Neutrino Beamline

1 Abstract

Project X, through its proposed high-intensity proton accelerator complex, could open up a new spectrum of opportunities in neutrino physics. The discovery of neutrino oscillations was the first experimentally observed phenomenon that departed from the very successful Standard Model of Particle Physics. This discovery strongly suggests a connection between neutrino physics and physics on a very high mass scale and identifies a number of key questions requiring further investigation. Project X is being designed to help explore these key questions, and in doing so, would open a path to new discovery in neutrino science.

Project X will provide an upgraded beam power for the Long-Baseline Neutrino Experiment (LBNE) neutrino beamline, which will send neutrinos 1,300 km from Fermilab to the Deep Underground Science and Engineering Laboratory (DUSEL) in Lead, South Dakota. LBNE is being designed to initially operate at 700 kW and to accommodate a beam power upgrade from 700 kW to 2.2 MW in the Project X era. LBNE's principal goal is to study accelerator-generated long-baseline neutrino oscillations - determining the neutrino mass hierarchy and searching for CP violation in the neutrino sector. Both of these scientific goals require that the value of the third neutrino mixing angle, θ_{13} be non-zero and in fact such that $\sin^2 2\theta_{13}$ is on the order of 0.01 or greater. If θ_{13} has not been determined to be of this order prior to the start of LBNE, LBNE has sensitivity to measure $\sin^2 2\theta_{13}$ to well below 0.01. With the upgraded beam power provided by Project X, the ultimate LBNE accelerator based science reach can be achieved with much higher precision.

Neutrino beamlines, by their very nature, allow multiple experiments to operate in the same beamline without interfering with each other. Thus, in addition to the LBNE's long-baseline oscillation experiment, the unprecedented high power of Project X would make possible a variety of other physics experiments located relatively close to the LBNE production target.

2 Introduction

The Project X accelerator complex has the capability to provide a proton source to generate a diverse range of neutrino beams, either from the first stage 2-3 GeV Cockroft-Walton (CW) linac, an intermediate 8 GeV stage, or from the downstream high-energy (60-120 GeV) Main Injector protons. Furthermore, because neutrinos interact so weakly, several experiments can be located in the same beamline without interfering with each other. The number of new experiments is only limited by space constraints in the detector halls.

As currently envisioned the LBNE far detector complex at DUSEL will be at the heart of a world class underground facility which will provide the opportunity to carry out a broad physics program ranging from neutrino oscillations to searches for dark matter and nucleon decay. LBNE, as currently configured with 700 kW, will be the most intense high energy neutrino beam in the world, With upgraded beam power from Project X it will remain the premier facility for neutrino science. This beam, coupled with LBNE's massive far detectors (water Cherenkov and/or liquid argon) at DUSEL would allow for the most precise studies of the frontier questions in neutrino physics. The most important areas of study involve the questions of mass hierarchy in the neutrino sector and the possibility of CP violation in neutrino interactions. Without a doubt, LBNE upgraded with Project X capabilities would become the flagship intensity frontier experiment at FNAL.

In addition to this flagship neutrino oscillation experiment, many new high-statistics precision neutrino experiments would become possible by placing detectors relatively close (~ a few hundred meters) to the LBNE target at Fermilab. Thus, in addition to generating a more powerful beam for the incisive study of neutrino oscillations, Project X would also provide opportunities for new experiments with new detectors. Some of these experiments could be based on the LBNE near detector(s) constructed as part of the LBNE Project. However, one could also envision other experiments with special purpose detectors, designed especially to optimize studies of specific issues. For example, experiments could be designed to study neutrino elastic scattering, providing information on $\sin^2\theta_W$ and the neutrino anomalous magnetic moment; measure the total and partial cross sections; and to search for other weakly interacting particles. Furthermore, if the question of the low energy anomalies in neutrino spectra seen in LSND/MiniBooNE experiments have still not been resolved by this time, much more precise experiments could be constructed either in the LBNE beamline or in other beamlines fed by the 2-3 GeV linac.

The neutrino physics sector is currently not nearly as well understood as is the quark sector, where a variety of different experiments address similar questions in a complementary way. LBNE and Project X would provide the opportunity to search for new physics beyond the Standard Model and expand knowledge of the neutrino sector. Possible theoretical scenarios include non-unitarity in the lepton mixing matrix (induced, for example, by the mixing of active and sterile neutrinos), non-standard interactions of neutrinos with other particles, and more exotic scenarios like CPT and Lorentz violation. Some of these effects are most easily studied in near detectors, while others require a far detector. In general, high statistics, a broad energy spectrum and low backgrounds are essential to search for new physics in the neutrino sector, and

LBNE and Project X meet these requirements. Simulations show that the high statistics data has the potential to improve current bounds on some nonstandard effects in the neutrino sector by up to an order of magnitude. Some models show that discovery of new physics could be possible. In addition, aside from neutrino experiments, the proposed near and far detectors can also be used to search for long-lived, weakly interacting hidden sector particles produced in the LBNE target, as predicted in some recent dark matter models.

3 The LBNE Neutrino Beamline in the Project X Era

The LBNE beamline facility will be constructed by the LBNE Project, and is assumed to exist and be operational at the start of Project X. LBNE will have 700kW beam power, using the accelerator complex provided by the Acclerator-NuMI Upgrade (ANU) of the NOvA Project.

The Project X baseline design, including a linac or rapid cycling synchrotron (RCS) to link the first stage linac with the Main Injector and a new 53-MHz RF system in Main Injector (amongst other upgrades) presents the same beam structure to the neutrino beamline as the ANU-era complex. From the point of view of the neutrino beamline, Project X represents an intensity upgrade to 2.2 MW, and the matters of concern are the challenges associated with this increased intensity.

Project X presents LBNE with the opportunity to choose to run at a lower beam energy (down to 60 GeV) without sacrificing beam power. The ANU-era Main Injector extraction kicker system will work with little or no modification anywhere in this energy range. The current design for the LBNE beamline has an acceptance of 360 π-mm-mr (normalized) and $dp/p = 2.8 \times 10^{-3}$ at 60 GeV (and somewhat larger acceptance at 120 GeV). The beam delivered from Main Injector is required to be 100% contained within these limits. The bunch length is not important, and the momentum spread is of interest only in so far as it is small enough to avoid losses in the beamline.

The pulse rate does not increase in the transition from NOvA/ANU to Project X, so there are no additional constraints on beamline devices beyond those present in the LBNE design.

There are beamline instrumentation issues that will need to be addressed for 2.2-MW operation (for example, titanium multiwire or segmented foil profile monitors are suitable for use in the beamline at 700 kW, but would be destroyed in the 2-MW beam). An AD instrumentation R&D program to produce a suitable beam profile monitor exists. The proton beamline is not expected to become significantly radioactive over its lifetime, so there are no special challenges associated with upgrading or replacing equipment.

The components of the LBNE primary beamline elements are designed to take a proton beam extracted from the Fermilab Main Injector and transport it to a target area, where a neutrino beam is generated and aimed toward the far detectors. After the neutrino beam is generated, residual particles produced in the target along with their decay products must be absorbed at the end of the decay region to prevent them from entering the surrounding rock and inducing radioactivity. A conceptual design of the neutrino beam facility is shown in Figure 1. While the technical components of the LBNE facility are designed for operation at 700 kW, all aspects of the facility involving civil construction are being designed to accommodate the shielding and components that would be needed for operation at Project X beam power of up to 2.2 MW.

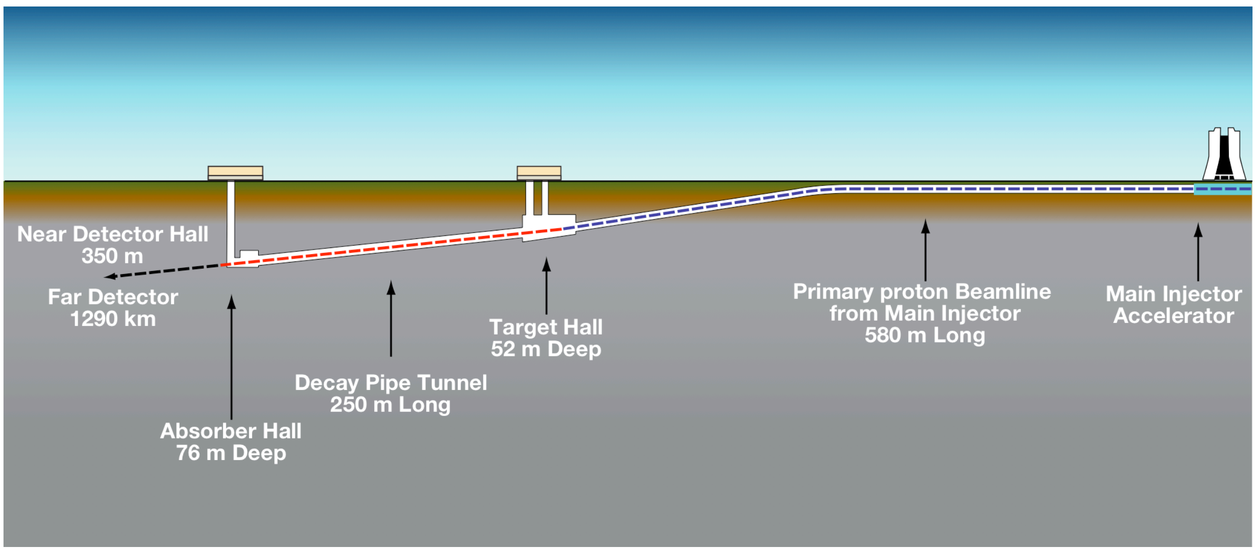

Figure 1: Schematic view of LBNE beamline

The primary beam (blue dashed line) transports protons from the Main Injector to a targeting station. The neutrino beam (red dashed line) is defined as the secondary beam from the target to the end of the Absorber Hall.

The primary proton beam is extracted from the Main Injector at the same location where the beam is extracted for the presently active NuMI beam to MINOS. This established extraction area will also be used for the neutrino beam for the NOvA experiment. A short distance downstream from the Main Injector extraction enclosure, the LBNE primary proton beam will be redirected along a different trajectory appropriate for guiding the beam to the LBNE target. The NuMI beam follows a roughly northwest direction, while the LBNE beam must be directed to the west from the Fermilab site. The conceptual design for LBNE allows both beamlines to operate together, using magnets to switch the beams without having to move components or realign them. This feature is not required for LBNE alone, but is appropriate for LBNE beamline commissioning if the NOvA experiment is still active.

The LBNE primary beam uses only conventional magnets with an optics design based on the Main Injector. The magnets are designed to transport the beam to the target with very low losses and an energy range of 60 to 120 GeV. Although the NuMI (and NOvA) beam operates at 120 GeV, the lower energy of 60 GeV may be preferred in some scenarios. Using a long series of dipole and quadrupole magnets, the primary proton beam is guided in the desired direction and brought to a focus at the target. To reach the far detectors, the generated neutrino beam must be aimed downward into the earth at an angle of approximately 5.6 degrees, or 10% slope relative to the surface.

The target marks the transition from the intense, narrowly directed primary proton beam to a more diffuse beam of particles that decay to produce the neutrino beam. The interaction of a single proton in the target creates, on average, four charged particles consisting mostly of pions with few percent kaons. These secondary particles are short-lived and decay. Upon their decay, each particle generates a neutrino, which does not decay, and a muon, which penetrates deep into the surrounding rock. The neutrinos must be optimized for direction and energy to be useful for the physics at the far detector.

Although the direction of the neutrinos themselves cannot be directly controlled, the pions and kaons can be collected from the target before they decay into neutrinos and directed toward the far detectors using specialized magnets. These magnets are called “horns” because of the shape of their conductors. The focus provided by the horns maximizes the number of pions and kaons that can emit a neutrino in the direction of the far detectors. After collection and focusing, the pions and kaons need a long, unobstructed volume in which they can decay. This decay volume in LBNE reference design is a circular cross-section pipe, its diameter and length being optimized for production of neutrinos in the energy range of interest and with its axis pointing toward the far detectors. The pipe will be filled with air or helium at atmospheric pressure.

About 15% of the primary protons leave the target without interacting. These protons, along with the non-decayed pions and kaons, must be absorbed to prevent them from entering the surrounding rock of the excavation and inducing radioactivity. This is accomplished with a specially designed aluminum and steel pile, which transforms the beam’s kinetic energy into heat, thus protecting the rock from beam-activated nuclides. The absorber occupies an excavated enclosure at the end of the decay pipe.

4 The LBNE Near Detectors in the Project X Era

The LBNE near detectors are going through the conceptual design phase, and many parameters for the detectors will be optimized to obtain the best scientific performance. The near detectors will need to be able to make measurements relevant to the candidate target material selected for the LBNE far detectors, thus both a water target fine-grained tracker and a liquid argon Time Projection Chamber (LAr TPC) are being developed. Designs being considered for the water fine-grained tracker are a scintillating tracker, like MINERvA, and a straw-tube tracker with transition radiation detectors. There are also two options for the LAr TPC for the near detectors – reconfiguring the MicroBooNE detector or building a smaller magnetized LAr TPC. To measure the flux, Michel decay detectors could be used, with the option of being placed in the alcoves or in the absorber. A threshold Cherenkov counter may also be necessary for measuring the post-absorber muon flux in terms of the absolute muon rate and the muon energy spectrum.

The preferred design for the LBNE near detectors has not yet been chosen. If a simple base design is chosen, however, one option would be to upgrade the LBNE near detectors as part of Project X so they have a higher resolution and can make measurements even more precisely.

5 The LBNE Far Detectors in the Project X Era

The LBNE Project is developing conceptual designs for two different technologies for the far detector – water Cherenkov (multi-purpose) and liquid argon (high-resolution). The LBNE Mission Need indicates that the Project should develop a conceptual design that accommodates two far detector modules with physics capability equivalent to that of two 100-kT water Cherenkov detectors. Hence there are three alternatives for the far detector configuration: two modules of water Cherenkov, two modules of liquid argon or one of each. The reference design for the LBNE Conceptual Design Report is likely to be one water Cherenkov module and one liquid argon module.

While large water Cherenkov detectors were originally proposed for proton decay searches, they have been constructed and demonstrated to be a cost-effective detector for neutrinos as well. The Super-Kamiokande detector in Japan is a 50-kT total volume detector that has provided definitive measurements of solar and atmospheric neutrino parameters. It is currently the far detector for the JPARC neutrino beam program in pursuit of the measurement of the θ_{13} mixing angle. Scaling the total mass of a water detector by a factor of two or three, though challenging, is deemed technically feasible.

A Liquid Argon Time Projection Chamber (LArTPC) is a promising technology under development for future beam-based neutrino research. This technology offers precise event reconstruction and particle identification, as well as potential scalability to large detectors. Preliminary analyses have indicated that liquid argon detectors perform with higher efficiency and better background rejection than water Cherenkov detectors. It has been suggested that a 50-kT liquid argon detector would have similar performance to a 300-kT water Cherenkov detector. If this is accurate, one could use smaller liquid argon detectors to achieve similar results as larger water Cherenkov detectors. Smaller detectors would require less excavated volume, potentially resulting in significant cost-savings for the civil construction. LAr TPC development has been endorsed as an important component of the long-baseline neutrino program. However, additional work is required to demonstrate the performance and cost ratios between the two technologies.

The LBNE Project will develop conceptual designs, cost estimates and construction schedules for both water Cherenkov and liquid argon detectors. For both technologies, it is assumed that the desired detector mass required to achieve the science goals of the experiment will need to be reached by modular construction, and a reference detector module has been specified for each. For water Cherenkov, the reference detector has a fiducial mass of 100 kT, which corresponds to a detector module with a total mass of about 140 kT. Water Cherenkov detector modules will be sited at the 4,850-ft level of the mine. For liquid argon, the reference detector will have a fiducial mass of about 17 kT, which corresponds to a total mass of about 20 kT. For liquid argon, a site at a depth is 800 ft below the surface is being designed.

Although the ultimate configuration of the LBNE far detectors is not yet determined, at this time we assume that over time both technologies will be developed and one or more modules of each will be constructed. Increased event rates projected for the Project X era do not affect the design of the far detectors, so what is initiated for LBNE can continue to function and grow in the Project X era.

6 Physics Opportunities

The Project X upgrade in beam power to the LBNE neutrino beamline will allow scientists to get results for the investigation of the key questions in neutrino oscillation physics with higher precision and greater potential for investigation of new physics effects. The oscillation phenomenon can be described by six independent parameters: two mass-squared differences, three mixing angles and a CP-violating phase. The mass-squared differences are already known at the level of a few percent uncertainty. Two of the angles, θ_{12} and θ_{23}, are known at the level of a few degrees uncertainty. The third angle, θ_{13}, however, has been shown to be smaller than approximately 10 deg, but the actual value is currently unknown.

At present, there are no reliable theoretical constructs based on fundamental principles that would either explain the values of the known parameters or predict what the value of θ_{13} should be. A surprising result of oscillation studies so far is that the structure of the mixing matrix in the neutrino sector is very different from that in the quark sector. The quark mixing matrix is close to diagonal, whereas the neutrino mixing matrix has very large off-diagonal elements (except for the one proportional to $\sin^2\theta_{13}$). There is a tantalizing pattern in the measured neutrino mixing angles: $\sin^2\theta_{23} \sim 1/2$, $\sin^2\theta_{12} \sim 1/3$, and $\sin^2\theta_{13}$ is much smaller. This pattern may be due to a hidden symmetry that leads to special values of the mixing angles. For example, if $\sin^2\theta_{23}$ is exactly equal to ½ (or very close to it), this may be an indication of a symmetry between the μ and τ leptonic families. Thus, it is important to obtain as precise values of these parameters as possible. The LBNE neutrino program enhanced by Project-X is well suited to investigate the possibility of a new symmetry through its capability to measure both θ_{13} and θ_{23} (by study of the energy dependence of the disappearance of muon neutrinos) with high precision and sensitivity.

Several experimental efforts around the world have embarked on the effort to measure θ_{13}. Recent results have tentatively suggested that this angle may be large enough to be within reach of the near-term experiments: the three reactor experiments (DoubleChooz, Daya Bay and RENO) and the upcoming long-baseline experiments (T2K and NOvA). If these indications hold up, detailed planning for the LBNE-Project X neutrino program could proceed with the knowledge of the value of θ_{13}. The first results from these experiments are expected around 2012. If this angle is too small to be accessible to these experiments, LBNE would be able to extend the sensitivity for this measurement to considerably smaller angles. LBNE sensitivity as a function of time is shown in Figure 2. LBNE combined with Project X will achieve high sensitivity to θ_{13} within several years.

Measurement of θ_{13} is an essential first step toward mapping the strategy for optimal pursuit of the two most important questions in the neutrino sector and in particle physics: “What is the mass ordering (or hierarchy) of the three neutrinos?” and “Is there matter-antimatter asymmetry (CP violation) in the neutrino sector?” Observation of CP violation would be strong evidence that neutrinos in the early universe played a central role in creating the cosmic predominance of matter over antimatter.

The mass of the lightest neutrino is at least a million times smaller than the mass of the lightest charged lepton, the electron. Currently the favored explanations for this remarkable difference are based on the so called “see-saw” mechanisms, which predict connection of the small neutrino masses to physics at a very high mass scale. It is not known today whether the neutrino masses exhibit similar hierarchical structure between the three families as the quarks and charged leptons (normal hierarchy) do or whether they have a very different pattern (inverted hierarchy). The mass hierarchy sensitivity increases with the length of the neutrino flight path through matter. The 1,300-km distance between Fermilab and the site of the proposed DUSEL in the Homestake Mine in South Dakota is a good compromise between the neutrino event rate, which decreases as the square of the distance, and sensitivity to the mass hierarchy.

Another very important question in neutrino physics is whether neutrinos are Dirac or Majorana particles. There is currently a large global effort to search for neutrinoless double-beta decay, which address this question. If neutrino mass hierarchy were to be determined by LBNE, the result would be crucial in some scenarios for the interpretation of double-beta decay experiments.

If the value of θ_{13} is large enough ($\sin^2 2\theta_{13} > 0.01$), the planned LBNE would be able to conclusively determine the neutrino mass hierarchy (if NOvA has not already done so) and would be sensitive to a large fraction of potential values of the CP violation phase. The requirements for the observation of CP violation are quite insensitive to the value of θ_{13}, as long as $\sin 2^2\theta_{13} > 0.01$, as shown in Figure 3. A conclusive and precise measurement, however, requires very high beam intensity such as that provided by the Project X beam power upgrade to LBNE and the very large-mass detectors at the proposed DUSEL.

The primary measurement of the Project X long-baseline neutrino experiment is the determination of the rate and energy dependence of the $\nu_\mu \rightarrow \nu_e$ transition. These measurements, for both neutrino and antineutrino exposures, can then yield information on the two issues identified above. The basic idea is that the observed spectrum from this reaction depends not only on the value of $\sin^2 2\theta_{13}$, but also on the mass hierarchy and the phase δ. The dependence is different for neutrino and antineutrino reactions. Thus, precise measurements of these spectra are required to determine all the parameters.

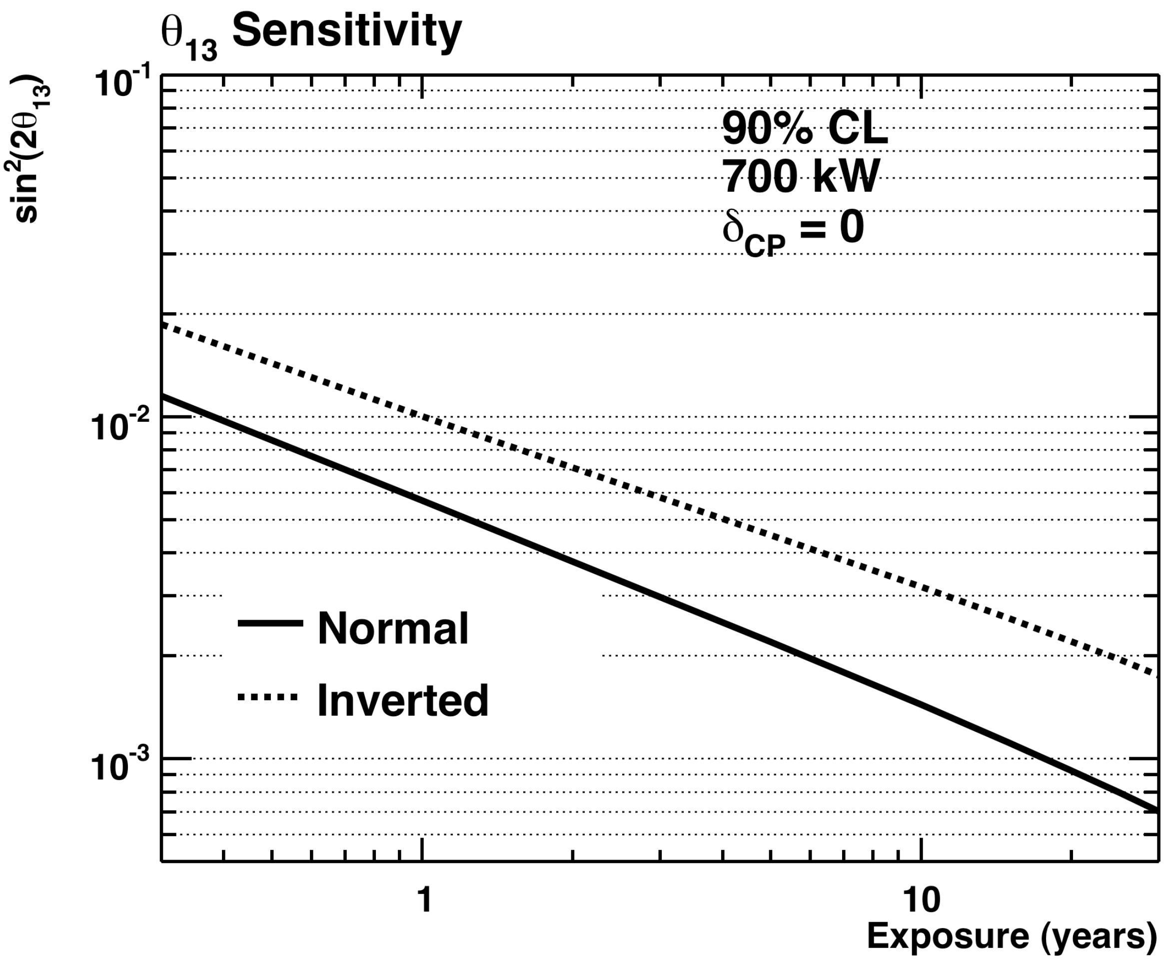

Figure 2: Plot showing 90% confidence level to measuring a non-zero value of $\sin^2 2\theta_{13}$ at an LBNE far detector complex composed of a 100-kT water Cherenkov detector and a 17-kT liquid argon detector. The exposure assumes a 700-kW proton beam, leading to an exposure time measured on the order of a decade. [Plot courtesy of Lisa Whitehead, Brookhaven National Laboratory]

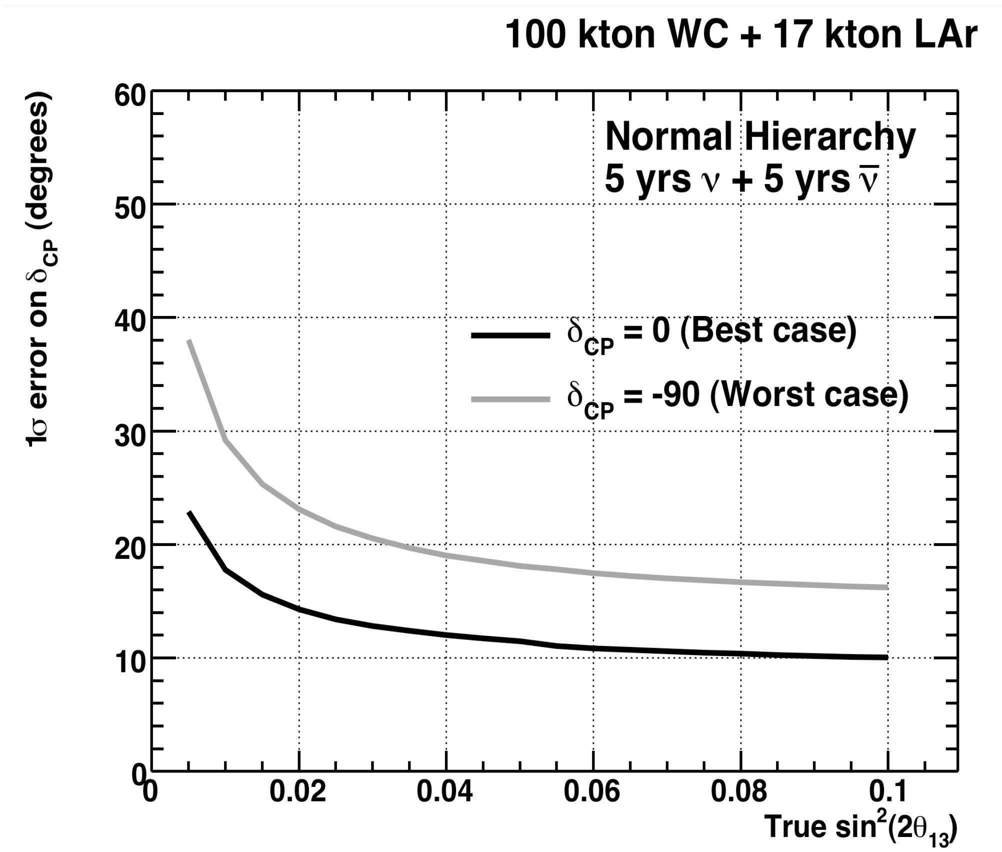

Figure 3: Plot showing 1 sigma error (in degrees) on δ_{CP} at an LBNE far detector complex composed of a 100-kT water Cherenkov detector and a 17-kT liquid argon detector. The exposure assumes a 700-kW proton beam. [Plot courtesy of Lisa Whitehead, Brookhaven National Laboratory]

7 Conclusion

As currently envisioned, the facility being planned within the framework of the LBNE Project will provide capabilities to carry out a world class program in neutrino oscillation measurements and enable us to address some of the most important questions in particle physics today. When LBNE will be combined with Project X, it would be able to achieve high precision results on these fundamental issues. In addition, the versatility of Project X would enable one to do a whole spectrum of additional neutrino experiments that might provide new insights into the nature of neutrinos.