for violation of Lorentz and CPT invariance. The MINOS collaboration measured the world's most precise measurement of one of the oscillation parameters,  $\Delta M^2_{\text{atm}}$ . With its latest analysis, MINOS has set limits on  $\theta_{13}$  near the CHOOZ bound, an impressive result for a detector not optimized for this type of measurement. MINOS has also performed the first long-baseline antineutrino disappearance search, observing an allowed region that is intriguingly inconsistent with their neutrino results at the  $2\sigma$  level, with added data on the way. The collaboration has additionally published measurements of the atmospheric muon charge ratio, the seasonal variation of cosmic muon intensity, and the atmospheric charged kaon/pion ratio; all of which are valuable inputs to models of atmospheric neutrino flux. Using their high statistics near detector data, MINOS has also measured inclusive charged current cross sections for neutrinos and antineutrinos on iron in the energy range from  $\sim 3$ -50 GeV, significantly increasing the precision with which these cross sections are known. ArgoNeuT (2009—2010) is preparing its first publication addressing kinematic reconstruction and identification of muons and line-like tracks in a LAr TPC. This marks an important step in the development of LAr TPCs in the United States, necessary for ensuring the success of proposed future large detectors. MINERvA (2010—present) completed their full detector installation last March and has already presented first results on antineutrino quasi-elastic scattering, a topic that has been of much interest to the neutrino community of late. MINERvA also completed the first phase of their test beam program, exposing a replica of the MINERvA detector to a tertiary pion beam at the Fermilab test beam facility in the summer of 2010.

The MINOS and MiniBooNE collaborations would like to extend their run for a couple of years (FY 2013 – FY 2015 after the shutdown for the NOvA) in order to resolve intriguing differences between neutrino and antineutrino oscillations observed by their experiments and other potential measurements. The laboratory management team will be discussing these requests with Fermilab Physics Advisory Committee this year.

The Fermilab neutrino program currently operates some of the most intense neutrino beams in the world, and its strong physics program attracts large numbers of talented scientists from around the world. Fermilab staff plays leading roles in these collaborations, serving as spokespeople for three of the experiments as well as holding key positions as analysis and run coordinators in many cases. The information learned from these experiments provides Fermilab with a clear advantage in the design and execution of future endeavors, especially as we move into a new era of precision measurements.

# Experiments at the Intensity Frontier: Future Neutrinos

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## Future Experiments: NOvA, MINERvA, MicroBooNE, and LBNE

The future program will significantly advance our understanding of neutrino mixing and provide fundamental measurements of neutrino interactions needed for such pursuits. The future experiments will provide a continuous stream of physics results for decades to come and would also directly benefit from a high-intensity neutrino source at Fermilab.

NOvA, a second-generation neutrino experiment that is off-axis to the NuMI neutrino beamline, will begin data-taking in 2013. Situated at a distance of 810 km, the NOvA baseline will give Fermilab the unique capability to settle some of the most crucial and challenging questions confronting the neutrino community. NOvA's primary physics goals are to:

- Measure the value of the remaining unknown mixing angle,  $\theta_{13}$ , through observation of a signal for electron-type neutrino appearance. This is key to obtaining a complete picture of the structure of the lepton sector. NOvA will extend the  $\theta_{13}$  search to an order of magnitude beyond the sensitivity of the MINOS experiment.
- Precisely measure the mixing parameters  $\theta_{23}$  and  $\Delta m^2_{\text{atmospheric}}$  by means of muon-type neutrino disappearance.
- Understand the relative ordering of the neutrino mass states and the extent to which neutrino mixing is invariant between neutrinos and antineutrinos. Such properties are critical holes in our current understanding of neutrino mixing. An initial indication of their effects could be obtained by NOvA if  $\theta_{13}$  is large enough.

MINERvA is a neutrino scattering experiment that will pursue a broad spectrum of physics topics utilizing high statistics samples of neutrino and antineutrino events collected in the NuMI beamline since 2010. These studies are essential to minimizing systematic uncertainties in neutrino oscillation experiments and complement studies of charged leptons at Jefferson Lab. MINERvA will:

- Measure a variety of neutrino-nucleus scattering cross sections over a broad energy range, improving the currently imprecise knowledge on these processes.
- Examine in detail nuclear effects in neutrino scattering by utilizing a variety of nuclear targets, ranging from helium to lead. This capability is unique to MINERvA and is key to better understanding the complex nuclear effects evidenced in existing neutrino data samples.

MicroBooNE, a 170 ton liquid argon time projection chamber (LAr TPC) in the Booster Neutrino Beamline, will begin operation in 2013. This device represents a major advance in neutrino detector technology. MicroBooNE will:

- Investigate the source of the excess of low energy electron-type neutrinos observed by the MiniBooNE experiment using the unique electron-photon discrimination power offered by a LAr TPC.
- Produce the first high-statistics measurements of neutrino interactions in argon. Currently, such measurements do not exist; they will provide the first constraints for future LAr-based neutrino oscillation experiments.
- Fully test the LAr TPC technology at a scope and scale that will help inform the design and operation of very large LAr TPC detectors for next-generation neutrino oscillation experiments.

The Long-Baseline Neutrino Experiment (LBNE) proposes to measure the oscillations of accelerator-generated neutrinos over a significantly longer baseline than previously achieved. The increased research capabilities afforded by such a long baseline (>1,000 km) enable a physics program with unprecedented sensitivity to the neutrino mass ordering and the nature of matter and antimatter. Use of a large, shielded far detector also provides opportunities for research in other areas of physics such as nucleon decay and neutrino astrophysics. LBNE will:

- Precisely measure the parameters that govern  $\nu_{\mu} \rightarrow \nu_e$  oscillations, including improved measurement of  $\theta_{13}$ . If  $\theta_{13}$  is large enough, LBNE will also measure the neutrino mass ordering and CP violation in the lepton sector.
- Precisely measure oscillation parameters associated with muon neutrino and antineutrino disappearance.
- Search for proton decay, yielding a significant improvement of current limits on the partial lifetime of the proton in one or more important candidate decay channels.
- Detect and measure neutrino flux from a core collapse supernova within our galaxy, should one occur during the operation of LBNE.

## Experiments at the Intensity Frontier: Rare Process Programs

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Fermilab is planning a broad program of rare process experiments at the intensity frontier. The program addresses the OHEP mission by probing the interactions between the most elementary constituents of matter. The diverse set of experiments all reside at the intersection of the intensity and energy frontiers. They are all expected to play an integral and perhaps crucial role, in interpreting the discoveries at the LHC. SeaQuest will produce the first high statistics data set of the antiquark parton distribution functions inside the proton in momentum regions relevant to LHC energies. This information is necessary for understanding S-channel production of heavy resonances at the LHC. Muon and Kaon experiments will probe couplings and symmetry breaking parameters of new TeV scale interactions discovered at the LHC and will play a central role in confirming or ruling out various new physics models.

SeaQuest is a fixed target experiment using protons from the Main Injector that will precisely map out the momentum distribution of antimatter in the sea of particles and antiparticles inside protons. It is the latest in a series of Drell-Yan experiments at Fermilab. The spectrometer has been constructed and installed and the experiment will take commissioning data in the last quarter of FY11. The first physics run will follow in FY12 accumulating sufficient statistics for the first round of PhD dissertations. A high statistics run will then take place in FY13-FY14.

The new g-2 experiment will determine the anomalous magnetic moment of the muon to 140 parts per billion precision by measuring the precession frequency of muons stored in a uniform magnetic field. The initial experiment will use protons from the Booster and the muon storage ring from the previous g-2 experiment at Brookhaven. A commissioning run is planned for FY15 and high statistics data runs are planned for FY16, FY17, and possibly beyond. In parallel, Fermilab scientists in the Theory Department plan to calculate QCD contributions to g-2 on the lattice. A similar muon storage ring technique will be used to search for a permanent electric dipole moment of the muon to  $10^{-24}$  e-cm using protons from Project X.

Mu2e is an experiment designed to discover charged lepton flavor violation. The experiment will search for the spontaneous conversion of a muon into an electron in the field of a nucleus. The initial experiment will use protons from the Booster and will have sensitivity to a conversion rate  $3 \times 10^{-17}$  times smaller than the rate that muons are captured in the nucleus. Commissioning runs are planned for FY17 and the first high statistics run is planned in FY18. A follow up experiment using protons from Project X will have a sensitivity of  $3 \times 10^{-19}$ .

Both the New g-2 and Mu2e experiments will take advantage of a reconfiguration of the antiproton complex into the world's leading muon production complex. Protons from the Booster will be used during cycles when the Main Injector is accelerating particles to 120 GeV so that muon production has no effect on the NuMI program. Fermilab scientists in the Particle Physics Division, Accelerator Division, and Accelerator Physics Center are now working to design an ideal configuration that serves the needs of both the New g-2 and Mu2e experiments and provides a stable transition into operations of the Project X muon facility. Fermilab Postdoctoral Research Associates from the DØ and CDF experiments are playing leading roles in designing many aspects of the muon experiments. This gives them unique opportunities to gain valuable experience in detector research and development while ensuring sufficient human resources to produce legacy measurements from the final Tevatron data sets.

Two Kaon experiments will make percent level determinations of the branching fractions  $K^+ \rightarrow \pi^+ \nu \nu$  and  $K^0 \rightarrow \pi^0 \nu \nu$ . The charged Kaon experiment can acquire several hundred events per year assuming a standard model branching fraction of  $8.5 \times 10^{-11}$  at Project X. The neutral Kaon experiment will acquire 200 events per year using protons from Project X assuming a standard model branching fraction of  $2.8 \times 10^{-11}$ . The proposed beam structure and energy of the Project X 3 GeV CW LINAC make it the first facility with the opportunity to make a high statistics measurement of  $K^0 \rightarrow \pi^0 \nu \nu$ , arguably the most difficult channel in flavor physics.

Fermilab scientists are designing a Kaon facility for Project X that will use the same target station for both a charged and neutral Kaon experiment allowing for simultaneous studies  $K^+ \rightarrow \pi^+ \nu \nu$  and  $K^0 \rightarrow \pi^0 \nu \nu$ . Fermilab scientists are also formulating plans to use protons from the Main Injector to feed the charged Kaon experiment. This will allow the Kaon program to begin this decade and would provide a fully commissioned detector as a day 1 experiment for Project X. The large data samples and multipurpose nature of the Kaon experiments will also ensure a rich program allowing for multiple publications and thesis topics.

## Experiments at the Cosmic Frontier

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Fermilab's Cosmic Frontier experimental program addresses the OHEP mission to understand the fundamental nature of matter, energy, space and time, and the interactions between them, using the tools of particle astrophysics. The experimental portfolio is aligned principally with the following programmatic thrusts to probe new physics beyond the Standard Model:

- **Dark Energy:** Measure large scale properties of the Universe to discover the detailed properties of the mysterious force that appears to accelerate the expansion of the universe, and comprises most of its total energy content.
- **Dark Matter:** Search for direct laboratory interactions of the particles that mysterious mass that appears to dominate the attractive gravitational mass of the universe, including our Galaxy.
- **High Energy Cosmic Particles:** Measure the properties of the highest energy (and rarest) cosmic rays in the universe, in order to understand their composition, interactions, and natural history.
- **Unification:** Perform laboratory experiments that search for effects of new physics beyond the energy reach of any accelerator, including new axion-like particles, and Planck-scale quantum behavior of space and time.

Fermilab's Dark Energy experiments began with its role as the anchor laboratory for the Sloan Digital Sky Survey, the world's first large, deep digital survey of the universe, and the most successful astronomy facility of the decade as measured by science impact. Fermilab participation in SDSS Dark Energy science is winding down this year, with the publication of results from the Fermilab-led SDSS-II Supernova Survey.

Fermilab's largest current Cosmic Frontier project is the Dark Energy Survey, a deeper, more precise successor to SDSS. Fermilab has led the construction of a new Dark Energy Camera, and this year will deploy and commission it on the 4-meter telescope at the Cerro Tololo Interamerican Observatory in the Chilean Andes. In the course of about 500 nights over the next five years, the DES collaboration, with more than 100 scientists from around the world, will again make the largest, deepest, most precise digital map of the sky. The final petabyte-scale survey will comprise about 300 million galaxies looking out into space, and back in time, more than half the age of the universe.

Fermilab participates in three major experimental searches for Dark Matter particles. Following on a strong theoretical hunch based on Big Bang cosmology that the Dark Matter is made of Weakly Interacting Massive Particles (WIMPs), these experiments 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, and Gran Sasso in Italy.

Fermilab is the anchor laboratory for the Pierre Auger Observatory in Argentina, the world's leading facility for studying the highest energy cosmic rays. PAO has operated now for about three years, and the international collaboration has published pathbreaking results on the composition, interactions, anisotropy, and spectrum of these extraordinary and rare particles.

With collaborators from the gravitational wave interferometer community, Fermilab is developing a new experimental capability using intense, ultrastable laser cavities and interferometers. These will be used in combination with Tevatron magnets to search for interactions mediated by new axion-like particles at energies far beyond the Terascale. A combination of correlated interferometers, called the Fermilab Holometer, will seek to probe rapid fluctuations in spacetime position caused by new Planckian quantum physics of the kind responsible for black hole evaporation. This experiment may achieve the sensitivity to address effects associated with ultimate unification, of matter and energy with space and time.

## General Detector R&D

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The Fermilab Generic Detector R&D Program supports the missions of the OHEP and the U.S. HEP community by nurturing and developing technologies that are critical for enabling the detectors of the future. The Detector Advisory group that manages the Fermilab program is composed of scientists doing proton research, lepton collider research, and particle astrophysics. Fermilab scientists working in those B&R categories lead, plan and execute a comprehensive, targeted program of generic detector research along 5 broad thrusts that are well aligned with the mission.

*Collider detector R&D:* This thrust encompasses silicon vertex and tracking sensors, ASIC readout architectures, calorimetry and photodetector research. Some of the major accomplishments include:

- Successful implementation (in collaboration with OKI of Japan) of nested well structures in a ‘silicon-on-insulator’ (SOI) device.
- Demonstration of extreme timing resolution (< 20 picoseconds) in time-of-flight measurements using commercial micro-channel plate phototubes and Silicon PhotoMultipliers.
- A systematic Monte Carlo study of Cerenkov and scintillator light yields and timing distributions in a dual readout crystal hadron calorimeter, to support 15%/sqrt(E) hadronic jet resolution.

*Liquid Argon R&D:* This thrust makes fundamental contributions to understanding the basic properties of liquid Argon detectors, with a focus on potential very large neutrino detectors and low background Dark Matter detectors. The progress includes:

- Construction of a 20 ton LAr cryostat that will be filled without evacuation. This device will test whether it is feasible to build extremely large LAr TPC’s, of order 20 Kilotons.
- First operation of readout electronics in the liquid Argon mass. In collaboration with BNL and MSU, Fermilab has recently shown that component level electronics can survive and operate in LAr.
- Successful operation of a distillation column to purify Argon obtained from underground wells. This Argon has a low concentration of the <sup>39</sup>Ar isotope and is thus useful for dark matter experiments. We developed this column in collaboration with Princeton University.

*Astrophysics Detectors:* This thrust supports the dynamic ideas generated by young researchers to build detectors for studying dark energy and dark matter. Examples are:

- Pioneering kilogram levels of solid Xenon for use in axion and other dark matter detection.
- Creation of a laser lab to support holographic interferometry and axion detection strategies.
- Use of CCD technology for dark matter and neutron detection.
- Studying acoustic signals in bubble chamber events and confirming their use in particle identification.

*Data Acquisition:* The activity in this thrust is geared towards incorporating new techniques for general data flow in high energy experiments. This includes:

- Testing new optical Gigabit transceivers in conjunction with CERN.
- With a local company, Fermilab is developing multi-band free-space optical data acquisition, using the 1.5 micron wavelength regime for which silicon is transparent.
- Porting the CAPTAN test beam data acquisition firmware to the new telecommunications standard xTCA. Fermilab is using this translation as a test bed for assessing xTCA ease of use.

Facilities:

- The centerpiece for detector facilities at Fermilab is the Test Beam Facility. It provides a high level of user support for visiting teams to put their detector into the versatile test beam. The facility provides 120 GeV proton beam and secondary beams all the way down to 0.5 GeV.
- The SiDet Facility remains as a center for detector research at Fermilab, with a wide array of support for testing and packaging new sensor or data acquisition devices.
- A new 400 MeV proton beamline, called MTA, is now available for irradiation studies.

Fermilab continues its involvement in national coordination of detector research and training of young researchers with the hosting of a national workshop on detector R&D in October, 2010 and the co-hosting of the second Techniques and Instrumentation in Particle Physics conference in June, 2011. Fermilab will host the second EDIT (Excellence in Detector and Instrumentation Techniques) detector school in February, 2012. In all research endeavors, Fermilab is interested in strategic collaborations with other national laboratories and institutions around the world.

## Accelerator Operations and Improvements

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Fermilab's accelerator operations supports the mission of the Office of High Energy Physics by providing colliding proton-antiproton beams and fixed-target neutrino beams. The accelerator complex consists of nine interlinked accelerators and storage rings. Together they provide a unique set of beams for particle physics research.

The Tevatron Collider has been the highest energy collider in the world for more than 25 years. The collision energy is 1.96 TeV, and it is the only facility in the world where proton-antiproton collisions are studied. Luminosities greater than  $4 \times 10^{32} \text{ cm}^{-2}\text{sec}^{-1}$  have been achieved, and yearly integrated luminosities are typically greater than  $2 \text{ fb}^{-1}$ . The Collider performance is supported by an antiproton source that collects and cools up to  $28 \times 10^{10}$  antiprotons per hour at 8 GeV. Antiprotons are created by hitting a target with 120 GeV protons from the Main Injector. Subsequently the antiprotons are collected and cooled in a series of 3 storage rings in order to produce a very bright antiproton beam for use in the Collider. Stochastic cooling is used in the first two rings, the Debuncher and the Accumulator. The final stage of cooling occurs in the Recycler and is accomplished by injecting a beam of cold electrons from the Pelletron into the antiproton beam. This high-energy electron cooling technique, pioneered at Fermilab and commissioned in 2005, has resulted in luminosities that are approximately 50% higher than they would be without electron cooling. In addition to the electron cooling improvement, a robust antiproton production target was developed approximately 3 years ago that greatly improved the reliability of antiproton production. Continuous improvements have also been made in the stochastic cooling systems in both the Debuncher and Accumulator rings.

During the course of Run II Tevatron beam stability has improved significantly as a result of many hardware and system improvements.

- maintaining the alignment of the Tevatron magnets for better beam stability.
- replacing worn cryostat supports within the Tevatron magnets.
- improving the beam stabilization software.
- establishing control of the coupling and tunes up the ramp and through the low beta squeeze.

Fermilab also operates two intense neutrino beams. A 300kW proton beam is delivered to the NuMI target to create a neutrino beam for the MINOS experiment in the Soudan Laboratory. Slip stacking was developed in the Main Injector to enable the 300kW beam to the NuMI target. However, the high intensity beam is a challenge for targets and focusing horns. Improvements are still being made to improve target robustness and lifetime. Nevertheless, more than  $1.2 \times 10^{21}$  protons have been delivered to the NuMI target since the 2005 startup of the beam.

An 8 GeV proton beam out of the Fermilab Booster synchrotron creates a neutrino beam for the MiniBooNE experiment. This beam runs up to 3 Hz, and more than  $1.3 \times 10^{20}$  protons have been delivered to the 8 GeV target since 2005. Horn and target reliability have been very good.

Fermilab also operates a test beam used for detector development. Beam is extracted from the Main Injector and sent to the Meson experimental area where a secondary beam is produced. The beam is primarily used for researchers developing new detector technologies. In addition Fermilab has recently commissioned the MuCool Test Area (MTA) beam off of the Linac to test muon cooling techniques and associated technology.

In order to support the increased demands for proton flux in the coming decade, a program of improvements to the Proton Source is in the planning stage. Requested integrated proton flux for the near-term operating program, including NOvA, MicroBooNE, Mu2e and g-2, requires increasing the proton source throughput and repetition rate. The NOvA Project is upgrading the Recycler (new RF), Main Injector (more RF and increased magnet ramp rate) and NuMI beam line (new target and additional cooling) to increase the accelerator complex power from 350 kW to 700 kW of 120 GeV protons for the neutrino program. The Proton Improvement Plan aims to upgrade the 40-year old Linac and Booster systems to enable a doubling of proton flux for the additional users while maintaining acceptable availability and residual activation levels and ensuring a useful operating life of the Proton Source through 2025. The major elements of scope include upgrading and replacing a number of systems and components that represent obsolescence vulnerabilities, increasing the repetition rate of the Booster RF system, replacing the Cockcroft-Walton injector with an RFQ, and reducing fractional beam loss with improved collimation and cogging. The Proton Improvement Plan is anticipated to require four to five years and approximately \$40M in M&S costs.

## General Accelerator Development

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The Fermilab General Accelerator Development (GAD) Program supports the missions of the Office of High Energy Physics and the U.S. HEP community by nurturing and developing those technologies that are critical for enabling the accelerator facilities of the future.

Fermilab's GAD program is conceptually positioned between the Accelerator Science (AS) program, dedicated to accelerator physics research and investigation of new accelerator concepts, and more focused Programs or Projects dedicated to the development or construction of specific equipment or production facilities. The GAD function is to:

- Take a need from AS (e.g. the need to develop a high intensity proton accel., or new lepton / hadron colliders)
- Develop and prototype the appropriate tools and technology to address this need (sometime performing basic R&D to facilitate this process, such as R&D on bulk materials or surface physics)
- Deliver prototypes to a construction project, or support an existing program with more focused goals.

Fermilab's GAD program leverages the substantial resources at the laboratory, in the form of infrastructure (magnet measurement stands, vertical test-stands, cryogenics, etc., etc.), local universities with active interest in accelerator science and technology (IIT, NIU, Northwestern), close proximity to ANL, and substantial computational capabilities. In addition, the program leverages the many existing collaborative activities underway at the laboratory.

Specific mission elements of the General Accelerator Development have focused, over the years, in expanding the technical knowledge to meet the scope of research on Fermilab frontiers. On the Energy Frontier, GAD has developed technologies required for LHC upgrades, future LHC beam energy increases, and next generation lepton colliders such as the Muon Collider. In particular, development of Nb<sub>3</sub>Sn and HTS (High Temperature Superconductor) magnet technology to provide ever-increasing magnetic fields under the generic *High Field Magnet* program has included the following achievements:

- Development and successful demonstration of the collaring techniques for Nb<sub>3</sub>Sn coils
- Demonstration of the 0.7 mm RRP-108/127 strand for operation at 1.9 K, cable with SS core to suppress eddy currents and affordable cable insulation based on E-glass and S2-glass tapes
- Conceptual studies of an 11 T Nb<sub>3</sub>Sn dipole compatible with the LHC lattice
- Fabrication and test of helical solenoid models based on NbTi cable for the 6D muon cooling channel.
- Conceptual design studies of Muon Collider dipoles and quadrupoles based on Nb<sub>3</sub>Sn superconductor.

Continued *HFM* development work will aim at the construction of hybrid magnets of 20+ Tesla.

On the Intensity Frontier, GAD has developed technologies suitable for acceleration of high average current, non-relativistic proton/H<sup>-</sup> beams such as those needed for the proposed ProjectX or for the front end of a future Muon Collider. Such developments are performed at frequencies of interest for ProjectX (325 and 650 MHz) and have included the following achievements:

- A radiation-shielded facility for testing 325 MHz RF cavities, normal and superconducting
- A 2.5 MW pulsed, 325 MHz RF power system with flexibility to serve multiple users
- An operating 50 keV proton source and a prototype magnetron-type 50 keV H<sup>-</sup> ion source
- A 50 keV to 2.5 MeV, 325 MHz RFQ that successfully accelerated protons
- Production high-power, 325 MHz RF vector modulators to control power distribution from a single RF source
- Two 325 MHz,  $\beta = 0.2$ , SC spoke-type RF cavities with world-class accelerating gradients
- Design of 650 MHz cavities for the acceleration of intermediate-energy hadrons ( $\beta \sim 0.6-0.9$ )

Continued Intensity Frontier front-end development will aim at the design of other specific cavities and at the completion of studies on power distribution controlled by vector modulators.

GAD supports basic materials R&D for applications in magnets and cavity construction. An R&D processing lab, called ICPA (Integrated Cavity Processing Apparatus) has recently been completed and brought to operation. GAD provides also support for application of software developments for accelerator modeling.

Finally, GAD supports the nurturing and engagement of the scientific community through a program of joint appointments with NIU, IIT and IC London as well as with the PARTI Student Program (PARTI=Physics of Accelerators and Related Technology for International students)

## Accelerator Science

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The Fermilab Accelerator Science (AS) Program supports the long term accelerator-based physics mission of Fermilab, of the Department of Energy's Office of High Energy Physics and the U.S. HEP community by developing technologies and tools aimed at energy frontier colliders and intensity frontier facilities, by providing critical support for ongoing accelerator based programs at the heart of the near term Fermilab research program (Collider Run II and the neutrino program, Large Hadron Collider at CERN), and by raising the next generation of accelerator designers and builders. Fermilab's AS program is based on and further expands upon pioneering accelerator science developments of the past several decades of the Tevatron Fixed Target and the Tevatron Collider runs.

Specific mission elements of the Accelerator Science Program include:

- Accelerator and Beam Physics: contribute to the fundamental understanding of beam dynamics through experiment, simulation and theory
- Advanced Accelerator R&D Program: develop and explore the transformative concepts and technologies for beyond next-generation accelerators
- Operational Support: advanced beam dynamics support for the operating accelerator complex at Fermilab, and the Large Hadron Collider at CERN
- Education: educate the next generation of accelerator designers and builders through the USPAS and Fermilab programs

Fermilab pursues a broad range of accelerator and beam physics activities in support of both the Energy and Intensity Frontiers. That includes developments of fundamental theory of beam instabilities and their control in current and future accelerator facilities, dynamics of space-charge dominated beams and colliding beams, analytical tools for analysis of emittance growth, intra-beam scattering and beam cooling, experimental studies of coherent effects in high intensity proton beams due to impedance and electron cloud effects, experimental studies of ground motion effects in accelerators and electron cloud effects in high-intensity proton beams, techniques for compensation of beam-beam effects with electron lenses and new collimation methods for high energy hadron beams employing bent crystals and hollow electron beams. The AS program supports the development of numerical tools for energy deposition simulations (including the upgrade, maintenance and distribution of the MARS code, a resource to the worldwide community), beam optics (OPTIM, MAD-X and CHEF), beam dynamics (ORBIT-M, SIXTRAC and ESME) and the integrated accelerator simulation suite SYNERGIA. Fermilab leads the US-wide ComPASS (Community Petascale for Accelerator Science and Simulation) collaboration.

Advanced accelerator R&D (AARD) activities include novel beam manipulation techniques, which follow pioneering experiments on round-to-flat beam transformation and transverse-to-longitudinal emittance exchange demonstration experiments conducted at the A0 PhotoInjector lab, development of high-brightness electron sources and novel beam diagnostics techniques. These activities are conducted in collaboration with other laboratories and universities and will further expand into the new AARD Users' Facility that will be created in conjunction with Fermilab's new superconducting radio-frequency test facility at the NML building. Among other experiments, the AARD program at the NML will include longitudinal bunch shape manipulation with double-emittance exchange line (in collaboration with ANL), integrable optics test accelerator ring and advanced beam cooling tests (in collaboration with ORNL) and test of a crystal-based high-brightness X-ray radiator (in collaboration with NIU, Vanderbilt University, Tech-X and RadiaBeam Technologies).

Fermilab's AS program also includes advanced accelerator and beam physics studies at the laboratory's operating accelerators and at the LHC in support of optimizing accelerator performance, such as energy deposition simulations, development of improved beam diagnostics tools, and exploration of the performance limiting factors such as efficiency of collimation system, generation and control of DC beam, modeling and optimization of stochastic and electron cooling systems, and methods to control beam optics imperfections.

Fermilab's AS program supports a comprehensive program for training the next generation of accelerator scientists and engineers that includes the Lee Teng Internship in accelerator science and technology for undergraduate students; the Bardeen Fellowship in accelerator engineering for M.S. and Ph.D. students; a Joint University-Fermilab Accelerator Ph.D. program; and the Peoples Fellowship in accelerator science for post-graduates. Fermilab hosts the U.S. Particle Accelerator School, a national consortium, which holds two sessions a year for undergraduate and graduate students.. The new Illinois Accelerator Research Center, to be constructed by 2013 with funds from a State of Illinois grant, will further enhance the accelerator science education program at Fermilab.

## Superconducting Radiofrequency Development

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Superconducting Radio Frequency (SRF) is an enabling technology applicable for a variety of future accelerator projects at the Energy and Intensity Frontiers in support of the DOE OHEP mission and is crucial to Fermilab's and the nation's long term science strategy. Rapid improvements in achievable accelerating gradients now make SRF technology the preferred method of efficiently generating high power particle beams. SRF is envisioned for use in essentially all planned accelerator facilities that require high efficiency conversion of wall plug AC power into beam power.

Developments in accelerator technologies, required to answer the most pressing questions in particle physics, have often found application in other fields of research or in industry. SRF R&D is expected to lead to new methods for superconducting cavity fabrication, processing and new cost effective high-power RF sources. SRF technology holds the promise of furthering future accelerator-based research capabilities beyond High Energy Physics, including next-generation light sources, accelerators for isotope generation and medicine, accelerators for industrial use, accelerators for waste water or flue gas treatment, accelerator to transmute and make safe radioactive waste from nuclear reactors while at the same time generating energy and creating new fissile fuels, accelerators for materials irradiation, and host of other high power beam applications aligned with DOE, SC and national goals.

Fermilab SRF activities are funded from several B&R categories with different objectives. However, the overall SRF effort is coordinated from the FNAL Directorate to insure optimal efficiency in the use of FNAL personnel and facilities. SRF R&D depends heavily on international collaboration. Fermilab currently has MOU's with 23 national and international laboratories and universities.

Activities supported by General Accelerator Development Program (KA15 GAD) are focused on the development of technology for near term projects like cavities and cryomodules for Project X. GAD also supports generic SRF materials and cavity development to advance the state-of-the-art. These activities are described elsewhere in this document. A separate but related activity is SRF R&D in support of the International Linear Collider (KA15 ILC). The SRF portion of this activity is focused on R&D to develop high gradient 1300 MHz cavities and cryomodules. This activity will prepare the Office of Science and U.S. industry for participation in a future ILC Project when and if results from LHC establish the mechanism and energy scale for electroweak symmetry breaking. If this new physics includes the discovery of the Higgs or super-symmetry then it is likely that a lepton collider like ILC will be needed to explore this sector. It should be noted that Project X envisions a 3-8 GeV pulsed linac that employs ILC cavities and cryomodules. Common overall management of GAD and ILC insures a coordinated effort.

While SRF technology exhibits extraordinary performance in accelerator applications, it also requires significant initial investment in personnel training and infrastructure. The SRF B&R (KA15 SRF) was created to fund the construction of the required SRF infrastructure at Fermilab and to develop a U.S. SRF industrial base. Currently European laboratories and industry are in the lead in SRF capabilities. It is Fermilab's goal to develop world-class SRF infrastructure and expertise that complement that at other U.S. SRF institutions such as TJNAF, ANL, and Cornell University. The SRF infrastructure and capability needed to construct and support SRF accelerators for high energy physics like Project X, ILC, or the Muon Collider is part of Fermilab's core mission as the lead U.S. HEP laboratory. This capability will also permit the DOE Office of Science to participate in other SRF based accelerator projects outside of HEP.

Viewed as a whole, the Fermilab SRF mission is comprised of the following objectives:

- Development of 325 and 650 MHz cavities, cryomodules, and test facilities for Project X
- Development of 1300 MHz cavities, cryomodules, and test facilities for ILC and Project X
- Establishment of new tools, infrastructure and procedures focused on R&D functions to develop the technology. While useful for them, these facilities are not part of any future construction project
- Leverage the substantial resources at the laboratory, in the form of infrastructure (buildings, cryogenic refrigerators, reuse of magnets, shielding blocks etc.), experienced RF, cryogenic, controls, fabrication, and accelerator scientific and engineering personnel.
- Leverage national resources such as the SRF facilities at ANL and JLAB

The Fermilab SRF R&D portfolio is aligned principally with the following programmatic thrusts:

- Development of SRF structures suitable for future high-intensity, high-energy, linear accelerators
- Fundamental R&D on superconducting radio frequency materials, surfaces, and their practical limitations.

## Project X

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The Fermilab Project X Program supports the missions of the OHEP and the U.S. HEP community by developing concepts and associated technologies for a high intensity proton facility that will provide a platform for a world-leading Intensity Frontier program in the U.S. A complete concept for Project X has been developed that supports the long term strategic goals of the U.S. program, including a forefront facility for Intensity Frontier physics, constructed in a manner that would provide a platform for a future Energy Frontier Muon Collider. Specific mission elements associated with the facility include:

- Provide MW-class, multi-GeV, proton beams supporting multiple kaon, muon, and neutrino based precision experiments.
- Provide a neutrino beam for long baseline neutrino oscillation experiments, based on a capability of targeting at least 2 MW of proton beam power at any energy between 60 – 120 GeV. Simultaneous operations of the rare processes and neutrino programs are required.
- Provide a path toward a muon source for possible future Neutrino Factory and/or a Muon Collider.
- Provide options for implementing a program of Standard Model tests with nuclei and/or nuclear energy applications

The Project X program includes both pre-conceptual design development and R&D of associated technologies. The goals of the program are:

- Develop concepts that meet the mission elements defined above, in a cost effective manner.
- Prepare for development and construction of the Project X facility in accordance with the requirements of DOE413.3b.
- Conduct this work within the context of a national collaboration with international contributions.
- A more specific goal is to be in a position to launch Project X as a formal project, i.e. obtain CD-0, in FY12.

A complete concept has been developed that meets the mission elements listed above based on a 3 GeV continuous wave (CW) linac coupled with a 3-8 GeV pulsed linac. The linacs accelerate H<sup>-</sup> ions and are based on superconducting radio frequency (SRF) acceleration. The 3 GeV linac supports the rare processes and nuclear mission elements; the 3-8 GeV pulsed linac connects directly into the existing Recycler/Main Injector complex and supports the long baseline neutrino mission. The integrated facility would provide a platform for a future muon facility. Unique aspects of this concept include the ability to operate the rare process and long baseline neutrino programs simultaneously, and the ability to deliver variable bunch structures to multiple experiments simultaneously. These capabilities are unique among any high intensity facility in operation, under construction, or in design anywhere in the world.

Project X requires beyond current state-of-the-art technologies in a number of areas, and these are the focus of the R&D program:

- Development of a front-end system including a wideband chopper capable of producing arbitrary bunch patterns by accepting or rejecting H<sup>-</sup> bunches at 162.5 MHz.
- Development of a multi-turn H<sup>-</sup> injection system into the Recycler Ring.
- Development of SRF accelerating structures at a variety of frequencies and particle velocities.
- Development of efficient and cost effective RF power sources.
- Accelerator design and simulation activities to support Project X performance goals.

Significant work is currently underway in all of these areas. The SRF development is conducted under KA15 – General Accelerator Development; the Project X and SRF programs are closely coordinated. These efforts engage staff at both Fermilab and collaborating institutions, both in the U.S. and abroad. The Project X Design and R&D phase is carried out as a collaborative activity with nine national and four international partners, governed through two MOUs and with semi-annual Collaboration Workshops.

# Accelerator Development at the Energy and Intensity Frontiers (1/2)

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## *LHC Accelerator Research Program*

The LARP program has made contributions to the initial operation of the LHC, but the majority of its activities are focused on future upgrades. Fermilab has played and continues to play a key role in LARP's development of superconducting quadrupoles based on Nb<sub>3</sub>Sn for the high luminosity upgrade of the LHC. In addition, Fermilab is involved with instrumentation and accelerator physics support. The lab developed the Schottky detector and, for passive beam diagnostics, the AC dipole, which allows measurement of optical parameters at high energy. Both of these were brought into full standard operation this year. Current LARP R&D includes several beam modeling studies as well as the exploration and development of hollow electron beams for the removal of beam halo. Recently, work has started in the energy deposition group to understand radiation issues of the Nb<sub>3</sub>Sn magnets. LARP-supported visitors from Fermilab over the last year have worked on abort gap studies as well as beam studies related to the Large Pwinski Angle optical solution for the LHC luminosity upgrade.

## *International Linear Collider*

Effort on International Linear Collider (ILC) R&D takes place under the umbrella of the larger American Regional Team (ART) of the ILC Global Design Effort (GDE). Fermilab contributes to work on Accelerator Physics & Machine Design, Conventional Facilities (CFS), Global Systems, and Superconducting Radio Frequency (SRF) R&D. The ILC SRF work is coordinated and well integrated with the larger FNAL SRF program that supports infrastructure and goals relevant for ILC, Project X, or other future U.S. SRF-based accelerator projects.

## *Muon Accelerator Program*

The Fermilab Accelerator Science and Muon Accelerator Programs support developing the concepts and technologies that are critical to enabling future energy and intensity frontier accelerator facilities. In addition to Project X, ILC related R&D, and LHC upgrade R&D, the accelerator R&D activities aimed at the longer term future are:

- Developing the concepts and technologies for a muon storage ring based Neutrino Factory.
- Developing the concepts and technologies for a high energy (multi-TeV) Muon Collider.

Neutrino Factory R&D and Muon Collider R&D are pursued within the context of the national Muon Accelerator Program (MAP). The mission of MAP is to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, accelerate, and store intense beams of muons for Muon Colliders and Neutrino Factories. 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 and/or a next-generation neutrino beam facility. Fermilab hosts MAP and makes contributions to MAP R&D, supported by KA15 02 03, which include:

- Leadership and coordination
- Developing muon ionization cooling channel concepts and design.
- Developing and testing ionization cooling channel components, including high field solenoid studies.
- Developing and operating the MuCool Test Facility (MTA) at the Fermilab Linac.
- Contributing instrumentation and expertise to the Muon Ionization Colling Experiment (MICE) at RAL.
- Studying Muon Collider lattices, magnets, and magnet shielding.
- Studying IP design, detector shielding and backgrounds.
- Studying the common front-end for a Muon Collider and Neutrino Factory, and contributing to the International Design Study for a Neutrino Factory (IDS-NF).
- Studying how Project X might be upgraded to serve as the proton source for a Neutrino Factory and/or Muon Collider.

Neutrino Factory activities are aimed at:

- Making critical contributions to the International Design Study for a Neutrino Factory.
- Understanding site-specific issues related to implementing the IDS-NF design at the Fermi National Laboratory, using an upgraded Project X to drive the facility.

## Accelerator Development at the Energy and Intensity Frontiers (2/2)

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Muon Collider activities are aimed at studying the critical issues that determine:

- Whether or not this new type of lepton collider is feasible.
- Whether it is likely to be cost-effective.
- What luminosity, and hence physics reach, might be achievable.
- What new technologies are needed, and how to develop them.

Muon Collider and Neutrino Factory R&D is aligned with the following programmatic thrusts:

- Exploring long-term options for Fermilab at the energy frontier.
- Exploring medium- and long-term options for future generations of neutrino experiments at the intensity frontier.

Fermilab's Muon Collider and Neutrino Factory R&D program leverages the substantial resources at the laboratory, in the form of infrastructure (MuCool Test Area, magnet measurement stands, vertical test-stands, cryogenics, etc., etc.), expertise (accelerator design and simulations, component development and testing), and local universities with active interest in accelerator science and technology (IIT, Univ. of Chicago). In addition, the program leverages the many existing collaborative activities that have been fostered within the muon accelerator R&D community, both nationally and internationally.

## Scientific Computing (1/2)

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The Computing Division provides production and analysis computing to the Tevatron experiments (CDF, DØ), CMS, the Fermilab Intensity Frontier programs, the astrophysics program, and theoretical and accelerator modeling activities. The computing facilities are operated within a context of close coordination with the scientific customers. The division operates production farms as part of FermiGrid with over 20,000 batch slots at greater than 75% utilization and above 99% availability.

### Computing for the Energy Frontier

Fermilab has successfully delivered computing resources to the Tevatron experiments to allow raw data reconstruction within one to two months of data taking, to provide data sets for physics analysis in a timely manner, and to permit users to analyze the datasets to meet the physics goals. Analysis users rely heavily on on-site computing resources of the CDF and DØ computing farms as well as opportunistic and shared use of other on-site resources to handle peak demands.

Extensive Monte Carlo simulations containing many 10's or even hundred times more events than the collected data set are required to exploit the Tevatron collider. Both CDF and DØ make extensive use of GRID computing resources all over the world - through the Open Science Grid(OSG), the LHC Computing Grid (LCG), native SamGrid (DØ) or dedicated facilities - to offload a lot of this work.

The CDF FermiGrid farm (5000+ cores) is OSG friendly and offers slots for opportunistic use when not needed by the collaboration. The list of opportunistic users includes other Fermilab experiments such MINOS and MiniBooNE, as well as several outside Virtual Organizations (VOs).

The primary DØ computing farm, known as the Central Analysis Backend (CAB), is mainly used for physics analysis in batch mode, but also includes the DØ data processing farm. The CAB cluster has about 6000 cores and is part of FermiGrid and OSG. DØ data processing has been able to make use of other resources through SAMGrid. About two-thirds of DØ data processing is now done on shared FermiGrid resources.

Access to DØ data is provided by SAM (Sequential Access via Metadata), which was developed by DØ and Fermilab, and is now widely used by Fermilab experiments. The SAM data handling system operates stably, providing reliable access to DØ data. DØ data storage requirements are about 1.6 PB per year.

Over the last year, the CDF data handling system stored 2.0 PB and delivered 25 PB of data to analysis users at CDF. In FY2011, CDF will reprocess much of the data to obtain improvement in Higgs sensitivity. Fermilab is working with the collaboration to allocate the CPU and storage resources to accommodate the reprocessing in a timely manner.

Fermilab has been a driving force in CMS Software and Computing since the preparatory phases of the international project. Fermilab was able to capitalize on the experience of the Tevatron program and applied or evolved solutions for use in the LHC. The dCache storage system, developed jointly by FNAL and DESY, is now used at more than half the LHC Tier-1s; the Frontier system was developed at FNAL for distributing conditions information initially for CDF, and is now utilized by both ATLAS and CMS; and many of the successful concepts utilized by FNAL developers in the design of the CMS framework were initially deployed in Tevatron frameworks.

One of the most visible contributions to the CMS Computing project is the U.S. CMS Tier-1 at FNAL. The US Tier-1 for CMS is the largest single Tier-1 center and consistently at or among the top of the availability and reliability metrics. This processing capacity was very successfully used in 2010 with frequent passes over the data. The accelerator live time has increased, which more uniformly fills the resources. Disk and tape storage capacity are heavily and effectively utilized during LHC operations.

Developers at Fermilab served as architects and implementers of the CMS framework, CMSSW. CMSSW based applications performed extremely well during the first year of data collection. The memory and performance profile of the application were very good and allowed CMS to process the data frequently during the first year. The CMSSW application is driven by advanced workflow tools to ensure the data is consistently processed. Fermilab developers implemented the framework used in the CERN Tier-0, the system that manages CMS prompt offline reconstruction.

## Scientific Computing (2/2)

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Studies and R&D for future facilities at the energy frontier have been on-going. Progress on future lepton colliders requires detailed simulations for both detectors and accelerators. Fermilab is continuing simulation efforts of ILC and Muon Collider accelerator designs and is working with the lepton collider community to develop tools to study Muon Collider detector concepts.

### Computing for the Intensity and Cosmic Frontiers

The experiments and projects in the Intensity Frontier area - including MINOS, MiniBooNE, MINERvA, NOvA, LBNE, MicroBooNE, Mu2e, g-2 and others - are in various stages of preparation, commissioning and official running/data taking and are producing many physics papers and PhD theses. These experiments rely on a broad range of computing development support (e.g. frameworks, databases, data handling), the shared Fermilab General Purpose (GP) farm that is part of FermiGrid for CPU resources, on BlueArc disk and Enstore for data storage and have the General Purpose Computing Facility (GPCF) as a shared resource for interactive analysis computing.

The demands from this part of the program are expected to grow. The shared computing resources have so far been adequate to meet the needs of the experiments. MiniBooNE and MINOS have been in operation for some time. The MINERvA collaboration has been collecting neutrino and anti-neutrino data and has already produced first results (March 2011). The NOvA collaboration recently started to commission the near detector. LBNE and Mu2e have run simulations in the preparation of their Conceptual Design Reports. The high intensity experiments associated with Project X are expected to need more significant computing resources.

The Cosmic Frontier program at Fermilab comprises a number of small and medium sized experiments, of which the largest to date has been the Sloan Digital Sky Survey (SDSS). The computational needs are generally met by a combination of experiment-specific cluster of servers plus shared facilities, including large-scale computational facilities (FermiGrid), disk storage (BlueArc), and tape storage (Enstore). The SDSS produced a 91 TB archive that is currently hosted at Fermilab and is open to the public. The database and web server clusters process over 30000 queries and distribute 1 Terabyte of data per day via network to the public. The upcoming Dark Energy Survey will follow in the footsteps of SDSS and is currently generating of order 10 terabytes of simulated image data per year to test the data processing framework in advance of the start of operations. SuperCDMS is a leading competitor in the search for Cold Dark Matter and will soon be generating data sets on the scale of SDSS; it has switched to using FermiGrid for its data analysis needs.

The Computational Cosmology group at Fermilab has worked closely with scientists at the University of Chicago (the Computational Cosmology (CC) cluster was jointly funded by the two institutions) and has formed a collaboration with the other DOE-HEP labs. The signature Chicagoland code ART (Astrophys.J.Supplement 111, 73, 1997) has been refined is now one of the most powerful in the world. Over the past three years, Fermilab/Chicago scientists have written 56 papers based on calculations and simulations carried out on the CC cluster. Much of this work is designed to understand how to extract information about dark energy from galaxy surveys.

The Fermilab lattice gauge theory computers are a facility that serves the entire US community of lattice gauge theorists. In the last three years, they have produced numerous results vital to U.S. High Energy Physics experimental programs and the field worldwide.

## Appendix: Fermilab Core Capabilities (1/5)

Core capabilities support activities at Fermilab and enable Fermilab to deliver the DOE Office of High Energy Physics mission. Based on the definition given by the DOE's Office of Science, Fermilab has three core capabilities:

- Particle Physics
- Accelerator Science
- Large Scale User Facilities, Advanced Instrumentation, and Computing

Each of these core capabilities is comprised of a combination of experts, facilities and equipment as listed below.

World-Leading Skills	Particle Physics	Accelerator Science	Large Scale User Facilities
Theory	X	X	X
Accelerator Technologies		X	X
Advanced Instrumentation	X	X	X
Simulation	X	X	X
Data Analysis & Distributed Computing	X	X	X
Systems Integration & Operations			X
Project Management			X

### Particle Physics

Skills in support of particle physics at the three interrelated frontiers

Particle Physics: Skill	Energy Frontier	Intensity Frontier	Cosmic Frontier
Theory	QCD, Beyond Standard Model, Monte Carlo Generator	Matter dominated universe, Rare processes, Neutrino mixing	Phenomenology and analysis of Cosmic Frontier experiments
Advanced Instrumentation	Silicon Vertex detectors, 3D ASIC Design	Large Water Cerenkov and Liquid Argon Time Projection Detectors	Cryogenic detector, Bubble chambers, CCD packing, Laser cavities
Simulation	Simulation for lepton and hadron colliders, GEANT4 detector simulation, Lattice QCD	Neutrino simulation Muon simulation	Large scale cosmological simulation
Data Analysis & Distributed Computing	Analysis of large Tevatron and LHC datasets, World-wide collaboration	Understanding low energy nuclear interactions and flux, World-wide collaboration	Management of data intensive cosmic surveys (SDSS, DES, LSST, etc.)

At the Energy Frontier, the CDF and  $D\bar{0}$  experiments provide a vital program in the next few years with physics analysis using the Tevatron collider data taken through FY 2011. Fermilab's accelerator, detector, computing and physics facilities support the ongoing Large Hadron Collider proton-proton collider program in Geneva, Switzerland. Fermilab is the principal U.S. contributor to the LHC accelerator and the CMS detector. Fermilab's Remote Operations Center and LHC Physics Center make the participation of U.S. institutions in the LHC and in CMS more effective. 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.

At the Intensity Frontier, experiments at Fermilab aim to uncover properties of neutrinos, such as their oscillation parameters, mass ordering, matter-antimatter asymmetry, and interactions with matter, and to probe new physics from rare processes in muons, kaons and nuclei. The NuMI neutrino beam, driven by 120 GeV protons from the Main Injector accelerator, is the most powerful in the world, serving the MINERvA detector at Fermilab and the MINOS detector in Soudan, Minnesota. Fermilab is currently upgrading the NuMI neutrino beam and constructing the NOvA detector. NOvA, located near Ash River, Minnesota, is a second-generation neutrino oscillation experiment that will use the upgraded NuMI beams. A third-generation neutrino experiment, the Long Baseline Neutrino Experiment, is being developed by Fermilab in cooperation with the large national LBNE collaboration.

## Appendix: Fermilab Core Capabilities (2/5)

The 8 GeV Proton Booster Ring drives a second beam of neutrinos to the MiniBooNE experiment, and will deliver neutrinos to the planned MicroBooNE experiment based on liquid argon time projection technology. The Booster Ring will also provide beams of muons for two future experiments: Mu2e, a major new experiment that searches for the conversion of muons to electrons, a critical signature for any unified theory of particle physics; and the muon g-2 experiment. Fermilab is also developing a multi-megawatt proton accelerator, *Project X*. This accelerator would provide a neutrino beam for the LBNE and beams of muons, kaons and nuclei for rare-process experiments simultaneously. It will be the most powerful and flexible facility at the Intensity Frontier anywhere in the world.

At the Cosmic Frontier, Fermilab is a critical partner in a number of non-accelerator-based particle astrophysics experiments. Fermilab manages the construction and operation of the Cryogenic Dark Matter Search (CDMS) and the Chicagoland Observatory for Underground Particle Physics (COUPP) that search for particles of dark matter; the Dark Energy Survey (DES) that probe the properties of dark energy; and the Pierre Auger Observatory that studies the source and nature of ultra-high-energy cosmic particles.

Theoretical work in particle physics and particle astrophysics are an essential part of the laboratory. Theoretical physicists 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 the 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.

### Accelerator Science

Skills in support of accelerator science at the frontiers of particle physics

Accelerator Science: Skill	Energy Frontier	Intensity Frontier
Theory	Collider beam dynamics (beam-beam, IBS, etc.)	Instabilities, Loss mitigation
Accelerator Technologies	SC Magnets (Nb <sub>3</sub> Sn, HTS), SC RF ( $\beta=1$ ), RF power	SC RF ( $\beta < 1$ ), Particle sources, RF power
Advanced Instrumentation	Beam diagnostics and feedback	Beam diagnostics and feedback
Simulation	Integrated accelerator simulations (Synergia, Muon Collider), Energy deposition (MARS)	Integrated accelerator simulation (Synergia, Muon Collider), Energy deposition (MARS)
Data Analysis & Distributed Computing	Shot Data Analysis	

Particle accelerators are key resources for DOE’s program of scientific discovery. Fermilab’s accelerator science capabilities—particle accelerator operation, design, development and research—form the foundation of the present and future accelerator-based activities at the laboratory and in the U.S. particle physics community. Fermilab is home to one of the largest accelerator facilities in the world, including a complex of nine accelerators, test accelerators, and infrastructure for the development of accelerator technologies. Nearly half of the laboratory’s staff are directly engaged in accelerator science activities.

Fermilab’s world-leading accelerator R&D efforts focus on the areas of superconducting radio-frequency (SCRF), superconducting-magnet, ionization-cooling, high-intensity proton accelerator and advanced beam manipulation technologies. Fermilab’s unique capabilities in superconducting magnet development are currently focused on upgrades to the LHC and the development of high-field solenoids for the Muon Collider. Fermilab provides U.S. leadership in the development of high-gradient SCRF technology for a future multi-megawatt proton source, known as *Project X*, and for the International Linear Collider, and Fermilab develops integrated design concepts and technologies for *Project X* in support of world-leading long-baseline neutrino and rare-process experiments. Fermilab leads U.S. technology development for ionization cooling required for muon-storage-ring based facilities, supplies integrated design concepts for the Muon Collider and a neutrino factory, and advances fundamental understanding of beams and their manipulation in dedicated test facilities. In addition, Fermilab pursues comprehensive integrated theoretical concepts and simulations of complete future facilities at both the Energy and Intensity Frontiers. These activities, while focused on particle physics, can be applied widely across other fields of science.

## Appendix: Fermilab Core Capabilities (3/5)

Advanced accelerator R&D (AARD) activities, currently centered at the A0 PhotoInjector, will move to the new AARD Users' Facility that will be created in conjunction with Fermilab's new superconducting radio-frequency test facility. These activities include novel beam manipulation techniques, high-performance electron source and diagnostics development, and advanced beam cooling tests, conducted in collaboration with other laboratories and universities.

Activities in accelerator and beam physics include advanced beam studies at the laboratory's operating accelerators in support of optimizing accelerator performance; energy deposition simulations, including the upgrade, maintenance and distribution of the MARS code, a resource to the worldwide community; theory of beam instabilities in current and future accelerator facilities; development of new techniques for compensation of beam-beam effects; experimental studies of ground motion effects in accelerators and electron cloud effects in high-intensity proton beams; as well as theory and experimentation on new collimation and cooling methods.

Fermilab, together with Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, and the SLAC National Accelerator Laboratory, provides joint leadership of the national Muon Accelerator Program. MAP manages the development of future facilities including a neutrino factory at the Intensity Frontier and the Muon Collider at the Energy Frontier. Fermilab is developing design concepts and major subsystem technology simulations and demonstrations for these muon-based facilities. This work also features strong cooperation with companies funded by the DOE's Small Business Innovation Research (SBIR) program.

Fermilab leads the ComPASS (Community Petascale for Accelerator Science and Simulation) collaboration which develops a comprehensive computational infrastructure for accelerator modeling and optimization and advances accelerator computational capabilities from the terascale to the exascale to support DOE priorities for the next decade and beyond. This project is funded by the DOE's Offices of HEP, NP, BES and ASCR.

Fermilab carries out a comprehensive program for training of the next generation of accelerator scientists and engineers. Fermilab hosts the U.S. Particle Accelerator School, a national consortium, which holds two sessions a year for undergraduate and graduate students. The program also includes the Lee Teng Internship in accelerator science and technology for undergraduate students; a Joint University-Fermilab Accelerator Ph.D. program; the Bardeen Fellowship in accelerator engineering for M.S. and Ph.D. students; and the Peoples Fellowship in accelerator science for post-graduates. The new Illinois Accelerator Research Center, to be constructed in 2011 and 2012 with funds from a State of Illinois grant, will significantly enhance the accelerator science education program at Fermilab.

### Large Scale User Facilities, Advanced Instrumentation, and Computing

Skills in support of large-scale user facilities at the frontiers of particle physics

Large Scale User Facilities: Skill	Energy Frontier	Intensity Frontier	Cosmic Frontier
<b>Theory</b>	Lattice QCD national facility	Lattice QCD national facility	Cosmological computing
<b>Accelerator Technologies</b>	NML Accelerator test facility, MuCOOL test area, Muon Collider, ILC	NML Accelerator test facility, NuMI, LBNE, Mu2e, muon g-2, SeaQuest, Project X, Neutrino Factory	
<b>Advanced Instrumentation</b>	Silicon detector facility center	Liquid Argon R&D facility, Extruded scintillator facility	Liquid Argon R&D facility, Silicon detector facility center (DES CCD packaging)
<b>Data Analysis &amp; Distributed Computing</b>	LHC physics center, Open Science Grid, CMS Tier-1 center, Advanced network, Massive data storage	Open Science Grid	Survey data archive
<b>Systems Integration &amp; Operations; Project Management</b>	Tevatron complex, CDF/DØ detectors, LHC remote operation center, Test beam	NuMI & BNB (neutrino beams), Neutrino and muon detectors, Soudan underground laboratory, Test beam and small experiments	Test beam, Soudan underground laboratory, Silicon detector facility center, Pierre Auger

## Appendix: Fermilab Core Capabilities (4/5)

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### *Large Scale User Facilities*

For more than four decades, Fermilab has conceived, planned, designed, constructed, managed and operated large-scale user facilities and hosted international scientific collaborations for particle physics and particle astrophysics. Research at these facilities has led to many discoveries, including the top quark, the bottom quark, the tau neutrino, and the matter-antimatter transition in the  $B_s$  system, and numerous precision measurements. Current user facilities include the Tevatron, the world's highest energy proton-antiproton collider; NuMI, which creates the world's highest-power neutrino beams; the CDF and  $D\bar{0}$  experiments at the Tevatron; and the MINOS, MINERvA, and MiniBooNE neutrino experiments. NOvA, a second-generation long-baseline neutrino experiment, and the Dark Energy Survey, a third-generation dark energy experiment, are currently under construction. Fermilab has established design concepts and begun technology development for the next generation of world-leading particle physics facilities including *Project X*, a multi-megawatt proton facility for Intensity Frontier physics; the International Linear Collider; longer baseline (>1000 km) neutrino beams and detectors, including the Long Baseline Neutrino Experiment; and facilities for the study of rare processes such as the muon-to-electron conversion experiment Mu2e and the muon g-2 experiment. Efforts are underway to establish design concepts for a multi-TeV Muon Collider and a neutrino factory.

### *Advanced Instrumentation*

Fermilab develops cutting-edge particle detector technologies and applies them to the construction of detectors for a variety of scientific disciplines. In the area of semiconductor-based detectors, Fermilab employed dedicated-readout integrated circuits and pioneered the construction of very low-mass silicon detectors for the Tevatron and LHC collider experiments. Fermilab currently pursues three-dimensional vertical integrated silicon technology and silicon-based multi-pixel photon detectors. In the area of cryogenic detectors, Fermilab uses an ultra-cold bolometric detector for dark matter searches and is developing liquid argon technology for neutrino and dark-matter detectors. The laboratory made additional innovative contributions to the development of scintillators and their applications, now used in a wide array of particle physics experiments. Fermilab's test beam facility, operated simultaneously with the collider and neutrino program, is used by the international particle physics community for the development of detector technologies. The laboratory advances the instrumentation of its test beams through the development of picosecond time-of-flight systems and versatile, integrated data acquisition systems.

### *Computing*

Fermilab's computing leadership and resources enable the particle physics community to deliver scientific results at the Energy, Intensity and Cosmic Frontiers. Fermilab has internationally recognized experts in programming languages, high-performance computing and networking, distributed computing infrastructure, petascale scientific data management, physics simulations and scientific visualization. Fermilab supports large-scale computing, data management, and data analysis facilities for the Tevatron program's CDF and  $D\bar{0}$  experiments; the CMS experiment at the LHC and the LHC Physics Center; the Sloan Digital Sky Survey; the Dark Energy Survey; neutrino and rare-process experiments; and computational cosmology.

Fermilab hosts the CMS Tier-1 center, the U.S. Lattice QCD computing project, the campus grid FermiGrid, leads the ComPASS collaboration for accelerator modeling and simulation, and is a leader in the Open Science Grid.

- *CMS Tier-1 Center:* The scientific challenges of particle physics require data storage, networks and processing power on an extreme scale. The CMS experiment uses a distributed computing model, in which seven national Tier-1 centers and more than 40 university- and laboratory-based Tier-2 computing and storage facilities distribute, process, and serve data. Fermilab's CMS Tier-1 center is the most powerful Tier-1 center for the CMS experiment. US CMS scientists make use of the LHC Physics Center's Tier-3 facility for analysis of CMS datasets.
- *Lattice QCD Computing:* Quantum Chromodynamics, describes how quarks and gluons interact via the strong force and predicts the properties of hadrons. Such predictions require the numerical simulation of QCD on a lattice of space-time points, known as Lattice QCD, which uses substantial computing resources. Fermilab builds and operates large clusters of computers for Lattice QCD as part of the national computational infrastructure for the Lattice QCD project established by DOE. Fermilab is also a participant in a DOE SciDAC-2 program devoted to the improvement of software for lattice gauge computing.

## Appendix: Fermilab Core Capabilities (5/5)

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- *FermiGrid*: Grid computing evolved as an extension of distributed computing to satisfy growing computing needs from science, industry, government and commerce. Grid computing involves the distribution of computing resources among geographically separated sites, thus creating a "grid" of computing resources. Fermilab operates a large Grid Computing Facility with shared computing and storage resources provided to the Fermilab experiments for data processing, storage and analysis. The laboratory makes these computing facilities available to other scientific organizations in a secure manner through the Open Science Grid.