Opportunities for Collaboration at Fermilab

Input to the European Strategy for Particle Physics, 2012

Pier Oddone, July 30, 2012

1. Introduction

The purpose of this letter is to describe the major opportunities for collaboration between European institutions and Fermilab over the next two decades. Fermilab is developing a leading program at the intensity frontier, where the currency is not the highest energy but the greatest flux of particles. Fermilab will provide the international particle physics community with the most powerful facilities for the study of neutrinos with accelerators in both long- and short-baseline configurations. Fermilab facilities will give the world's researchers their best opportunity to study the rare processes of kaons and muons that are sensitive to mass scales well beyond the direct reach of the Large Hadron Collider. The large flux of particles available from Fermilab accelerators will also allow the greatest reach in the study of the neutron electric dipole moment, the muon electric dipole moment and the electron dipole moment through the production and measurement of copious amounts of rare isotopes. The intensity frontier program is an important and necessary addition to the world's particle physics program, complementary to and independent of the discoveries made at the LHC.

Fermilab's intensity frontier program includes two major projects that work synergistically: the Long-Baseline Neutrino Experiment (LBNE) that will send a new neutrino beam from Fermilab to Homestake (1300 km baseline); and the Project X accelerator and experimental program that includes megawatt-class beams at several energies. Both projects provide unequaled opportunity for scientific discovery at the intensity frontier. International collaborators would derive the maximum scientific benefit from participation in these projects since a large fraction of the necessary infrastructure will be provided by Fermilab. Multiple additional opportunities exist for collaboration in significant but shorter-term experiments at Fermilab during the development and construction phases of LBNE and Project X.

2. Long-Baseline Neutrino Experiment (LBNE)

LBNE will comprise a new neutrino beam and a massive neutrino detector located 1300 km from Fermilab. Approval of mission need (CD-0) for LBNE was granted in 2010 by the U.S. Department of Energy (DOE). Two detector options, 200 kton of water Cerenkov and 35 kton of liquid argon, were subsequently studied in great detail and a liquid argon (LAr) TPC detector was selected as the favored option (1). A range of baselines was also explored, from the existing 700-800 km available with Fermilab's NuMI beam to as far as 2600 km. A 1300 km baseline was determined to be the ideal distance for resolving the neutrino mass hierarchy and maintaining significant reach for CP violation. This is illustrated in Figure 1 for a LAr TPC detector of 35 kton fiducial mass.

In the spring of 2012, DOE agreed to proceed with LBNE (2) in a phased approach. The DOE investment in the project's first phase is limited to about $800M, including escalation and contingency. The favored option for the first phase of the project that fits within DOE financial guidelines consists of a new beamline from Fermilab to Homestake (1300 km baseline) and a 10 kton fiducial mass LAr TPC detector located on or close to the surface (3). The power of the proton beam in the first phase will be 700 kW, the same as for the NuMI beam to NOνA that will start running in 2013. The first phase of LBNE will determine the mass hierarchy and explore the CP-violating phase δ_{CP}, as well as measure the other oscillation parameters θ_{13}, θ_{23}, and $|\Delta m^2_{32}|$ with unprecedented precision. The physics reach of the first phase for the neutrino mass hierarchy and CP violation is shown in Figure 2. We plan to obtain the next stage of DOE approval (CD-1, approval of the conceptual design, overall cost scale and schedule) for the first phase of LBNE by the end of this year.

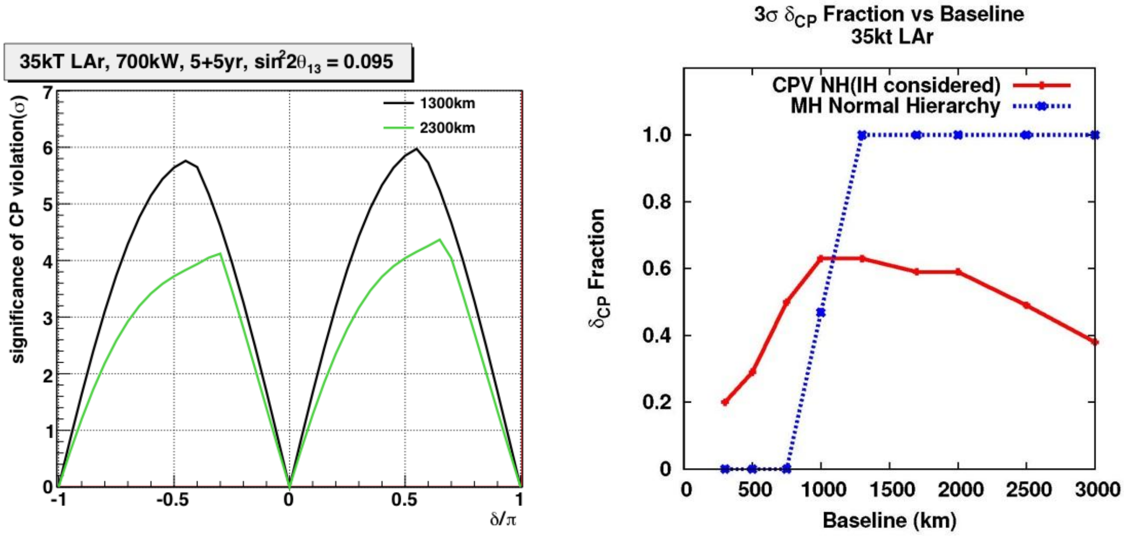

***Figure 1**: Left: comparison of the CP violation sensitivity for a 35 kton (fiducial mass) LAr detector in 5+5 years of neutrino+antineutrino running in a 700 kW beam for baselines of 1300 km and 2300 km assuming $\sin^2 2\theta_{13}$=0.095. Right: fraction of δ_{CP} values covered for a 3σ measurement of the mass hierarchy (blue curve) and CP violation (red curve) as a function of baseline. This shows that the beam from Fermilab to Homestake is optimized for CP measurements and that the experiment can definitively resolve the mass hierarchy. The energy of the first oscillation maximum increases with baseline, so in both plots the beam focusing is adjusted to optimize the spectrum in the oscillation probability.*

Additional national or international collaborators have the opportunity to increase the scope of the first phase of LBNE or accelerate the implementation of subsequent phases. In particular, we seek partnerships with institutions and agencies that would add sufficient additional resources to place the initial 10 kton LAr TPC detector 4850 feet underground. Placing the detector underground from the beginning would greatly enhance the physics program of the project's first phase by enabling the study of proton decay and neutrinos from supernova collapse. Both studies are complementary to those being performed with existing water Cerenkov detectors. For the study of supernova collapse, LAr TPCs are sensitive to neutrinos whereas water Cerenkov detectors are sensitive to antineutrinos; for the study of proton decay, the LAr TPC is much more sensitive to the decay of protons into kaons as preferred by supersymmetric theories (4). There are also a large number of other nucleon decay modes for which liquid argon has high detection efficiency. Detection of even a single event in any of these modes would be revolutionary for particle physics. The additional resources needed to place the detector underground sum to approximately 15% of the cost of the project's first phase.

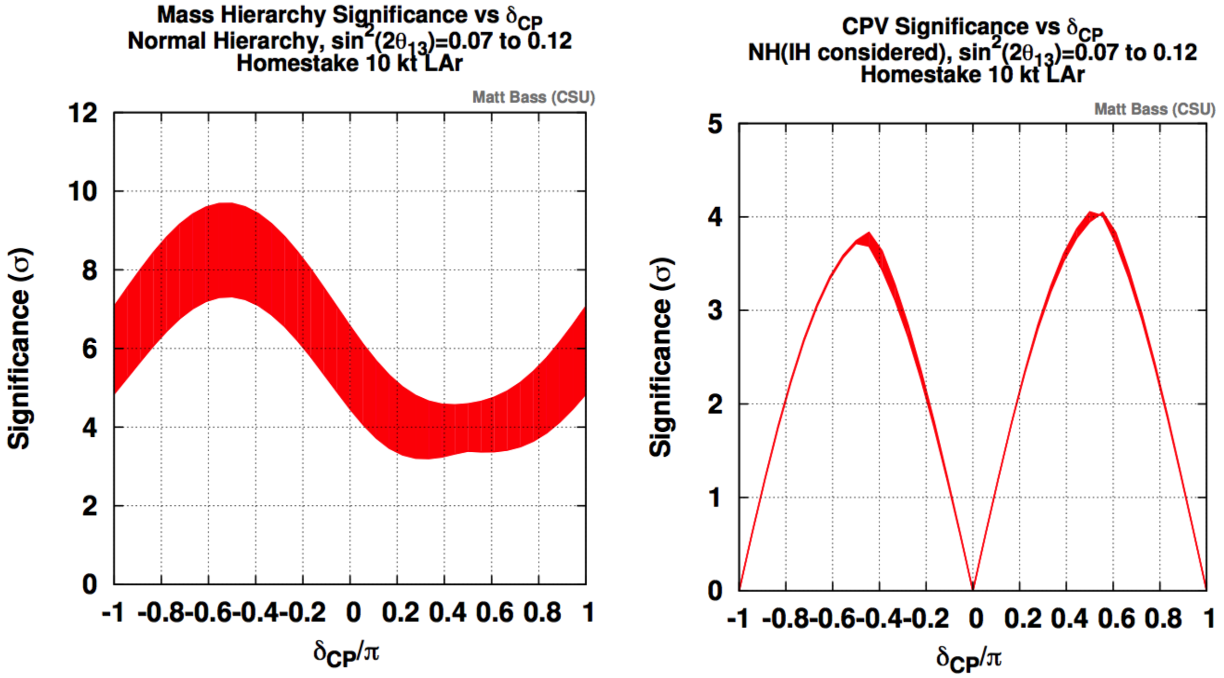

Figure 2*: Significance ($\sigma=\sqrt{\chi^2}$) with which the neutrino mass hierarchy (left) and CP violation (right) can be determined as a function of δ_{CP} for the first phase of LBNE, leveraging the knowledge we will have gained from NOvA and T2K beforehand. Projections are for 5+5 years of 700 kW neutrino+antineutrino running of a 10 kton fiducial mass LAr TPC at Homestake combined with anticipated results from NOvA (3+3 years at 700 kW) and T2K ($5\text{x}10^{21}$ POT or ~6 years). The colored band indicates the change in significance when the assumed value of $\sin^2 2\theta_{13}$ is varied from 0.07 to 0.12, corresponding to roughly a ±2σ variation in $\sin^2 2\theta_{13}$ based on the latest results presented by Daya Bay at Neutrino 2012.*

The 10 kton LAr TPC detector and 700kW beam represents only the first phase of a long-term program. LBNE's capabilities will progressively expand in both detector mass and beam power. Subsequent phases will include:

- A highly capable near neutrino detector, which would reduce systematic errors on the oscillation measurements and enable a broad program of short-baseline neutrino physics.
- An increase in far detector mass from 10 to 35 kton fiducial mass placed at the 4850 ft (4300m water equivalent) level at Homestake.
- A staged increase in beam power from 700 kW to 2.3 MW with the development of a new proton source at Fermilab, Project X (5).

The 35 kton LAr TPC detector at the 4850 ft level at Homestake will further improve the precision of the primary long-baseline oscillation measurements and open or enhance the program in non-accelerator-based physics, including searches for baryon-number-violating processes and measurements of supernova neutrinos. The reach for both mass hierarchy and CP violation for the 35 kton detector using the initial beam of 700 kW from Fermilab's Main Injector is shown in Figure 3. This stage exceeds the requirement for determining the mass hierarchy. Its main purposes are to give greater reach for the study of CP violation and to determine whether the three-neutrino oscillation physics that we assume in our theories is the complete and correct description. As can be seen in Figure 4, the clear bimodal structure in the measured disappearance channel spectrum will provide an extraordinary verification of the three-flavor oscillation hypothesis.

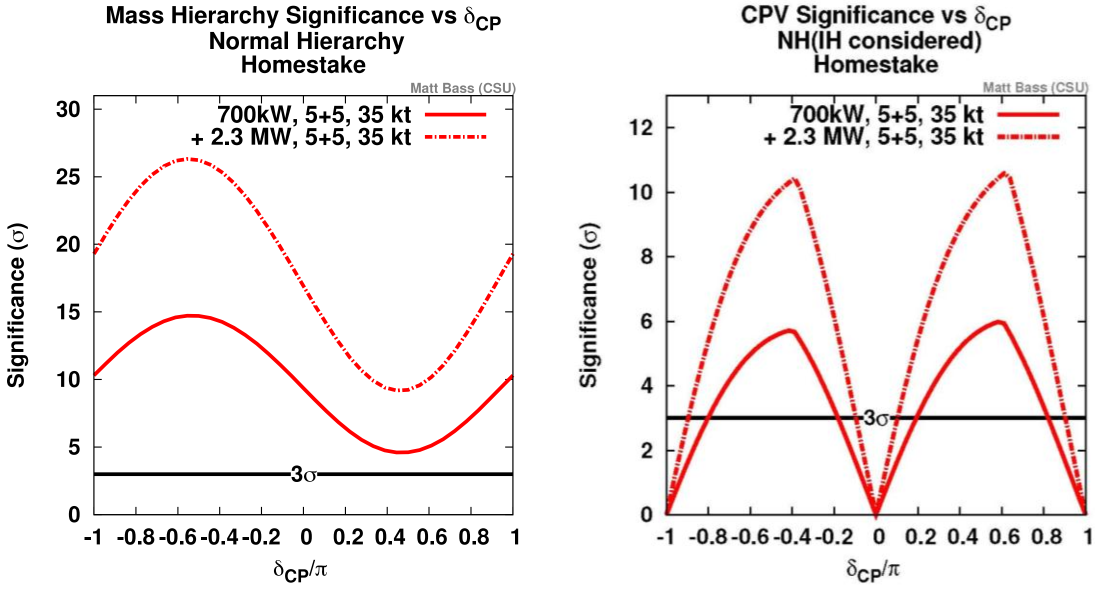

Figure 3*: Mass hierarchy and CP violation reach in LBNE for a 35 kton (fiducial mass) detector running for 5+5 years of neutrino+antineutrino running in the standard 700 kW LBNE beam (solid curves) and with the addition of 5+5 years of running with a 2.3 MW beam upgrade made possible with Project X (dashed curves). Both plots assume a* $\sin^2 2\theta_{13}$ *value of 0.095.*

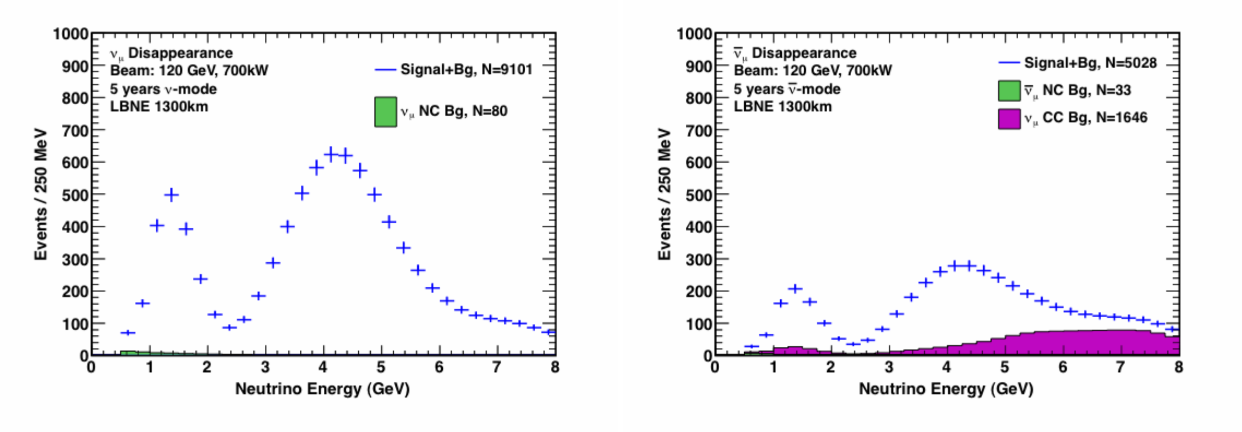

Figure 4: *The expected spectra for oscillated* ν_μ *events in neutrino mode (left) and anti-*ν_μ *events in antineutrino mode (right) for a 34 kton LAr TPC at 1300 km in 5 years of running in a 700 kW beam assuming normal mass ordering,* $\Delta m^2_{32}=2.35\times10^{-3}$ eV^2*, and* $\sin^2 2\theta_{23}=0.1$*. Backgrounds from neutral current events (NC) in both modes and neutrino contamination or wrong-sign neutrino events (CC) in antineutrino mode are also shown. The bimodal oscillation pattern is clearly visible at these large distances.*

The final phase of LBNE could be the addition of Project X (5), which would increase the power of the proton beam for the Fermilab-to-Homestake neutrino beam by a factor of three. A vigorous international R&D effort on Project X is already underway as described later in this letter. LBNE's full reach for CP violation with Project X is the 2.3 MW curve in Figure 3. In addition to measuring CP violation in the neutrino sector, this final phase of LBNE will also provide a very precise measurement of the CP violating phase, δ_{CP}, with a resolution approaching the sub-10^0 level.

3. Neutrino opportunities on the way to LBNE

A suite of four Fermilab neutrino experiments that will operate in the next decade offer important scientific opportunities before the construction of the first phase of LBNE is complete. All four already include European collaborators, and additional collaboration would be welcome. The experiments are fed by two neutrino beams that run simultaneously: the high-energy Main Injector (NuMI) beam to Minnesota and the low-energy Booster beam.

NOνA (810 km baseline)

The NOνA project (6) includes a new 15 kton liquid-scintillator far detector a near detector, and an upgrade of Fermilab's Main Injector accelerator complex to 700 kW of available beam power. NOνA's 15 kton totally active tracking neutrino detector uses 368,000 16 m long PVC tubes filled with liquid scintillator and read-out through wave-shifting fibers and APDs. The upgraded Main Injector complex will provide double the beam power used to date in the Fermilab neutrino program. Because NOνA is placed 15 milliradians off-axis in the NuMI beam, the energy spectrum is narrow and centered around 2 GeV, minimizing backgrounds. NOνA will study the mass hierarchy with significant reach for roughly half of all possible CP phase values, measure neutrino and anti-neutrino mixing angles and mass differences in both appearance and disappearance modes, and may provide some early glimpses of CP violation. It will be the first experiment to explore the matter effect. The experiment will start operating in 2013 with a partially completed far detector. The full detector will be completed in 2014.

MINOS+ (735 km baseline)

MINOS+ (7) is the continuation of the successful MINOS detector with a different and more intense beam. Using its 5 kton magnetized iron calorimeter, MINOS has already provided the best measurement of the mass difference $|\Delta m^2_{32}|$, measured the oscillation parameters of neutrinos and antineutrinos, and provided early information on electron appearance. MINOS+ will run in the NOνA era with the same detector and a different configuration of the focusing horns that will greatly increase the flux of neutrinos on-axis at higher energies, centered around 3.5 GeV. The increased flux and consequently greater statistical significance will allow MINOS+ to study anomalous interactions of neutrinos and be sensitive to new physics models such as extra dimensions.

MicroBooNE (short baseline)

MicroBooNE (8) is a second-generation LAr TPC detector, currently under construction, that will use Fermilab's Booster neutrino beam and run simultaneously with NOνA. It aims at resolving the nature of the low-energy neutrino excess observed by MiniBooNE, which may be a hint of the possible existence of sterile neutrinos. MicroBooNE will also provide important measurements of neutrino interactions on argon. It is a platform to further develop LAr TPC technology with an eye towards the 10+ kton scale detectors that will be necessary for LBNE.

MINERνA (short baseline)

MINERνA (9) is a fine-grain calorimeter that studies neutrino cross sections for different nuclei. It uses the MINOS near detector as a muon spectrometer. Beyond the great utility of measuring cross sections and topologies to aid the long-baseline experiments, MINERνA studies nuclear structure functions relevant to nuclear structure and the behavior of nucleons in the nucleus.

4. Opportunities for additional neutrino experiments

Because neutrino beams are not exhausted by any one set of experiments, multiple neutrino experiments are possible in any given beamline. In particular, there are several proposals to extend Fermilab's short-baseline neutrino program using the Booster beam. LAr1 (10), a proposed 1 kton liquid argon experiment, would study the neutrino anomalies suggested by LSND and MiniBooNE with two liquid argon TPC detectors at different (short) baselines, with the farther detector much larger than the MicroBooNE detector currently under construction.

Another proposed experiment, nuSTORM (11), represents a more powerful approach to study these short-baseline neutrino anomalies and capable of measuring ν_e and anti-ν_e cross sections. It would use a muon storage ring on the Fermilab site to produce well-characterized short-baseline neutrino beams. The initial version using the existing Main Injector beam to generate muons would definitively resolve the observed short-baseline anomalies while providing cross sections that would be otherwise impossible to measure with any precision. The addition of a cooling channel prior to injection of protons into the storage ring would further enhance the power of this short-baseline program and would support the development of an eventual neutrino factory or muon collider.

The physics reach of both experiments would be greatly enhanced in the long term from the much greater fluxes provided by Project X. These experiments are only in the proposal stage and would benefit from strong international participation.

5. Non-neutrino intensity frontier physics program

Fermilab's intensity frontier physics program includes experiments to study rare processes involving muons and karons and to measure fundamental parameters such as g-2 and electric dipole moments, in addition to the substantial neutrino physics program. The next generation of these experiments requires high-intensity proton sources capable of delivering continuous beams to several experiments (12). Fermilab's present accelerator complex is quite capable, including the Main Injector's 120 GeV, 700 kW proton beam with slow and fast extraction, an 8 GeV Booster beam used for injection into the Main Injector and to deliver additional beams at 8 GeV, and various additional rings that allow for the configuration of specially tailored beams.

In the long term, however, a new proton source will be needed that can deliver megawatt beams at several energies. Project X is such a source. It will extend detailed studies of neutrinos with LBNE by multiplying the 120 GeV beam intensity by a factor of three; enable more powerful short-baseline neutrino experiments by multiplying the power at 8 GeV several-fold as needed; and promote the study of the rarest processes involving muons and kaons with the most intense 3 GeV continuous-wave beam in the world delivering 3 MW. This 3 GeV beam can be split cleanly to serve different experiments in simultaneous operation at megawatt intensities with specifically tailored time structures. Project X will also produce ultra-cold neutrons and rare isotopes that provide unprecedented sensitivity for next-generation searches for neutron, nuclear and electron dipole moments.

Short- and long-term experiments to study rare processes and measure fundamental parameters include:

Muon physics

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

The anomalous magnetic moment of the muon, g-2, measured by the E821 experiment at Brookhaven National Laboratory with a precision of 0.54 parts per million, remains discrepant with the Standard Model and is a possible indication of new physics. A new Muon g-2 (13) experiment at Fermilab, which will reuse the Brookhaven muon storage ring and the former Fermilab antiproton source, will achieve a fourfold improvement in precision in this decade. Combined with improved theoretical analysis, the new g-2 measurement will provide an important constraint on new physics phenomena.

The observation of an electric dipole moment for any elementary particle would constitute a major discovery of a new source of CP violation. The current 95% CL muon EDM limit is 10^{-19}. The Muon g-2 experiment will search for a muon EDM with a sensitivity 100 times better than current experiments. A next-generation experiment with Project X could further improve the sensitivity by another three orders of magnitude using the frozen-spin technique proposed at JPARC in 2003 (14) and and studied for PSI in 2010 (15).

Rare decays of muons, if observed, could be harbingers of new physics phenomena. Starting late this decade, the Mu2e (16) experiment will search for one such rare-decay process, the conversion of a muon to an electron in the field of a nucleus.

Many theories that include new physics predict this charged lepton flavor violating process to occur at rates that could be within reach of Mu2e. Such studies provide sensitivity to mass scales of new physics phenomena that may lie at thousands of TeV for certain scenarios, significantly beyond the reach of the LHC. Mu2e will use the 8 GeV proton beam from the Fermilab Booster and the beamline from the former antiproton source to search for the muon-to-electron conversion process with sensitivity at the 10^{-16} to 10^{-17} level, 1,000 to 10,000 times better than previous experiments. Project X would increase the beam power to the experiment by more than a factor of 10, further improving the sensitivity to the 10^{-19} level if the first phase of the Mu2e experiment does not discover charged lepton flavor violation (17). If a discovery is made in the first phase, a Project X-era experiment would offer the unique capability of distinguishing the underlying new physics by measuring the muon-to-electron conversion rate using a variety of nuclear targets.

Kaon physics

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

The rare kaon decay processes $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ provide an opportunity to test the Standard Model with high precision or discover new physics, since both modes are extremely suppressed in the Standard Model (18). The decay $K_L \to \pi^0 \nu\bar{\nu}$ is a purely CP-violating process, with a hadronic matrix element that is known theoretically at the one percent level of precision. The observation and precise measurement of this rare process will constitute a major triumph in kaon physics.

Fully exploiting the opportunities of kaon physics requires experiments capable of detecting about 1000 decays in each mode, thus achieving a statistical error that approaches the theoretical uncertainty. The high-intensity proton beam of Project X would readily enable experiments at the 1000-event level. The continuous-wave linac technology proposed for Project X would provide ideal conditions for these experiments, which would yield simplifications of the experimental apparatus and reduced technical risks. Both neutral and charged kaon-decay measurements would reach precisions of a few percent, comparable to the uncertainty on the Standard Model prediction, thus offering greatly increased sensitivity for new physics phenomena in these processes. The neutral decay mode is the most challenging and Project X is ideally suited to measure it precisely (19). Kaon experiments at Project X would also be sensitive to a variety of other rare decays involving possible exotic final states.

A program leading to precision measurements can begin at Fermilab with the ORKA (20) experiment using beams from the Main Injector. The ORKA experiment is based on the pioneering program developed at Brookhaven National Laboratory that discovered the $K^+ \to \pi^+ \nu\bar{\nu}$ process, and these techniques scale well to Project X beams and intensities. The ORKA experiment has received scientific approval from Fermilab and is now building an international collaboration to pursue a precision measurement of $K^+ \to \pi^+ \nu\bar{\nu}$.

Search for new physics with heavy nuclei

Project X can be used to produce large quantities of heavy short-lived nuclei, such as radon, radium, americium and francium, which offer significantly amplified sensitivity to the electron and nuclear EDMs (21) that are deeply incisive probes of CP violation and physics beyond the Standard Model. The current 90% CL limit on the electron EDM of 10^{-27} e-cm already rules out generic models of supersymmetry. Project X-era experiments using heavy nuclei and a combination of nuclear shape and relativistic enhancements could approach limits of 10^{-31} e-cm, or discover a new type of CP violation in the strong interaction. The target station of a facility to produce heavy nuclei with Project X could also include an ultra-cold neutron capability, the development of isotope-production techniques for beta-beams, biological studies with radiotherapeutic (alpha-emitting) isotopes, and materials-science studies with implanted radioisotopes.

Nuclear energy/nuclear materials applications of Project X

In addition to its broad program in fundamental science, Project X could support R&D towards the destruction of spent fuel from conventional nuclear reactors, and the development of accelerator-driven subcritical systems for safe and abundant nuclear energy production (22). The issue of high radio-toxicity and the long lifetime of conventional spent nuclear fuel is a global challenge. Accelerator-driven systems can be used to transmute spent nuclear fuel, significantly reducing the lifetime and toxicity of nuclear waste. Accelerators can also drive fission reactors that incorporate advanced fuels, such as those based on thorium. This has advantages over conventional reactor fuels, including a fuel supply that can meet global demand for 100 to 1000 times longer; less long-lived nuclear waste; reduced possibility of nuclear weapons production; and relatively safer operation. Fermilab will not establish a full-scale accelerator-driven nuclear reactor development program, but key elements for the future of accelerator-driven nuclear energy can be studied and developed with Project X.

6. Project X accelerator complex

Project X (5) will be unique in the world in its ability to deliver high-power proton beams with flexible beam formats to multiple users. A Project X reference design (23) has been developed based on a 3 GeV continuous-wave superconducting linac operating at an average current of 1 mA followed by a 3–8 GeV pulsed linac operating with a duty factor of 4%. These facilities are further augmented by upgrades to the Main Injector/Recycler complex to support higher-power operations. A total of 5 MW of beam power will be available at Project X: 2.9 MW at 3 GeV; initially up to 200 kW at 8 GeV, extendable as needed; and 2.3 MW at 60–120 GeV.

Project X is currently in the pre-conceptual design and development stage and an R&D program targeting the critical technical issues is underway in international collaboration with 14 universities and laboratories. While no project schedule has yet been agreed upon with DOE, Project X could be ready to begin construction late in this decade.

Operating scenarios

The Project X continuous-wave linac primarily supports a program of precision experiments with muons, kaons and nuclei at 3 GeV. Key to the success of this program is the delivery of different bunch patterns to three experiments simultaneously. This is achieved by the coordinated utilization of a wideband chopper (24) at the linac front end and a transverse deflecting RF separator at the exit. The power available to the 3 GeV experimental program is 2.9 MW when 4% of the CW linac beam is diverted to the pulsed linac.

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

GeV experimental program when the Main Injector is operating at 120 GeV, and 50 kW available at 60 GeV. This power could be increased if needed.

Neutrino factories and muon colliders

We are developing Project X to eventually serve as the front end of a neutrino factory or a muon collider. This requires designing a path where the intensity of the delivered beam is increased in later phases to 4 MW at 8 GeV, and the required pulse structure for either a neutrino factory or a muon collider is achieved by reformatting the pulsed linac beam with low-energy storage rings (25) (26).

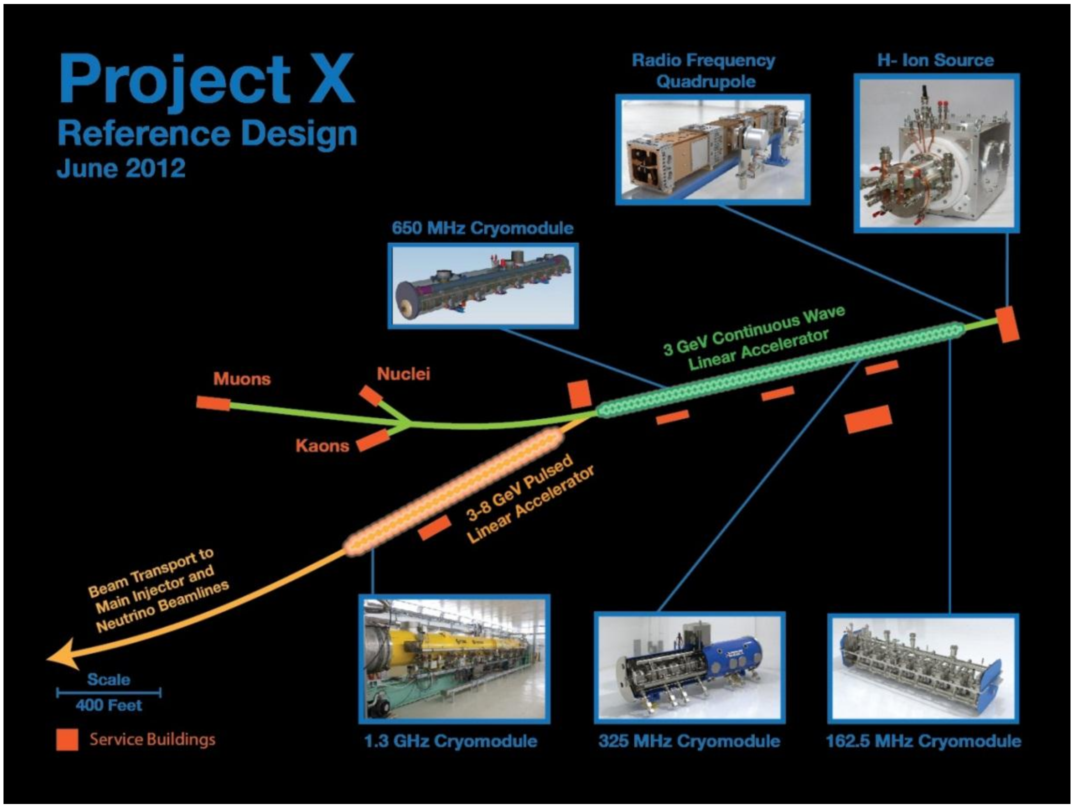

***Figure 5**: The Project X reference design with associated technologies indicated. The 3 GeV CW linac delivers 2.9 MW of beam power to the experimental facilities labeled Kaons, Muons, and Nuclei. Approximately 4% to the total beam power delivered by the 3 GeV linac is diverted into the pulsed linac for delivery to the Main Injector. This beam is sufficient to support 2.3 MW of beam power to a long-baseline neutrino experiment at 60-120 GeV, simultaneous with the delivery of 2.9 MW to the 3 GeV experimental program.*

7. Summary

There is a long history of collaboration between European institutions and U.S. laboratories, both in facilities sited in Europe and in the United States. Europe has made major contributions and participated in discoveries with DZero, CDF and BaBar among others. The United States has made major investments in the H1, ZEUS, ALEPH, L3, OPAL, ATLAS and CMS experiments, among others, and in the

LHC accelerator, and scientists from U.S. institutions have participated in many discoveries. As we move forward in a global program that requires large-scale facilities, collaboration among nations will be ever more important. The United States is planning to continue its major investment in the LHC with contributions to the upgrades of both the LHC accelerator and its detectors. The LHC will remain the focus of the global program at the energy frontier for at least the next two decades. At the intensity frontier, there are now opportunities for European institutions interested in the study of neutrinos and rare processes to engage in collaboration with U.S. institutions using facilities sited at Fermilab. The two projects that, due to their scale, would most strongly benefit from—and provide benefits to—international collaborators are LBNE and Project X. Both can be structured in phases with valuable physics achieved in each phase and ultimately provide opportunities for discovery that are unique in the world.

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