THE LONG-BASELINE NEUTRINO EXPERIMENT

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Abstract The Long-Baseline Neutrino Experiment (LBNE) plans a comprehensive program that will fully characterize neutrino oscillation phenomenology using a high intensity 1300 km baseline accelerator neutrino beam and a massive liquid argon TPC as the far detector. The goals for this program are the determination of leptonic CP violation, the neutrino mass hierarchy, and underground physics, including the exploration of proton decay and supernova neutrinos. The science potential for these goals was characterized as *absolutely central* in the 2003 "High Energy Physics Facilities Recommended for the DOE Office of Science Twenty-Year Roadmap." The collaboration and the project are well organized and the U.S. Department of Energy has stated its intention to carry out this program in a phased manner. The scope of the first phase, for which CD-1 approval has been given, focuses on accelerator neutrino physics utilizing a far detector at the surface and a minimal near detector system. LBNE is aggressively pursuing non-DOE partners, both foreign and domestic, to increase the experimental capabilities before the first phase of LBNE is baselined at CD-2. If additional domestic or international commitments are secured, LBNE could include additional scope such as an underground location for the far detector or a near neutrino detector, which would not only improve the accuracy of the long-baseline oscillation measurements, but also have a rich physics program in its own right. LBNE is designed to be able to exploit the higher beam power from Project X.

Introduction In the Standard Model of particle physics, neutrinos are massless, neutral, spin one-half particles. Left-handed neutrinos form an electroweak isospin doublet with their charged, massive partners, electrons, muons and taus. The right-handed neutrinos form an electroweak isospin singlet. Results from the last decade, that neutrinos have nonzero mass, mix with one another and oscillate between generations, are one of the few indications of physics beyond the Standard Model and new theoretical and experimental work is needed to understand neutrino properties and their role in the Universe as the most abundant known particle of matter. As a result of the remarkable progress in understanding neutrino oscillations, we now have all the necessary ingredients for a scientifically well-motivated, comprehensive, and elegant 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 beam, operated in both ν_μ and $\bar{\nu}_\mu$ beam 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 science potential for these neutrino physics goals, along those for proton decay and supernova burst neutrinos, were characterized as *absolutely central* in the 2003 "High Energy Physics Facilities Recommended for the DOE Office of Science Twenty-Year Roadmap" [1].

The LBNE Collaboration [2] consists of more than 360 members from 65 institutions in the United States, Europe and Asia. 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 [3]. A DOE SC/Office of Project Assessment independent review found the project to be sound and capable of achieving LBNE's scientific goals [4].

The U.S. Department of Energy (DOE), Office of Science approved "Critical Decision 0" (CD-0) for LBNE in January 2010 [5], recognizing the importance of the science of LBNE. To support LBNE, Fermilab established a project management structure, which involves also Brookhaven National Lab and Los Alamos National Lab in project management roles. DOE approved Critical Decision 1 (CD-1) in December 2012 for the 1st phase LBNE Project [6] releasing funds that will allow LBNE to move forward to complete the design and prepare for construction. 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 $|\Delta m^2_{32}|$, is planned to be complete in 2023. The CD-1 approval document from DOE recognizes that, “The physics opportunities offered by the beam from Fermilab and the long baseline may attract the support of other agencies both domestic and international. Contributions from such other agencies offer alternative funding scenarios that could enhance the science capabilities of the Project. If additional domestic or international funding commitments are secured sufficiently prior to CD-2, the DOE LBNE Project baseline scope could be refined before CD-2 to include scope opportunities such as a Near Neutrino Detector complex at Fermilab or an underground location at SURF for the far detector.”

This document summarizes the design of LBNE, the reasons that it represents the optimal configuration for this physics, and the opportunities for new partners to add capability to LBNE.

Key Elements of a Long-Baseline Neutrino Experiment There are several key elements that are necessary to execute this program. First and most importantly, we need *the best baseline* from the neutrino source to the detector. This is the defining characteristic of an oscillation experiment that ultimately determines the science it can do. Next, we need a large *and highly capable detector* that 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, broadband, high-purity, sign-selected neutrino beam*, with a spectrum that covers full oscillation patterns at the optimal baseline. Finally, we need a *highly capable near detector* that 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 that combines all of these features, which we describe next.

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. If the baseline is too short, there may be fundamental ambiguities between these two effects. An example of this is illustrated in Fig.1. 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. The longer baseline allows an 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.

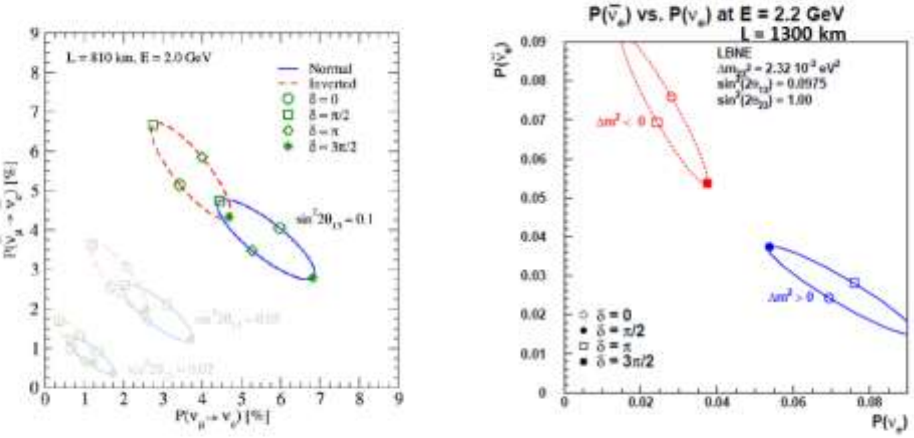

Figure 1. Probabilities for $\nu_\mu \rightarrow \nu_e$ versus that for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for $\sin^2 2\theta_{13} = 0.1$ and for an 810 km baseline (left [7]) and a 1300 km baseline (right [8]).

However, there are several additional factors that point to a limit on the optimal baseline distance. Generally, if the high-energy proton accelerator is able to adjust the peak energy of the neutrino spectrum to keep L/E constant then, absent the matter effect, it would be beneficial to use a longer baseline. This is because, to leading order, the boost factor in pion decay and the increasing cross section lead to a higher event rate for the same sized detector for the higher energy beam even after accounting for the $1/L^2$ factor. However, for large distances the asymmetry due to the matter effect is so large that it can almost fully suppress the event rate of $\bar{\nu}_e(\nu_{\square})$ in the case of the normal (inverted) mass hierarchy. Fig. 2 (left) shows the asymmetry between ν_e and $\bar{\nu}_e$ appearance probability at the first oscillation peak (defined by $E_\nu(GeV) = \frac{2.5\Delta m^2_{32}(eV^2)L(km)}{\pi}$) as a function of baseline distance. Assuming that the maximum statistical power comes from the first node, the optimum baseline considering this effect occurs between 1000 and 2000 km, where the matter asymmetry is larger and is distinguishable from the CP effect but is not so large that the CP effect is suppressed. Also, at a very long baseline, and the higher average neutrino energy this requires, there is a significant charged current interaction rate for tau neutrinos. The tau particles produced in these interactions will decay and produce background for the electron neutrino signal. For electron neutrino physics, it is therefore beneficial to keep the majority of the events below approximately 3.5 GeV, the tau production threshold.

The resolution for measuring δ_{CP} depends on various competing effects that tend to cancel as the baseline is changed; however, the resolution is not exactly constant with baseline. Figure 2 (right) is a plot of the fraction of values 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, assuming $\sin^2 2\theta_{13} = 0.09$. In this study, the beam spectrum has been optimized for each baseline to cover the full region of the first oscillation maximum. We conclude that the mass ordering can be determined for all values of δ_{CP} for baselines above 1000 km with a 35 kt LBNE far detector. 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 $1000\text{ km} \leq L \leq 1300$ km, and the capability to see CP violation is substantially worse at 2500 km than it is at half that distance [9]. For this calculation we have assumed that the tau background can be completely eliminated.

At a baseline of 1300 km and with the broadband beam described below, it will also be possible to observe the full oscillation pattern in the ν_μ, disappearance channel, as shown in Fig. 3 [9]. This will permit measurements of θ_{23} and $|\Delta m^2_{32}|$ of unprecedented precision.

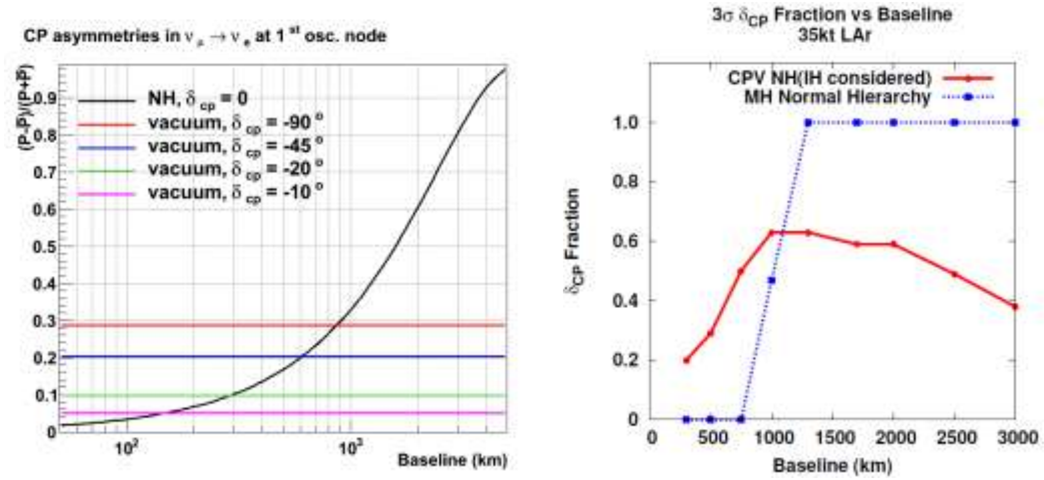

Figure 2. The asymmetry between neutrino and anti-neutrino (ν_e, and $\bar{\nu}_e$) appearance probability at the first oscillation peak without matter effects for several values of δ_{CP} and with the matter effect for $\delta_{CP} = 0$ (left); the fraction of δ_{CP} values for which CP violation and the mass hierarchy can be determined at a significance of 3σ or greater as a function of baseline, for $\sin^2 2\theta_{13} = 0.1$ (right).

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. It is important to note that our conclusion is independent of the proton beam energy; it only depends on the known oscillation parameters and the reasonable assumption that the maximum statistical power will come from the first oscillation node. The broadband nature of the beam and obtaining events at lower energies is extremely important for removing parameter degeneracies and full exploitation of the physics, but our main conclusion about the baseline is remarkably robust.

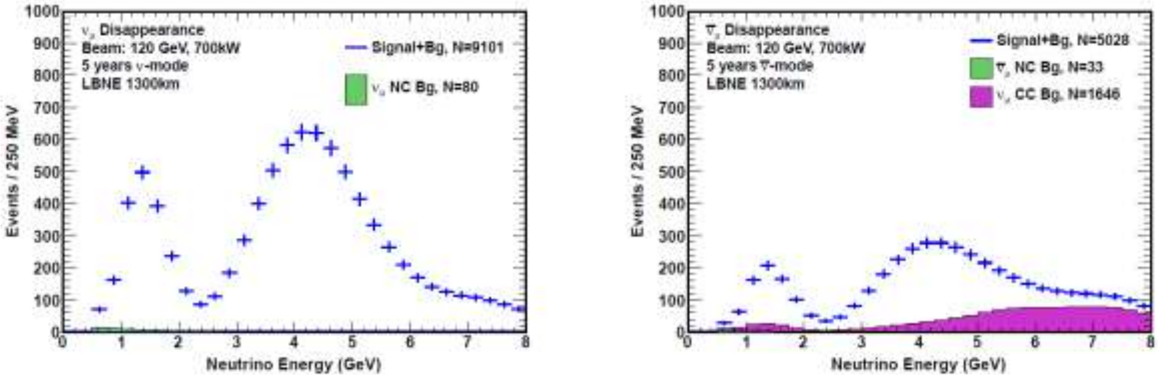

Figure 3. The expected spectrum of ν_μ and $\bar{\nu}_\mu$ oscillation events in a 34-kt LArTPC for 5 years of neutrino (left) and anti-neutrino (right) running with a 700 kW beam. The points with error bars are the expected total event rate for $|\Delta m^2_{32}| = 2.35 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 0.97$.

Highly-Capable Far Detector For this physics, a large and highly capable far detector is required to provide:

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

Based on these criteria, LBNE has chosen a liquid argon (LAr) TPC with a fiducial mass of 34 kt 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. SURF is a currently operating underground laboratory (see Fig. 4), thus providing future access to operate LBNE at great depth.

Figure 4. Sanford Underground Research Facility: Billet of radiopure electroformed copper for the Majorana Demonstrator experiment on a lathe in a clean room at 4850 ft depth (left); LUX experiment at 4850 ft (right).

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 [9].

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 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 [3].

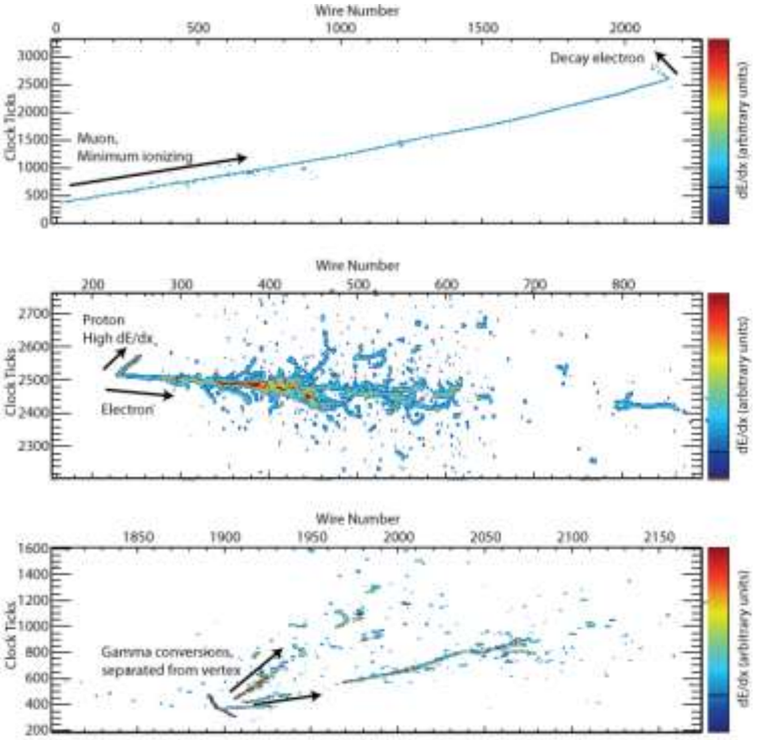

Figure 5. Examples of neutrino beam interactions in an LArTPC obtained from a GEANT4 simulation [10]. A CC ν_μ interaction with a stopped μ followed by a decay Michel electron (top), a QE ν_e interaction with a single electron and a proton (middle), an NC interaction that produces a π^0 that then decays into two γ's with separate conversion vertices (bottom).

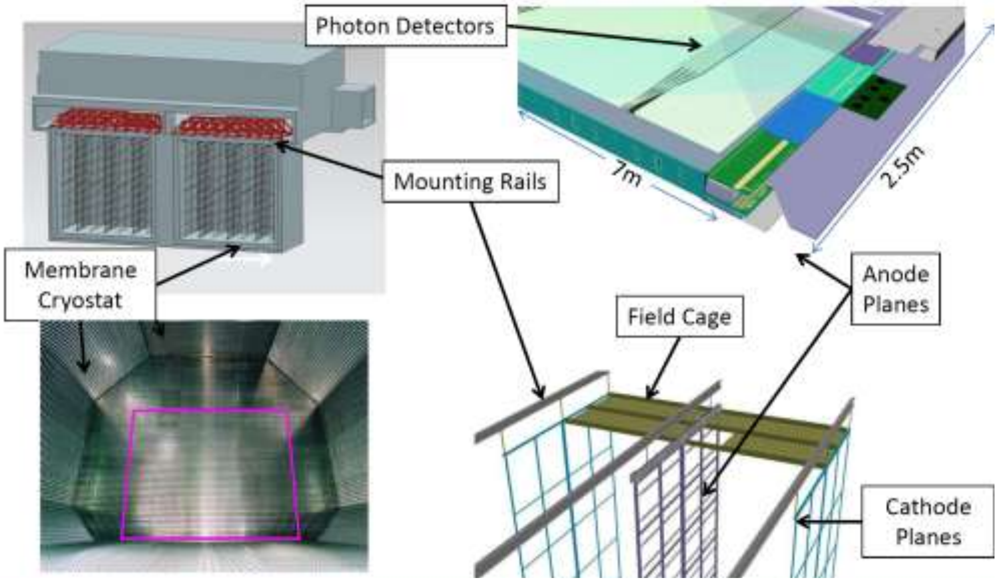

Figure 6. Main design elements of the LBNE LArTPC far detector. Upper left is an isometric cut-away drawing of the LArTPC in it membrane cryostat, with alternating vertical anode and cathode planes. Lower left is a membrane cryostat in a liquefied natural gas tanker—the pink rectangle indicates roughly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

Neutrino Beam LBNE has designed a broad-band, high-purity, sign-selected ν_μ beam [3] that will utilize the 700 kW Fermilab Main Injector proton beam, and which will be able to utilize the much higher power ($\geq$2.3 MW) beam that future planned upgrades at Fermilab (Project X [11]) 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. Figure 7 compares the neutrino flux spectrum for two different designs of the system of the target plus first horn [12]. The "Reference" design horn has a cylindrical neck closely surrounding the target and is designed to operate at a higher current than the NuMI horn. This increases the collection and focusing of low-energy pions, and 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. Since one of the prime physics goals is the 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 is 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 (200-250 m) decay pipe, as shown in Fig. 8. The shielding and the systems for dealing with tritium containment are designed for extended running with proton beam power of 2.3 MW, with significant safety margin.

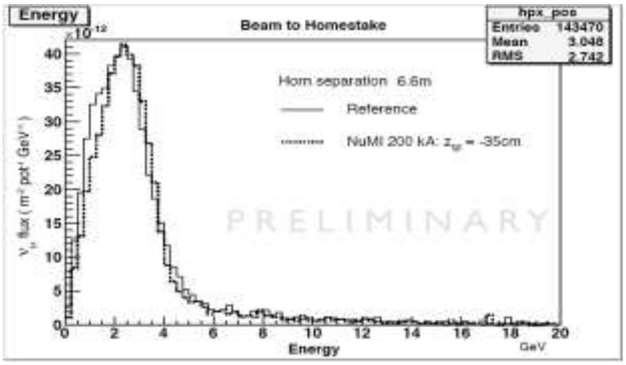

Figure 7. Neutrino flux spectrum for two different designs for the first horn. The "Reference" design has a cylindrical neck around the target to maximize the focusing of large-angle, low-energy pions. The NuMI design has a double parabolic cross-section.

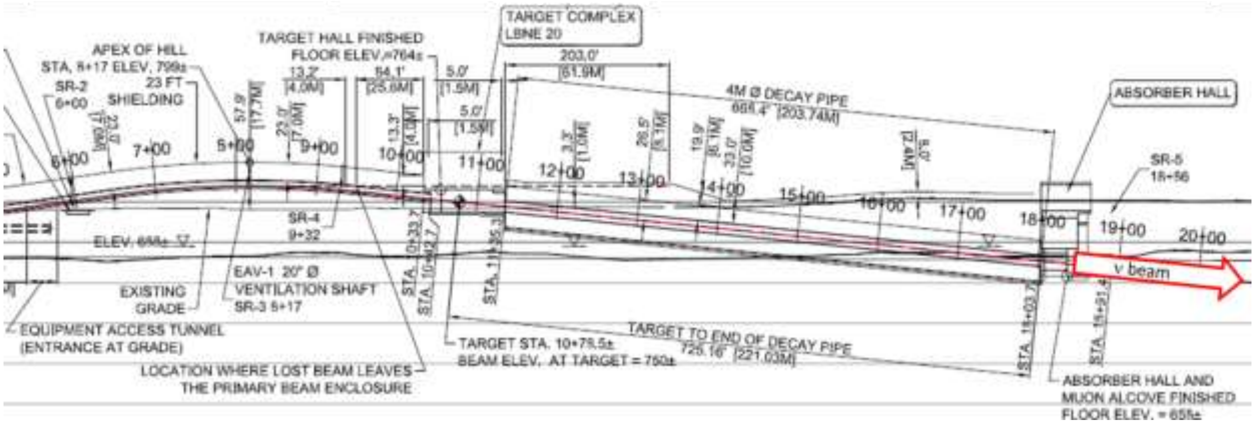

Figure 8. Design drawing for the LBNE decay pipe region.

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 that has good efficiency for identifying and measuring electrons and muons. If we in addition require the detector 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 near detector design candidates: a magnetized LAr TPC and a magnetized straw-tube tracker with embedded high-pressure argon gas targets [3]. See Fig. 9. 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. In addition to enhancing the long-baseline program, this configuration enables a significantly enhanced short-baseline and neutrino interactions program.

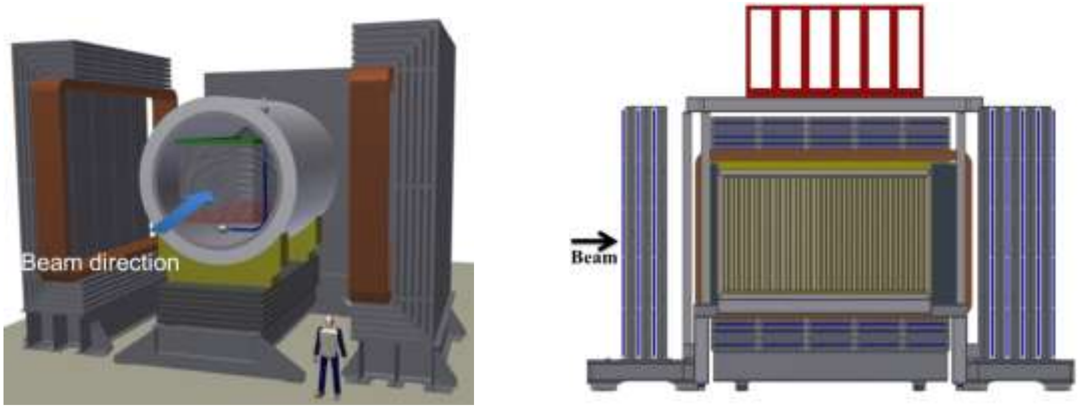

Figure 9. Two candidate near detectors: a magnetized LAr TPC (left) and a magnetized straw-tube tracker with embedded high-pressure argon gas targets (right).

Phased Program Fiscal constraints require that LBNE be implemented in a phased way [13]. In the first phase, LBNE will build the neutrino beam described above, aimed at SURF/Homestake, where a 10 kt 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 Fig. 10, 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 [14].

The first phase of LBNE will not include a near neutrino detector. The neutrino beam will be monitored with a sophisticated array of muon detectors [3] placed just downstream of the absorber, as shown in Fig. 11. The ionization chamber array will provide pulse-by-pulse monitoring of the beam profile and direction. The variable-threshold gas Cherenkov detectors will map the energy spectrum of the muons exiting the absorber 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 [15]. Nevertheless, a full near detector complex is needed to achieve the full scientific agenda of LBNE in the long term.

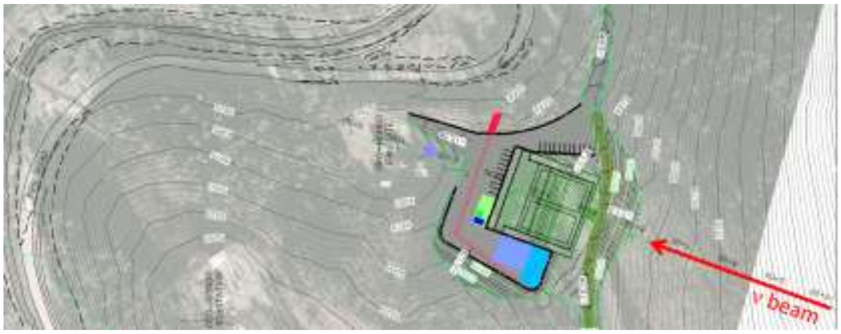

Figure 10. Plan view showing the placement of the LAr TPC detector relative to the local topography, which provides shielding against cosmic rays coming from within 25° of the beam direction.

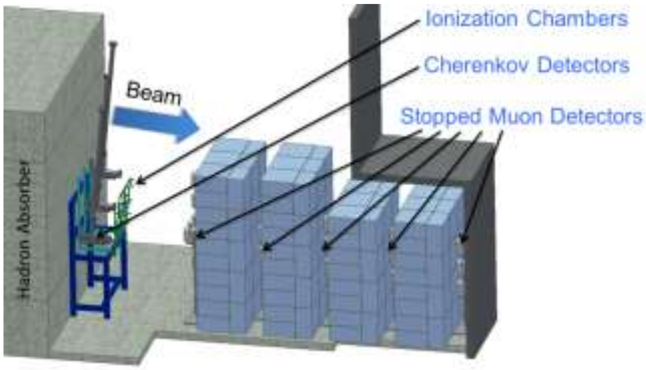

Figure 11. System of tertiary muon detectors, which will monitor the LBNE neutrino beam in the first phase.

Full 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 12 (top). This is the start of a long-term program that will achieve the full goals of LBNE in time and allow the Standard Model with massive neutrinos to be probed well beyond our current understanding. Subsequent phases will include [13,16]:

- 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 kt fiducial mass placed at 1480 m depth, which will further improve the precision of the primary long-baseline oscillation measurements (Fig. 12 (bottom), solid-line), 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 (Fig. 12 (bottom), dashed-line).

Project Planning and Time Line The conceptual design for LBNE has been completed, and preliminary but solidly grounded cost and schedule estimates have been assembled. Discussions are in progress with potential non-U.S. collaborators that may provide sufficient resources to allow LBNE to include a near detector in the first phase and place the detector underground. CD-1 for the 1st phase LBNE Project was approved in December 2012 with a Total Project Cost of $867M and 40% contingency on the remaining project costs. Early construction at Fermilab will start in spring 2015, CD-2 is planned by the end of 2015, full construction will start in 2016, and the project will be completed in 2023. Expanding the scope with the help of non-DOE partners could delay completion by 1-2 years, depending on what is added. The current timeline is shown in Fig. 13.

Opportunities for Collaboration The initial phase of LBNE will perform the world's best measurements of neutrino oscillations parameters such as mass hierarchy and the three-flavor model CP phase. Subsequent phases of the experiment will expand the science scope to higher precision measurements of neutrino properties including sensitivity to non-standard interactions, the possibility to observe nucleon decay and the unique sensitivity to the electron-flavor of the neutrino flux from supernovae. To enable the broader science scope of the experiment will require some combination of a larger far detector mass, placement of the far detector deep underground and a highly capable near neutrino detector. Each of these enhancements will cost roughly an additional 15% of the phase 1 project cost [17]. The opportunity to leverage the large US investment in the phase 1 program with a modest incremental investment is likely to be very attractive to international partners. Japan and Europe have both established this science as very high priority but recognize that the US is substantially ahead in the planning process. The LBNE leadership and FNAL directorate are actively engaged in discussions with a number of potential partners, in Europe, Asia, and the Americas, with respect to potential scientific, technical and financial contributions.

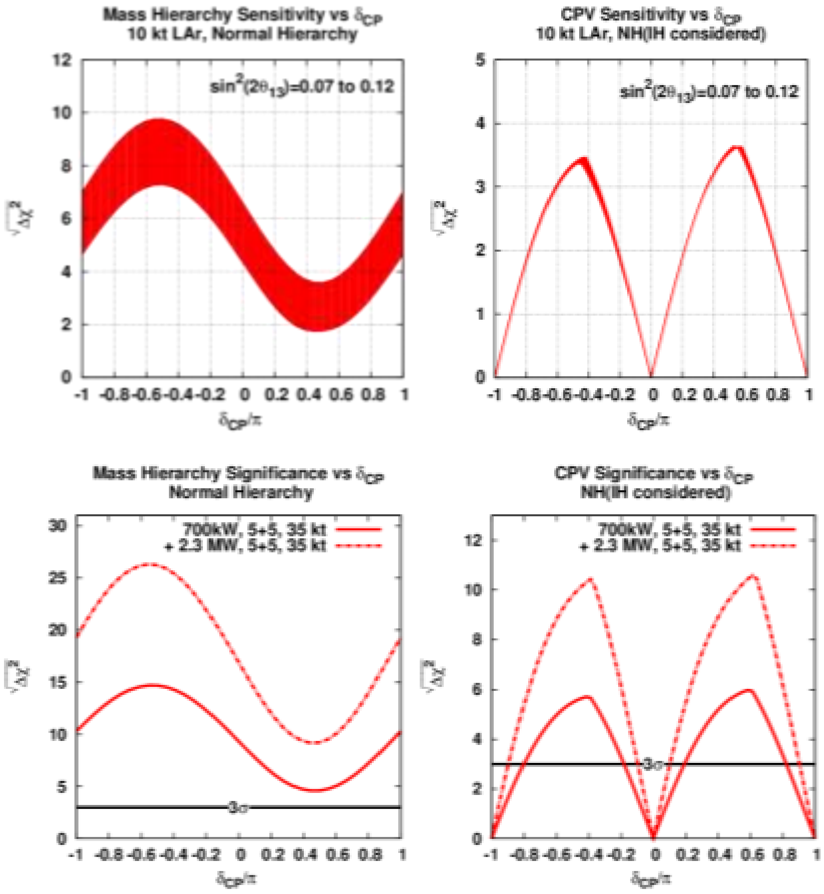

Figure 12. Significance[1] for determining the hierarchy (top left) and CP violation (top right) as a function of δ_{CP} for the first phase of LBNE (Note: Prior results from NOvA and T2K will increase the significance of LBNE results by a modest amount). Projections are for 5+5 years of 700 kW $\nu + \bar{\nu}$ of a 10 kt fiducial mass LAr TPC at Homestake. 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 results presented by Daya Bay at Neutrino 2012. The bottom plots shows MH and CPV significance with the full LBNE detector mass (solid line) and with the increased beam power of Project X (dashed line).

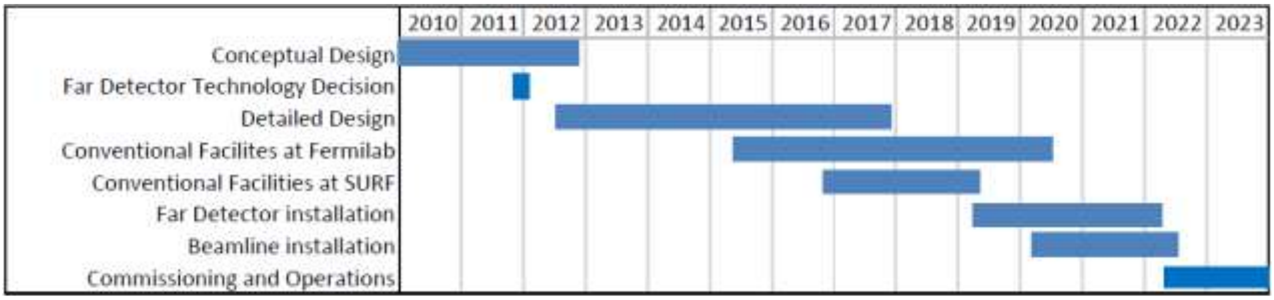

Figure 13. The current schedule for LBNE construction. The schedule remains flexible and may depend on the level of international participation.

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[1] For sufficiently large values of $\Delta\chi^2$, the square root of this value for Gaussian distributions yields the significance in units of σ.

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