The Long-Baseline Neutrino Experiment

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Introduction Although the Standard Model of particle physics presents a remarkably accurate description of the elementary particles and their interactions, it is known that the current model is incomplete and that a more fundamental underlying theory must exist. Results from the last decade, that the three known types of neutrinos have nonzero mass, mix with one another and oscillate between generations, implies physics beyond the Standard Model. Remarkable progress has been made decade to understand the new phenomena of neutrino oscillations. We are now in possession of all the needed ingredients for a scientifically well motivated, comprehensive, and stunningly beautiful program of measurements of neutrino oscillations and fundamental symmetries using leptons.

The Long-Baseline Neutrino Experiment Collaboration (LBNE) plans a comprehensive experiment that will fully characterize neutrino oscillation phenomenology using a high-purity ν_μ, operated in both ν_μ and $\bar{\nu}_\mu$ polarities, which will

- Measure full oscillation patterns in multiple channels, precisely constraining mixing angles and mass differences.
- Search for CP violation both by measuring the CKM phase δ_{CP} and by explicitly observing differences in ν_μ and $\bar{\nu}_\mu$ oscillations.
- Cleanly separate matter effects from CP-violating effects, to determine the ordering of the three neutrino mass eigenstates.

The LBNE Collaboration consists 347 members from 62 institutions in the United States, Europe and Asia [1]. Over the past several years, it has developed a complete, practical and achievable configuration for this experiment, including: selection of Fermilab as the neutrino source, the Sanford Underground Research Facility (SURF) in the former Homestake gold mine in Lead, South Dakota as the far detector site, development of technical designs for the neutrino beam, far detector and near detector, and designs for all of the civil engineering for all of the facilities at Fermilab and SURF required to support this program [2]. This design was thoroughly reviewed by an independent committee reporting to the Fermilab Director and found to be sound and capable of achieving LBNE's scientific goals [3].

The U.S. Department of Energy (DOE), which provides the major support for High-Energy Physics in the U.S., approved "Critical Decision 0" (CD-0) for LBNE in January 2010 [4]. This decision recognizes the importance of the science of LBNE, and authorized funding to develop a complete conceptual design and a project plan. To support LBNE, Fermilab established a project

management structure, which involves also Brookhaven National Lab and Los Alamos National Lab in leadership roles. DOE has strongly encouraged LBNE to achieve Critical Decision 1 (CD-1) this year. CD-1 represents DOE's approval of the conceptual design and the overall cost and schedule of the project, and it will release funds that will allow LBNE to move forward to complete the design and prepare for construction. Based on expected funding from DOE, construction of the first phase of LBNE, which will determine the neutrino mass hierarchy, explore the CP-violating phase δ_{CP}, and make precision measurements of the other oscillation parameters θ_{13}, θ_{23}, and $|\Delta m^2_{32}|$, will be complete about 10 years from now.

In this document, we will summarize the design of LBNE and the reasons we believe that this represents the optimal configuration for this physics, and then discuss opportunities for European collaboration on LBNE, to add capability to LBNE, accelerate its schedule, or both.

Key Elements of a Long-Baseline Neutrino Experiment There are several key element that are necessary to execute this program. First and most importantly, we need **the right baseline** from the neutrino source to the detector. This is the defining characteristic of an oscillation experiment, which ultimately determines the science it can or cannot do. Next, we need a large **and highly capable detector** which can make high statistics measurements, efficiently measure complex final states, and cleanly separate signals from background. Ideally, it should be placed at sufficient depth to suppress cosmic ray backgrounds to a negligible level, and if it is placed deep enough, it can also be used as a powerful tool for searching for proton decay and other baryon number violating processes, and for measuring astrophysical neutrinos. We need a **high-power, broad-band, high-purity, sign-selected neutrino beam**, with a spectrum that can cover full oscillation patterns at the optimal baseline. Finally, we need a **highly capable near detector** which can measure the flux spectra of all neutrino species in the beam (ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$) and which can measure cross-sections relevant for the oscillation physics. We have designed an experiment which combines all of these features, which we describe next.

The Optimal Baseline The baseline should be long enough to cleanly separate the oscillation asymmetry between ν and $\bar{\nu}$ due to the (non-CP-violating) matter effect from that due to true CP violation. It is well known that if the baseline is too short, then there may be fundamental ambiguities between these two effects. The left side of Fig. 1 shows the oscillation probability for $\nu_\mu \rightarrow \nu_e$ versus that for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for an 810 km baseline and a 2 GeV beam, which is near the oscillation maximum at this distance. For a given value of $\sin^2 2\theta_{13}$, the point that nature chooses in this plane lies on one of two ellipses, depending on the sign of Δm^2_{32} and the value of δ_{CP}. For $\sin^2 2\theta_{13} = 0.1$, near the currently measured value, the two ellipses overlap, and in the overlap region it is extremely difficult to sort out one effect from the other. As the baseline increases, the matter effect grows, and the two ellipses separate, as shown in right side of Fig. 1 for a baseline of 1300 km, allowing unambiguous determination of both the mass hierarchy and the value of δ_{CP}. For the clean separation of the two effects, a baseline > 1000 km is required.

On the other hand, if the baseline is too long, then the asymmetry due to the matter effect can become so large that it can almost fully suppress the flux of $\bar{\nu}$ (ν) in the case of the normal (inverted) mass hierarchy. This is shown in Fig. 2, which, for the normal mass ordering, compares the expected ν_e, and $\bar{\nu}_e$ appearance spectra at 1300 km with those at 2500 km [7]. The huge matter-effect asymmetry makes determination of the mass ordering very straightforward, but the almost complete lack of $\bar{\nu}_e$ events makes it very difficult to see a CP-violating difference between the $\bar{\nu}$ and ν oscillation behavior.

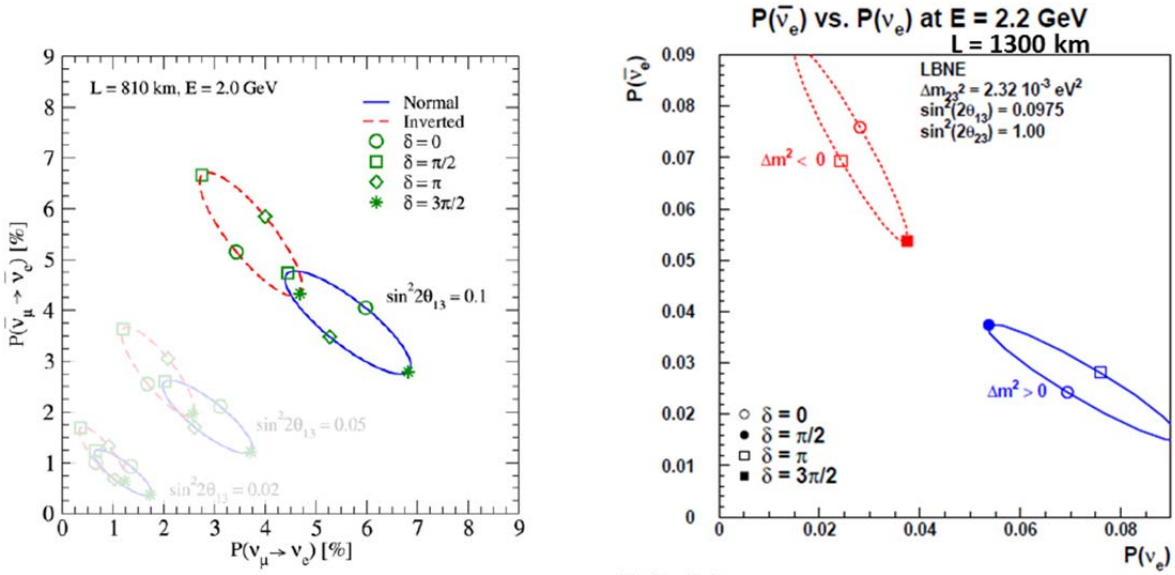

Figure 1. Probabilities for $\nu_\mu \rightarrow \nu_e$ versus that for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for $\sin^2 2\theta_{13} = 0.1$ and for an 810 km baseline (left [5]) and a 1300 km baseline (right [6]).

If the beam is optimized for each possible baseline, that is if the energy of the neutrinos is made to be proportional to the baseline, then the appearance event statistics are not a strong function of the baseline, as seen in Fig. 2. This calculation was performed under the constraint that the proton beam energy is fixed at 120 GeV. Various competing effects that determine the resolution for measuring δ_{CP} tend to cancel as the baseline is changed; however, the resolution is not constant with baseline, and is optimal for distances in the 1000 km to 1300 km range. Figure 3 is a plot of the fraction of valued of δ_{CP} for which 3σ determinations of the mass ordering and of the existence of CP violation ($\delta_{CP} \neq 0$ or π) can be made, considering the known value of $\sin^2 2\theta_{13} = 0.09$. In this study, the beam spectrum has been optimized for each baseline to cover the full region of the first oscillation maximum. Above 1000 km, the mass ordering can be determined for all values of δ_{CP}. The reach for finding CP violation has a broad maximum in the 1000 km to 2000 km range, but the best reach is achieved for 1000 km $\leq$ L $\leq$ 1300 km, and the capability to see CP violation is substantially worse at 2500 km than at half that distance [8].

At this baseline, and with the broad-band beam described below, it will be possible to observe the full oscillation pattern also in the ν_μ, disappearance channel, as shown in Fig. 4 [8]. This will permit measurements of θ_{23} and $|\Delta m^2_{32}|$ of unprecedented precision.

From these considerations, we conclude that the 1300 km distance from Fermilab to SURF/Homestake is the optimal baseline for making the definitive experiment in long-baseline neutrino oscillations.

<u>A Highly-Capable Far Detector</u> For this physics, a large and highly capable far detector is required, which can provide:

- High statistics for rare ν_e appearance events and ν_μ survival at the oscillation maximum.
- Efficient detection of signal and rejection of backgrounds.
- Reconstruction of complex final states.

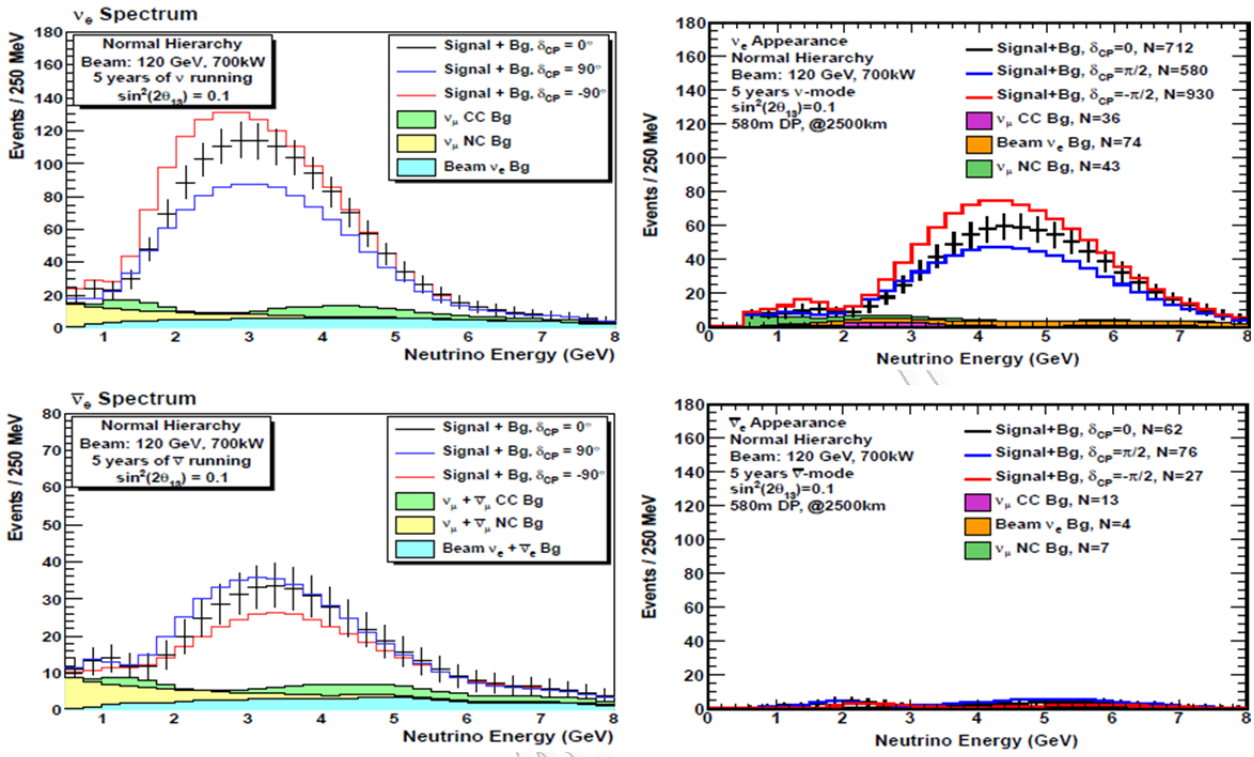

Figure 2. Expected ν_e, (top) and $\bar{\nu}_e$ (bottom) appearance spectra at 1300 km (left) and 2500 km (right) for $\Delta m^2_{32} > 0$, $\sin^2 2\theta_{13} = 0.1$, and different values of δ_{CP}.

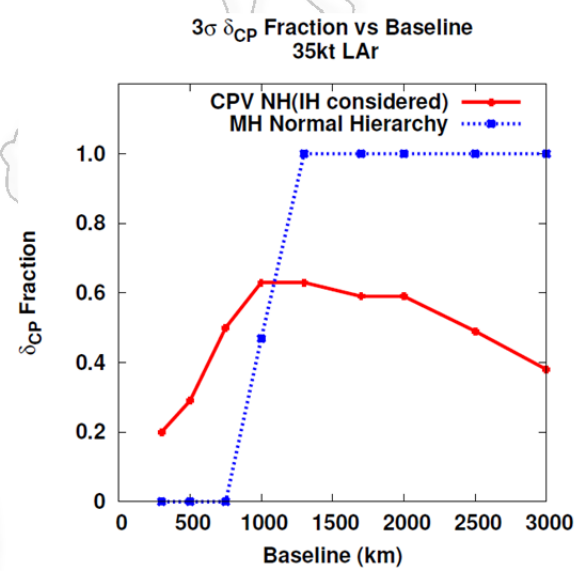

Figure 3. The fraction of δ_{CP} values for which CP violation and the mass hierarchy can be determined at a significance of 3σ or greater as a function of baseline, for $\sin^2 2\theta_{13} = 0.1$

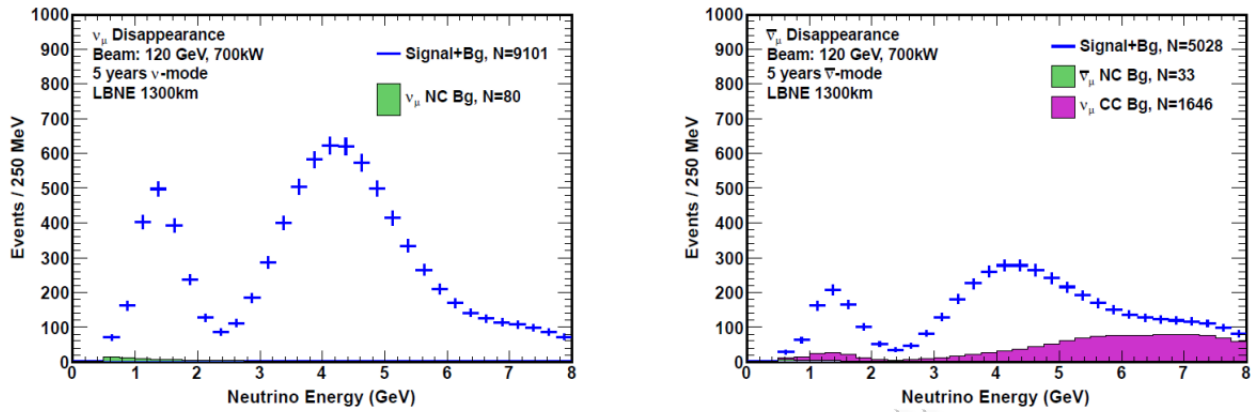

Figure 4. The expected spectrum of ν_μ and $\bar{\nu}_\mu$ oscillation events in a 34-kton LArTPC for 5 years of neutrino (left) and anti-neutrino (right) running with a 700 kW beam. The points with error bars are the expected total event rate for $|\Delta m^2_{32}| = 2{:}35 \times 10^{-3}\ eV^2$ and $\sin^2 2\theta_{23} = 0.97$.

Based on this, LBNE has chosen a liquid argon (LAr) TPC with a fiducial mass of 34 kton placed at a depth of 1480 m ≈ 4300 meters water equivalent (mwe) at SURF/Homestake. The underground location assures that cosmic ray backgrounds to even the rarest and most complex beam neutrino signatures will be negligible, and will enable a broader program of non-beam physics, including searches for proton decay or other baryon number violating processes, and measurements of supernova neutrinos and other neutrinos of astrophysical origin.

A LAr TPC is the detector of choice for a low-rate, large-volume, high-precision particle physics experiments due to its excellent 3D position resolutions and particle identification in large volumes. In addition to detailed event topologies and measurements of particle kinematics, dE/dx measurements allow LAr TPCs to unambiguously distinguish electrons, muons, photons, kaons, pions and protons over a wide range of energies. Examples of how event topologies can be used to identify ν_μ / ν_e CC and ν NC events in a LAr-TPC are shown in Fig.5 [8].

The cryostat and cryogenic system designs are based on standard commercial products that are in wide use in the liquefied natural gas industry. The detector system is simple and robust. It is based on simple, modular wire planes with multiple views that builds on the successful ICARUS design and which requires little R&D to develop. Figure 6 illustrates some of the key features of the design [2].

<u>Neutrino Beam</u> LBNE has designed a broad-band, high-purity, sign-selected ν_μ beam [2] that will utilize the 700 kW Fermilab Main Injector proton beam, and which will be able to utilize the much higher power (≥2.3 MW) beam that future planned upgrades at Fermilab (Project X [10]) will provide. A conventional horn-focused beam is used to provide a broad neutrino energy spectrum and provide the sign selection. The beam spectrum should cover the range of the first two oscillation maxima at 1300 km, which are at 2.5 GeV and 0.8 GeV respectively. This leads to a close-spaced two-horn system, with the target fully inserted in the first horn and a 4 m diameter decay pipe to maximize the collection of low-energy pions. (See Fig.7.) Figure 8 compares the neutrino flux spectrum for two different designs of the first horn [11]. The "Reference" design has a cylindrical neck closely surrounding the target to maximize the

collection and focusing of low-energy pions. It provides ~40% more flux near the second oscillation maximum than the double parabolic NuMI-design horn would.

The beam should be as pure a ν_μ ($\bar{\nu}_\mu$) beam as possible. In particular, since one of the prime physics goals is precision measurement of ν_e appearance, the intrinsic ν_e component of the beam should be minimized. A major source of ν_e in the beam are muon decays in flight, $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$, which are also a source of wrong "sign" $\bar{\nu}_\mu$. This leads to a design with a relatively short (200-

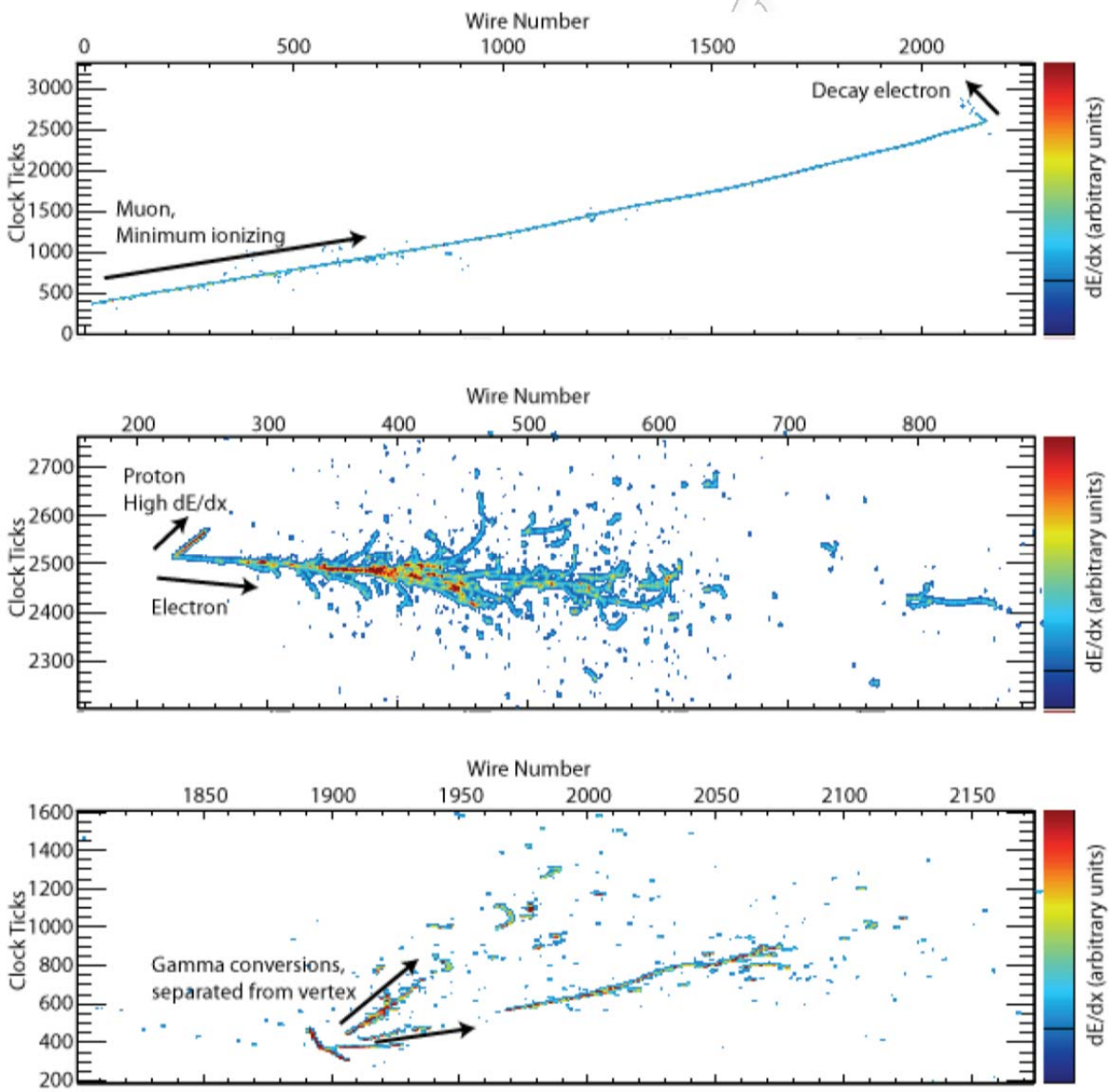

Figure 5. Examples of neutrino beam interactions in an LArTPC obtained from a GEANT4 simulation [9]. A CC ν_μ interaction with a stopped μ followed by a decay Michel electron (top), a QE ν_e interaction with a single electron and a proton (middle), an NC interaction which produces a π^0 that then decays into two 's with separate conversion vertices (bottom).

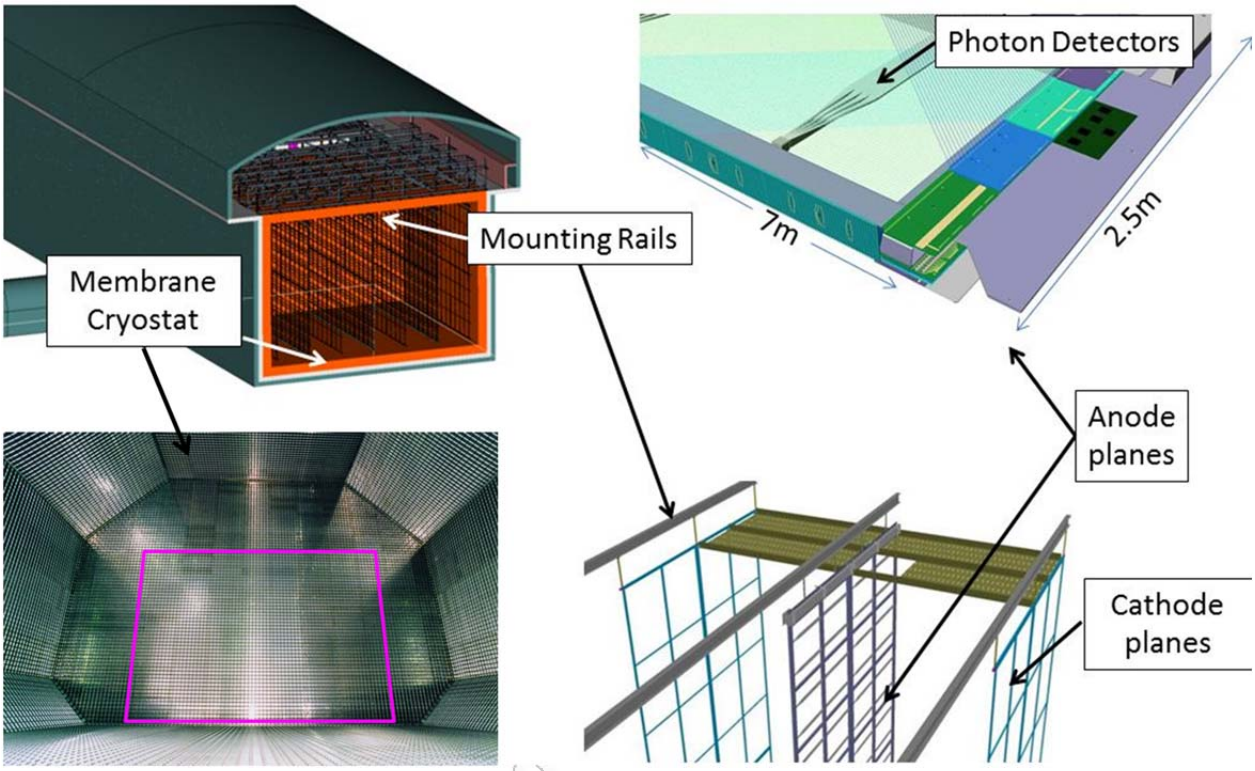

Figure 6. Main design elements of the LBNE LAr TPC far detector. Upper left is an isometric cut-away drawing of the LAr TPC in it membrane cryostat, with alternating vertical anode and cathode planes. Lower left is a membrane cryostat in a liquefied natural gas tanker. The pink rectangle indicates roughly the cross-section size of the LBNE cryostat. Upper right is a conceptual design of one anode plane assembly module. Lower right shows the design for the mounting rail system that will support the anode and cathode planes.

250 m) decay pipe, as shown in Figs. 9 and 10. The shielding shown in Figs. 7 and 9, as well as the systems for dealing with tritium containment, are designed for extended running with proton beam power of 2.3 MW, with significant margin.

Near Detector The near detector needs to measure the unoscillated flux spectrum for all species in the beam: ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$. This requires a magnetized detector which has good efficiency for identifying and measuring electrons and muons. If we in addition require to distinguish e^+ from e^- a low-density detector with a long physical radiation length would be required. The near detector should also make measurements using the same argon target nucleus as the far detector, and ideally should use the same detection technique as the far detector to allow cancellation of systematic errors. The last requirement suggests the use of a magnetized LAr TPC. However the multiple requirements are somewhat at odds, and as a consequence LBNE is considering two candidate near detector designs: a magnetized LAr TPC and a magnetized straw-tube tracker with embedded high-pressure Ar gas targets [2]. See Fig. 11. Both are placed inside a 0.4 T dipole magnet, with muon detectors in the yoke steel and downstream steel absorbers. The lower-density straw-tube detector is also surrounded by an electromagnetic calorimeter inside the dipole coil.

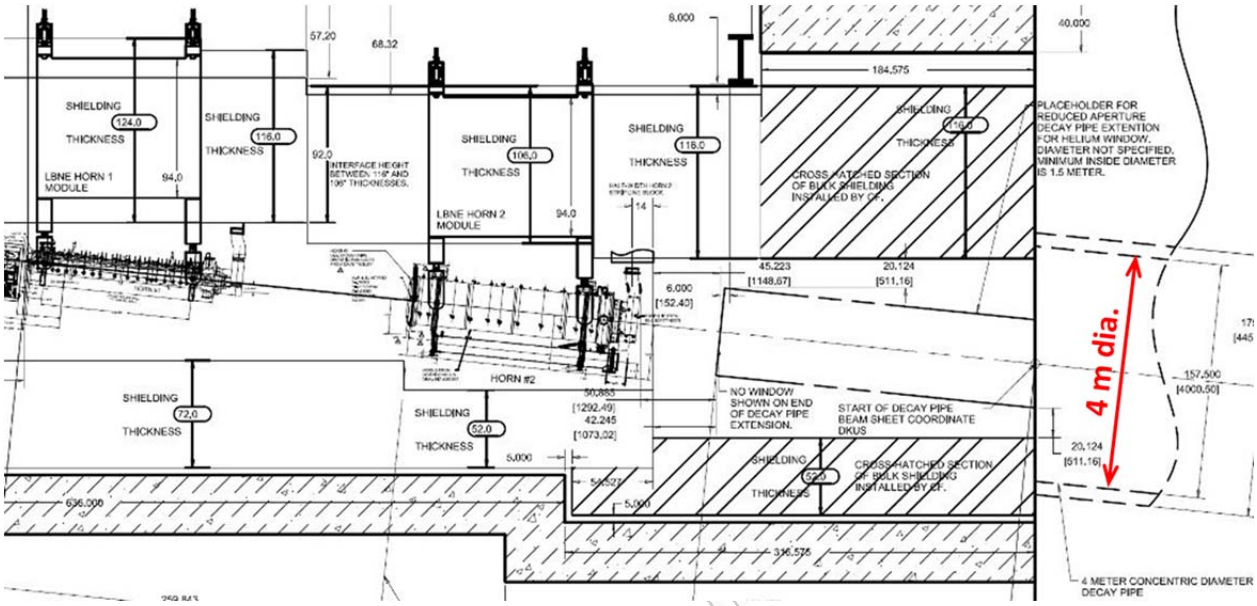

Figure 7. Layout of the LBNE horn focusing system and upstream end of the decay pipe.

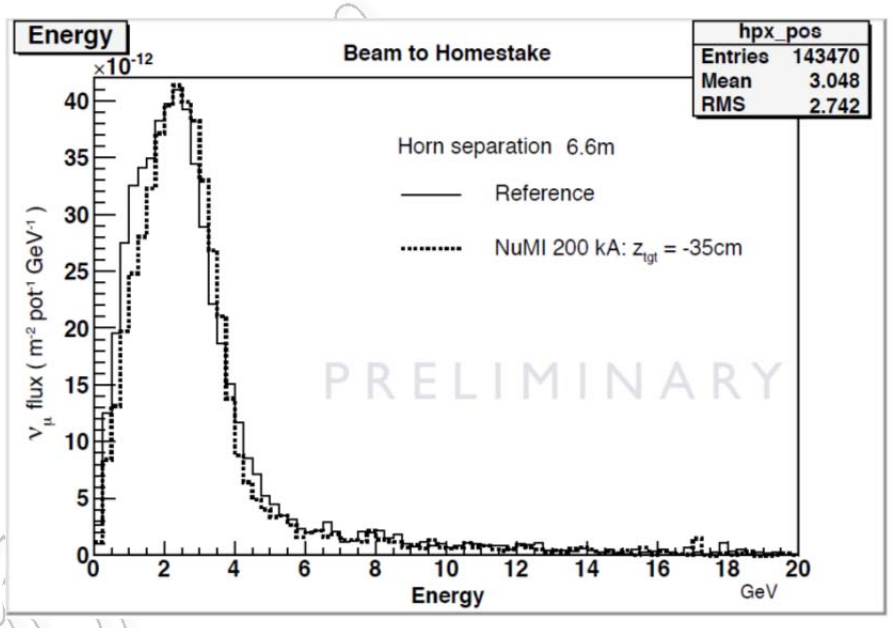

Figure 8. Neutrino flux spectrum for two different designs for the first horn. The "Reference" design has a cylindrical neck around the target to maximize the focusing of large-angle, low-energy pions. The NuMI design has a double parabolic cross-section.

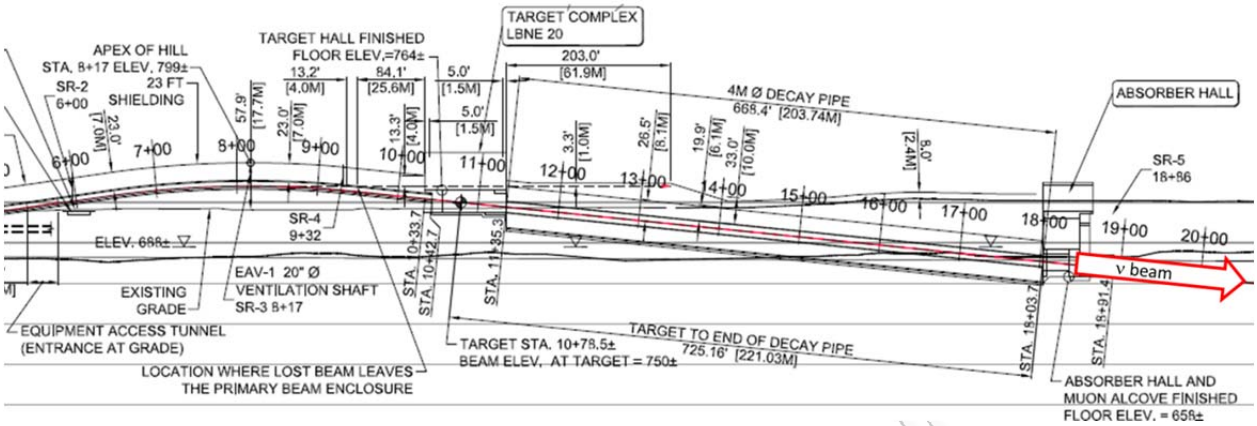

Figure 9. Design drawing for the LBNE decay pipe region.

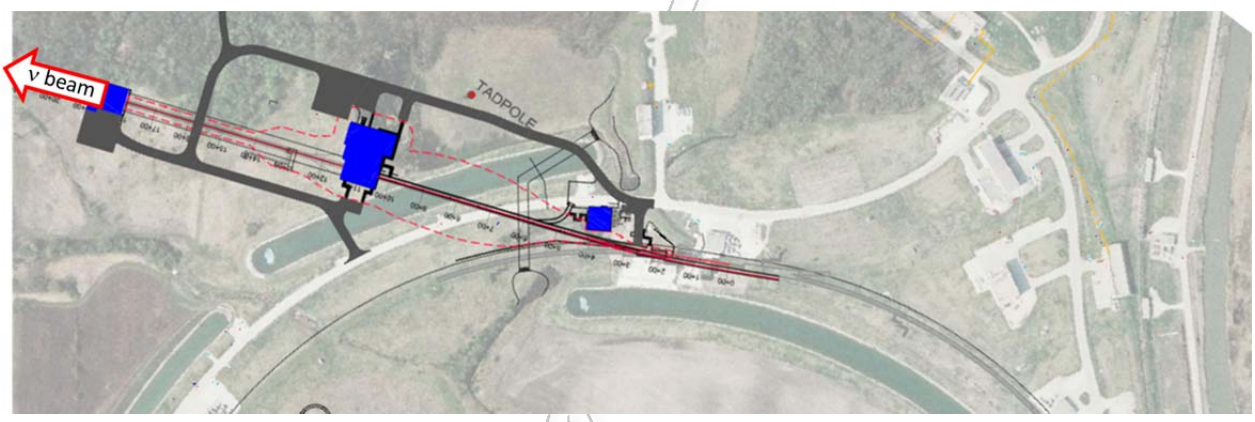

Figure 10. Plan view of the LBNE beamline, showing the extraction from the Main Injector, primary beamline, target hall, decay pipe, and absorber.

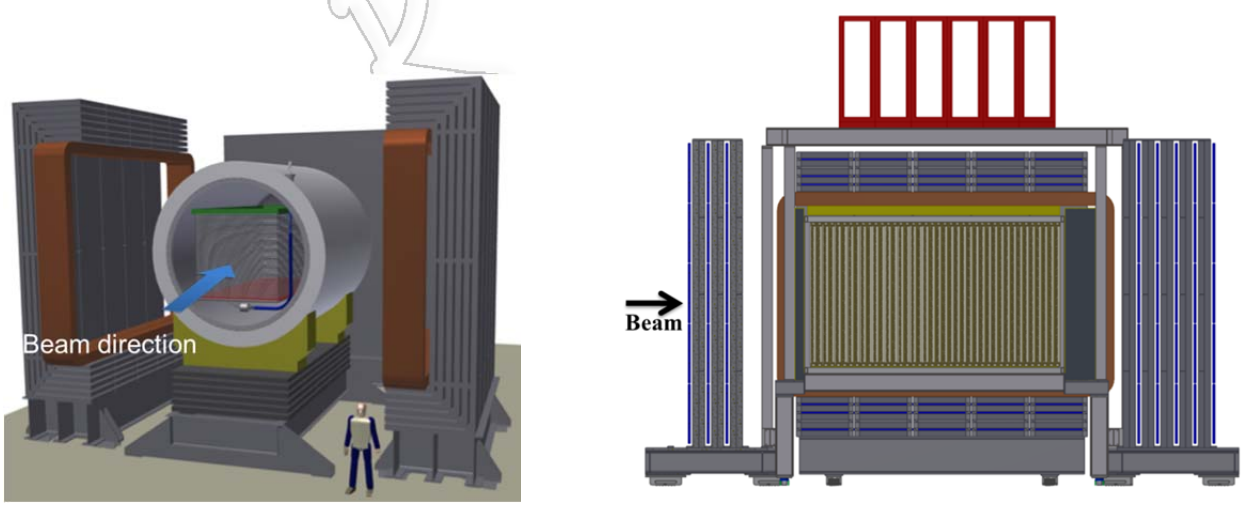

Figure 11. Two candidate near detectors: a magnetized LAr TPC (left) and a magnetized straw-tube tracker with embedded high-pressure Ar gas targets (right).

A Phased Program Fiscal constraints require that LBNE be implemented in a phased way [12]. In the first phase, LBNE will build the neutrino beam described above, aimed at SURF/Homestake, where a 10 kton LAr TPC detector will be built near the surface, in a pit just below grade level. Sufficient overburden will be provided to eliminate the hadronic and electromagnetic component of cosmic ray showers. As shown in Figs. 12 and 13, the detector will be placed at the base of a hill that is in the direction of Fermilab. This will provide 300 m of shielding against cosmic rays coming from within 25° of the beam direction, which are the most dangerous source of cosmic ray background for the beam physics. Although the near-surface location is not ideal, preliminary studies suggest that simple and robust kinematical cuts can reduce the cosmic ray backgrounds to a small fraction of the expected ν_e appearance signal [13].

The first phase will not include a near neutrino detector. The neutrino beam will be monitored with a sophisticated array of muon detectors [2] placed just downstream of the absorber, as shown in Fig. 14. The ionization chamber array will provide pulse-by-pulse monitoring of the beam profile and direction. The array of variable-threshold gas Cherenkov detectors will allow the energy spectrum of the muons exiting the absorber to be mapped on an on-going basis. The stopped muon detectors will sample the lowest energy muons. The muons measured by this system correlate fully with the neutrino flux above 3 GeV. They sample the equivalent of about half the neutrino flux near the first oscillation maximum, and sample a decreasing fraction at lower energy. Preliminary studies show that this system, augmented by our good understanding of the similar NuMI beam and several other strategies, will be adequate for the initial period of LBNE running because of the choice of a liquid argon TPC for the far detector and its extremely high performance in particle identification [14]. Nevertheless, a full near detector complex is highly desirable in the long term, and is needed to achieve the full scientific agenda of LBNE.

The first phase of LBNE will determine the mass hierarchy and explore the CP-violating phase δ_{CP}, as well as make precision measurements of the other oscillation parameters θ_{13}, θ_{23}, and $|\Delta m^2_{32}|$. The physics reach of the first phase for the neutrino mass hierarchy and CP violation is shown in Figure 15. This is the start of a long-term program that will achieve the full goals of LBNE in time and allow the Standard Model to be incisively probed beyond its current state. Subsequent phases will include [12,15]:

- A highly capable near neutrino detector, which will reduce systematic errors on the oscillation measurements and enable a broad program of short-baseline neutrino physics.
- An increase in far detector mass to 35 kton fiducial mass placed at 1480 m depth, which will further improve the precision of the primary long-baseline oscillation measurements, enable measurement of more difficult channels to make a fully comprehensive test of the three-neutrino mixing model, and open or enhance the program in non-accelerator-based physics, including searches for baryon-number-violating processes and measurements of supernova neutrinos.
- A staged increase in beam power from 700 kW to 2.3 MW with the development of Project X, which will enhance the sensitivity and statistical precision of all of the long- and short-baseline neutrino measurements.

Project Planning The conceptual design for LBNE has been completed, and preliminary but solidly grounded cost and schedule estimates have assembled. Although an underground placement of the far detector is not included in the current plans for the first phase, LBNE is

continuing to develop the civil engineering design for the deep underground location. Discussions are in progress with potential non-U.S. collaborators which may provide sufficient resources to allow LBNE to include a near detector in the first phase.

The next step in the DOE project approval process is "Critical Decision 1" (CD-1), which approves the conceptual design and the overall cost and schedule of the project. Importantly, approval of CD-1 will release funds that will allow LBNE to move forward to complete the design and prepare for construction. The DOE has strongly encouraged LBNE to achieve this

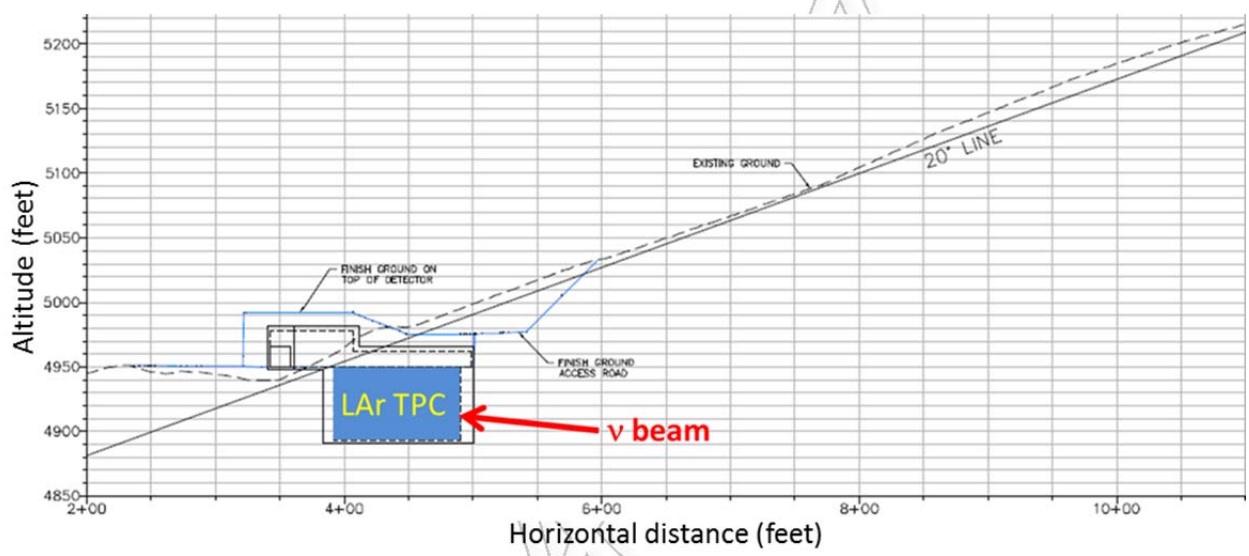

Figure 12. Profile view showing the LAr TPC detector just below the natural ground level in the "shadow" of a hill. The neutrino beam is coming from the right at an upward angle of 6°, and the hill provides >300 m of shielding against cosmic rays with zenith angle >70°.

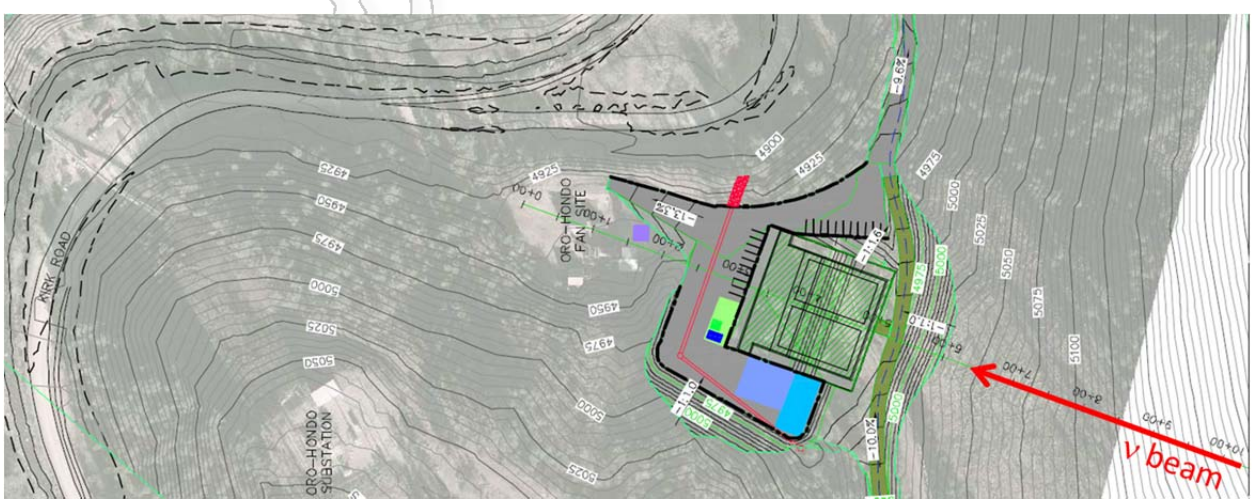

Figure 13. Plan view showing the placement of the LAr TPC detector relative to the local topography, which provides shielding against cosmic rays coming from within 25° of the beam direction.

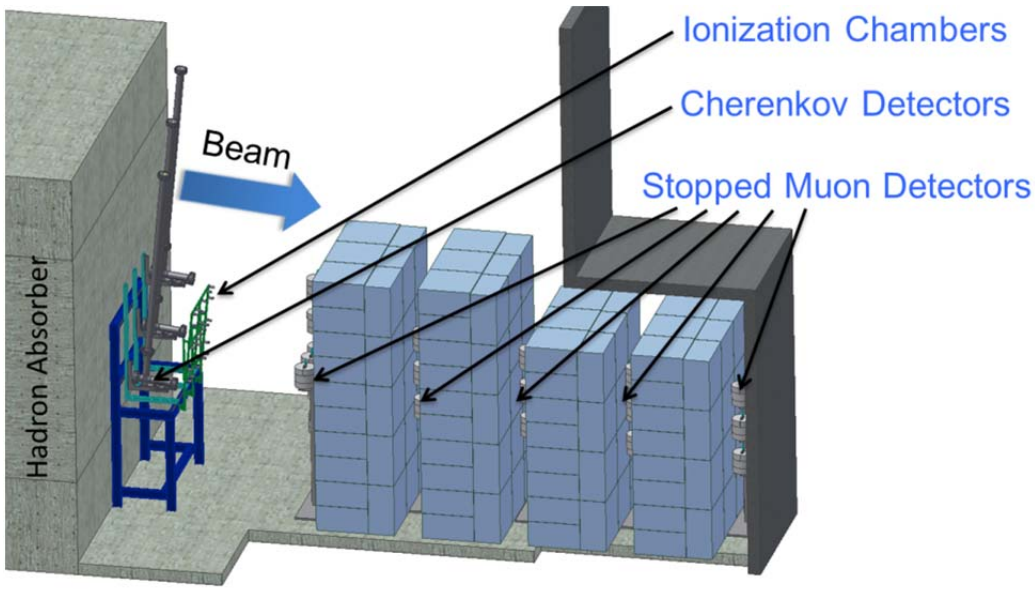

Figure 15. System of tertiary muon detectors, which will monitor the LBNE neutrino beam in the first phase.

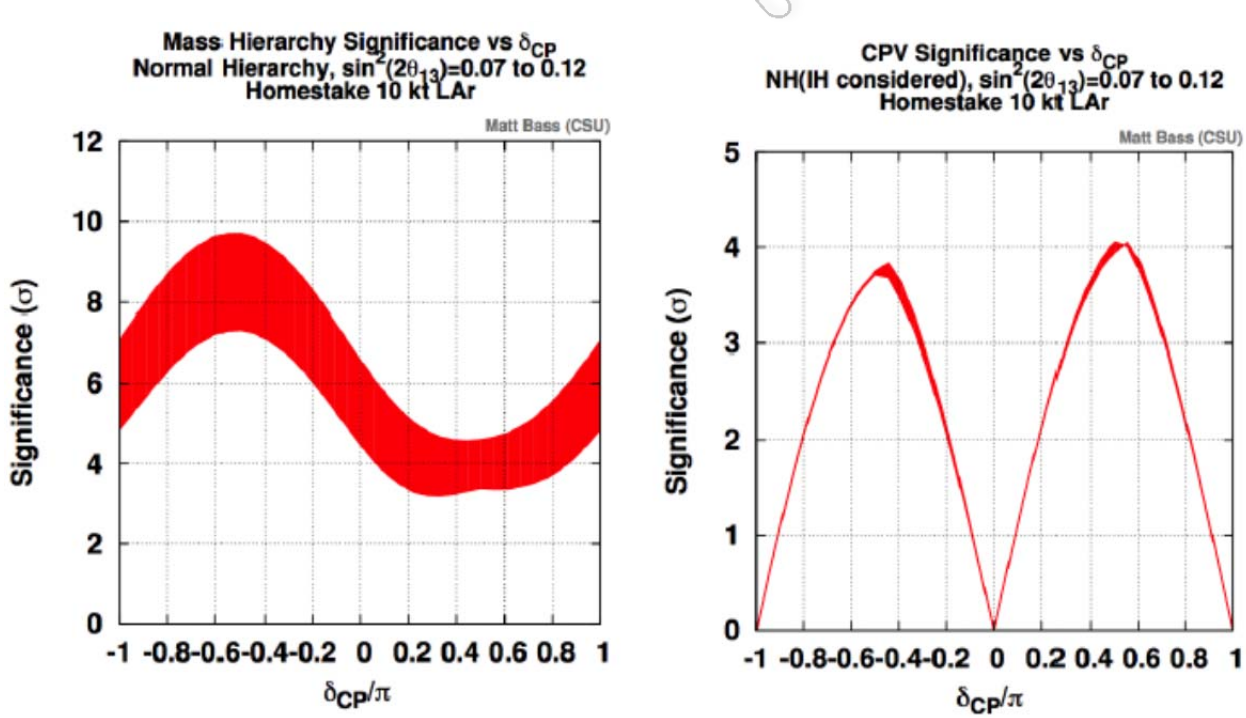

Figure 15. Significance for determining the hierarchy (left) and CP violation (right) as a function of δ_{CP} for the first phase of LBNE, leveraging the knowledge that will have been gained from NOvA and T2K beforehand. Projections are for 5+5 years of 700 kW $\nu + \bar{\nu}$ of a 10 kton fiducial mass LAr TPC at Homestake combined with anticipated results from NOvA (3+3 years at 700 kW) and T2K ($5x10^{21}$ POT or ~6 years). The bands 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 $\pm 2\sigma$ variation relative to the latest results presented by Daya Bay at Neutrino 2012.

milestone before the end of 2012. The DOE has also provided a preliminary funding plan for LBNE, which provides for completion of the first phase project in about 10 years.

Opportunities for Collaboration The U.S. Long-Baseline Neutrino Experiment will have a unique combination of the optimal baseline for this physics, a neutrino beam designed specifically for it which will be capable of utilizing multi-megawatt proton beam power from Fermilab's Project X accelerator upgrades, and large liquid argon TPC far detector. The far detector will be placed at the Sanford Underground Research Facility, which is a currently operating underground laboratory (see Fig. 16), thus providing future access to operate LBNE at great depth. In a phased program, the capabilities and science program of LBNE will be expanded with the addition of a very sophisticated near detector, additional detector mass placed underground, and a factor of three (or more) increase in beam power.

Figure 16. Sanford Underground Research Facility: Administration building and Yates shaft headframe (top left); corridor at 4850 ft (1480 m) depth leading to clean rooms and experimental halls (top right); billet of radiopure electroformed copper the Majorana Demonstrator experiment being placed on a lathe in a clean room at 4850 ft depth (bottom left); LUX experiment at 4850 ft depth (bottom right).

The incremental cost of moving the phase 1 detector underground or of building a full-capability near detector complex or are relatively modest: the cost of each of these is only about 15% of the LBNE phase 1 cost [16]. Thus, there is significant opportunity for new collaborators to leverage the major investment that the United States has made and will make in providing the beam, the initial far detector, and an operating research facility with access to a depth of 1480 m.

Collaboration on the design and construction of the far detector, near detector or neutrino beam could provide sufficient additional resources to allow us, together, to place the far detector underground in the first phase, and include a sophisticated near detector which would not only improve the accuracy of the long-baseline oscillation measurements, but have rich physics program in its own right. Given the significant interest in and the advanced state of LAr TPC development in both Europe and the U.S, collaboration on the far detector, in which both sides work together to develop and implement the best possible configuration, would be natural. Collaboration on the any aspect of the near detector or the beam would also make sense and would be a major step in advancing this science.

We welcome full collaboration with our European colleagues, whose expertise and experience would be extremely valuable to further develop the design of LBNE and expand its capabilities, to allow us to jointly carry out this comprehensive, and stunningly beautiful program of measurements of neutrino oscillations and fundamental symmetries using leptons.

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