Chapter 1 Introduction and Executive Summary

The Long-Baseline Neutrino Experiment (LBNE) will provide a unique, world-leading program for the exploration of key questions at the forefront of particle physics and astrophysics.

Chief among its potential discoveries is that of matter-antimatter symmetry violation in neutrino flavor mixing — a step toward unraveling the mystery of matter generation in the early Universe. Independently, determination of the neutrino mass ordering and precise measurement of neutrino mixing parameters by LBNE may reveal new fundamental symmetries of Nature.

To achieve its ambitious physics objectives as a world-class facility, LBNE has been conceived around three central components:

1. an intense, wide-band neutrino beam
2. a fine-grained *near* neutrino detector just downstream of the neutrino source
3. a massive liquid argon time-projection chamber (LArTPC) deployed as a *far* neutrino detector deep underground, 1,300 km downstream; this distance between the neutrino source and far detector — the *baseline* — is measured along the line of travel through the Earth

The neutrino beam and near detector will be installed at the Fermi National Accelerator Laboratory (Fermilab), in Batavia, Illinois. The far detector will be installed at the Sanford Underground Research Facility in Lead, South Dakota.

The location of its massive high-resolution far detector deep underground will enable LBNE to significantly expand the search for proton decay as predicted by Grand Unified Theories, as well as study the dynamics of core-collapse supernovae through observation of their neutrino bursts, should any occur in our galaxy during LBNE's operating lifetime.

The near neutrino detector will enable high-precision measurements of neutrino oscillations, thereby enhancing the sensitivity to matter-antimatter symmetry violations and will exploit the potential of high-intensity neutrino beams as probes of new physics.

With its extensively developed design and flexible configuration, LBNE provides a blueprint for an experimental program made even more relevant by recent neutrino mixing parameter measurements.

1.1 Overview

Although neutrinos are the most abundant of known matter particles (fermions) in the Universe, their properties are the least well understood. The very existence of neutrino mass constitutes evidence of physics beyond the Standard Model. Understanding the nature of neutrinos has consequently become an essential goal for particle physics.

Observations of oscillations of neutrinos from one type (flavor) to another in numerous recent experiments have provided evidence for neutrino flavor mixing and for small, but nonzero, neutrino masses. The framework characterizing these observations is similar to that describing corresponding phenomena in the quark sector, but with a very different pattern of mixing angle values. As in the quark case, this framework involves a phase parameter, $\delta_{\rm CP}$, that changes sign under combined charge conjugation and parity (CP) reversal operations and thus would lead to CP symmetry-violating asymmetries between the pattern of oscillations for neutrinos and antineutrinos. While groundbreaking on its own, the observation of such asymmetries would also provide an experimental underpinning for the basic idea of leptogenesis* as an explanation for the Baryon Asymmetry of the Universe (BAU).

Neutrino oscillation data so far tell us about differences in the squared masses of the neutrino mass states, and about the sign of the mass-squared difference between two of the states, but not about the difference of those with respect to the third, which may be heavier (*normal* ordering) or lighter (*inverted* ordering) than the other two. Resolving this neutrino mass hierarchy ambiguity, along with precise measurements of neutrino mixing angles, would have significant theoretical, cosmological and experimental implications. One important consequence of mass hierarchy determination, in particular, would be the impact on future experiments designed to determine whether — uniquely among the fundamental fermions — neutrinos are their own antiparticles, so-called *Majorana* particles. Though long suspected, this hypothesis that neutrinos are Majorana particles has yet to be either established or ruled out. Strong evidence for the *inverted* hierarchy would establish conditions required by the next generation of neutrinoless double-beta decay searches to settle this question even with a null result (no observation). Because the forward scattering of neutrinos in matter alters the oscillation pattern in a hierarchy-dependent way, the long baseline of LBNE — with the neutrinos traveling through the Earth's mantle — enables a decisive determination of the hierarchy, independent of the value of $\delta_{\rm CP}$.

Additionally, the high-precision determination of oscillation parameters such as mixing angles and squared-mass differences will provide insight into the differences between the quark and lepton mixing patterns, which is necessary for deciphering the flavor structure of physics in the Standard Model. Taken together, the above suite of measurements will thoroughly test the standard three-neutrino flavor paradigm that guides our current understanding, and will provide greatly extended

*Leptogenesis refers to the mechanisms that generated an asymmetry between leptons and antileptons in the early Universe, described in Section 2.2.1.

sensitivity to signatures for nonstandard neutrino interactions in matter.

The arena of non-accelerator physics using massive underground detectors such as the LBNE far detector is also ripe with discovery potential. The observation of nucleon decay would be a watershed event for the understanding of physics at high energy scales. Neutrinos from supernovae are expected to provide key insights into the physics of gravitational collapse, and may also reveal fundamental properties of the neutrino.

Among massive detectors designed for neutrino and nucleon decay physics, the LArTPC technology offers unmatched capabilities for position and energy resolution and for high-precision reconstruction of complex interaction topologies over a broad energy range. It also provides a compact, scalable approach for achieving the required sensitivity to the primary physics signatures to be explored by LBNE. As these capabilities are also important for non-accelerator neutrino physics, LBNE will complement the large, underground water Cherenkov and/or scintillator-based detectors that may be operating in parallel. LArTPC detectors are especially well-suited to proton decay modes such as the supersymmetry-favored $p \to K^+\overline{\nu}$ mode, uniquely providing detection efficiency and background rejection sufficient to enable a discovery with a single well-reconstructed event. With regard to supernova-neutrino detection, liquid argon detectors are primarily sensitive to the ν_e component of the flux, while $\overline{\nu}_e$ interactions dominate for water and scintillator-based detectors. Thus, LBNE will be sensitive to different features of the supernova-neutrino production process. Finally, the LArTPC technology opens up an avenue for precision studies of oscillation physics with atmospheric neutrinos, thereby augmenting the results of the beam-based measurements at the core of the experiment.

The highly capable near detector will measure the absolute flux and energy scales of all four neutrino species in the LBNE beam, as well as neutrino cross sections on argon, water, and other nuclear targets in the beam's energy range. These measurements are needed to attain the ultimately desired precision of the oscillation parameter measurements. Additionally, the near detector will enable a broad range of precision neutrino-interaction measurements, thereby adding a compelling scientific program of its own.

The unique combination in LBNE of a 1,300-km baseline, exceptional resolution, large target mass and deep underground location offers opportunity for discovery of entirely unanticipated phenomena. History shows that ambitious scientific endeavors with leading-edge instruments have often been rewarded with unexpected signatures of new physics.

LBNE is an extensively developed experiment whose execution will have substantial impact on the overall direction of high energy physics (HEP) in the U.S. The U.S. Department of Energy (DOE) has endorsed the science objectives of LBNE, envisioning the experiment as a phased program, and has given first stage (CD-1) approval with a budget of $867M toward the initial phase. The science scope of this and subsequent phases will depend on the level of investment by additional national and international partners.

This document outlines the LBNE physics program and how it may evolve in the context of long-term planning studies [1]. The physics reach of this program is summarized under scenarios that are consistent with short-, medium- and long-term considerations. The general conclusions regarding the scientific capabilities of LBNE in a phased program are twofold:

1. A full-scope LBNE will provide an exciting broad-based physics program with exceptional capabilities for all of the identified core physics objectives, and many additional ones.

2. A first phase with a LArTPC far detector of fiducial[†] mass 10 kt[‡] or greater will substantially advance the field of neutrino oscillation physics while laying the foundations for a broader physics program in a later phase.

Section 1.2 provides the context for development of LBNE as a phased program that maintains flexibility for enhancements in each of its stages through the contributions of additional partners. The physics reach of LBNE at various stages is summarized in Section 1.3.

[†]In neutrino experiments, not all neutrino interactions in the instrumented (active) volume of a detector are used for physics studies. Only interactions that are well contained within the instrumented volume are used. The smaller volume of detector that encompasses the neutrino interactions is known as the *fiducial volume* and the target mass contained within it is known as the *fiducial mass*. Unless otherwise noted, this document will use fiducial mass to characterize the far detector size.

[‡]The *kt* refers to a metric kiloton. A metric ton is equivalent to 1,000 kg.

1.2 Development of a World-Class Experiment

To achieve the transformative physics goals of LBNE in an era of highly constrained funding for basic research in the U.S., the conceptual design has evolved so as to provide a scalable, phased and global approach, while maintaining a U.S. leadership role as the host for a global facility. International partnerships are being actively pursued to both enhance and accelerate the LBNE Project.

LBNE's primary beamline is designed to operate initially with a beam power of 1.2 MW, upgradable to 2.3 MW. This beamline extracts protons with energies from 60 to 120 GeV from the Fermilab Main Injector. The protons collide with a target to generate a secondary beam of charged particles, which in turn decay to generate the neutrino beam.

The liquid argon TPC far detector technology combines fine-grained tracking with total absorption calorimetry. Installed 4,850 ft underground to minimize backgrounds, this detector will be a powerful tool for long-baseline neutrino oscillation physics and underground physics such as proton decay, supernova neutrinos and atmospheric neutrinos. The far detector design is scalable and flexible, allowing for a phased approach, with an initial fiducial mass of at least 10 kt and a final configuration of at least 34 kt.

A high-precision near detector is planned as a separate facility allowing maximal flexibility in phasing and deployment.

The concept of a high-intensity neutrino beam directed toward a distant, massive underground detector to simultaneously investigate the nature of the neutrino, proton decay and astrophysical sources of neutrinos has been under serious investigation since the late 1990s [2,3,4,5,6,7,8,9]. Since that time both the science goals and concepts for implementation have been the subject of intense study and review by distinguished panels. These panels include the National Academies Neutrino Facilities Assessment Committee in 2003 [10], the National Science and Technology Council Committee on Science in 2004 [11], the National Academies EPP2010 panel in 2006 [12], the HEPAP/NSAC Neutrino Scientific Assessment Group in 2007 [13], the HEPAP Particle Physics Project Prioritization Panel (P5) in 2008 [14], the National Academies ad hoc Committee to Assess the Science Proposed for DUSEL in 2011 [15], and most recently the HEPAP Facilities Subpanel in 2013 [16]. High-level studies performed in Europe and Asia have come to similar conclusions (e.g., [17]) about the merits and feasibility of such a program.

1.2.1 Long-Term Vision

LBNE as described in this document has been developed by a collaboration formally established in 2009, which currently comprises over 475 collaborators from over 80 institutions in six countries. In January 2010 the DOE formally recognized the LBNE science objectives with approval of the mission need statement (CD-0) [18]. This action established LBNE as a DOE project. Fermilab has recognized LBNE as a central component of its long-term future program.

The central role of LBNE within the U.S. particle physics program has been acknowledged in other documents prepared for the 2013 particle physics community planning exercise [1], including the Project X Physics Book [19] and the reports from Intensity Frontier working groups on neutrino physics [20] and baryon number violation [21].

The LBNE conceptual design reflects a flexible and cost-effective approach to next-generation neutrino physics experiments that maintains a world-leadership role for the U.S. over the long term. The full-scope LBNE includes a 34-kt fiducial mass (50-kt total) far detector located in a new experimental area to be excavated at the 4,850-ft level of the Sanford Underground Research Facility[§] in the former Homestake Mine, and a fine-grained near neutrino detector located on the Fermilab site. Simultaneous construction of a new neutrino beamline at Fermilab would permit operation with an initial beam power of 1.2 MW, enabled by upgrades to the front end of the accelerator complex carried out within the Proton Improvement Plan-II (PIP-II) program [22]. In anticipation of potential enhancements beyond PIP-II [23], the beamline is designed to support upgrades to accommodate a beam power of 2.3 MW. The 1,300-km baseline is in the optimal range for the neutrino oscillation program. The cosmic ray shielding provided by the deep underground site for the far detector enables the non-accelerator portion of the physics program, including proton decay searches, detailed studies of neutrino bursts from galactic supernovae, and precision analyses of atmospheric-neutrino samples.

The overall physics reach of LBNE is predominantly limited by detector mass. From the outset, a guiding principle of the far detector design has been scalability. The conceptual design for the full-scope detector, consisting of two identical 17-kt (25-kt total) TPC modules housed within separate vessels (cryostats), employs technology developed by the liquefied natural gas (LNG) storage and transport industry. The TPC modules themselves consist of arrays of modular anode and cathode plane assemblies (APAs and CPAs) that are suspended from rails affixed to the top of the cryostats. The APA/CPA dimensions are chosen for ease of transportation and installation. The modularity of the detectors allows flexibility in the geometry and phased construction of the LBNE far detector complex. Cost-effective designs for larger detector masses are readily obtained by increasing the vessel size and simply adding APA/CPA units, thereby also exploiting economies of scale and benefiting from an increased ratio of volume to surface area. Detector mass may also be increased through the addition of distinct detectors of the same or a different technology, either during initial

[§]Much larger detectors could also be accommodated at this facility.

construction or in a later phase.

1.2.2 Present Status of the LBNE Project

Since DOE CD-0 approval, a compete conceptual design for the full-scope LBNE has been developed, consisting of a 34-kt LArTPC far detector located 4,850 feet underground, a 1,300-km baseline, a highly capable near neutrino detector, and a multi-megawatt-capable neutrino beamline. This design has been thoroughly reviewed, and found to be sound, most recently at a Fermilab Director's CD-1 Readiness Review in March 2012 [24]. Since then, considerable effort has been devoted to understanding how the LBNE Project can be staged so as to accommodate anticipated budget conditions while maintaining compelling physics output at each stage [25]. This process led to a first-phase configuration that was reviewed by the DOE in October [26] and November 2012 [27], and that received CD-1 approval [28] in December 2012. This configuration [29,30,31,32,33,34] maintained the most important aspects of LBNE: the 1,300-km baseline to the Sanford Underground Research Facility, a large — of order tens of kilotons in fiducial mass — LArTPC far detector design, and a multi-megawatt-capable, wide-band neutrino/antineutrino beam. However, the far detector size was limited at CD-1 to 10 kt and placed at the surface under minimal overburden, and the near detector was deferred to a later phase.

The DOE CD-1 approval document [28] explicitly allows adjustment of the scope of the first phase of LBNE in advance of CD-2 if additional partners bring significant contributions to LBNE. *Using the CD-1 DOE funding as the foundation, the goal for the first phase of LBNE is a deep underground far detector of at least 10 kt, placed in a cavern that will accommodate up to a 34-kt detector, coupled with a 1.2-MW neutrino beamline, and a highly capable near detector.* This goal has been endorsed by the LBNE Collaboration, the LBNE Project, the Fermilab directorate, and the DOE Office of High Energy Physics. Since a large portion of the LBNE Project cost is in civil infrastructure, funding contributions from new partners could have considerable impact on the experimental facilities, and therefore the physics scope, in the first phase.

1.2.3 Global Partnerships

Global conditions are favorable for significant international partnerships in developing and building LBNE. As an example, the 2013 update [17] of the European Strategy for Particle Physics document places long-baseline neutrino physics among the highest-priority large-scale activities for Europe, recognizing that it requires "significant resources, sizeable collaborations and sustained commitment." It includes the primary recommendation of exploring "the possibility of major participation in leading long-baseline neutrino projects in the U.S. and Japan." As of March 2014 the LBNE Collaboration includes institutions from the U.S., Brazil, India, Italy, Japan and the United Kingdom. Discussions with a number of potential international partners are underway — some already at an advanced stage. A summary of recent progress in these discussions can be found in the presentation of LBNE status to the U.S. Particle Physics Projects Prioritization Panel in November 2013 [35].

1.2.4 Context for Discussion of Physics Sensitivities

To reflect the physics reach of various phasing scenarios, this document presents many of the parameter sensitivities for the accelerator-based neutrino topics as functions of exposure, defined as the product of detector fiducial mass, beam power and run time. As needed, the capabilities of both a 10-kt first-phase configuration and the full 34-kt configuration are explicitly highlighted, each benchmarked for six to ten years of operations with a 1.2-MW beam power from the PIP-II accelerator upgrades at Fermilab. Since the U.S. program planning exercises currently under way look beyond the present decade, this document also presents the long-term physics impact of the full-scope LBNE operating with the 2.3-MW beam power available with further anticipated upgrades to the Fermilab accelerator complex.

1.3 The LBNE Physics Program

The technologies and configuration of the planned LBNE facilities offer excellent sensitivity to a range of physics processes:

- The muon-neutrino (ν_μ) beam produced at Fermilab with a peak flux at 2.5 GeV, coupled to the baseline of 1,300 km, will present near-optimal sensitivity to neutrino/antineutrino charge-parity (CP) symmetry violation effects.
- The long baseline of LBNE will ensure a large matter-induced asymmetry in the oscillations of neutrinos and antineutrinos, thus providing a clear, unambiguous determination of the mass ordering of the neutrino states.
- The near detector located just downstream of the neutrino beamline at Fermilab will enable high-precision long-baseline oscillation measurements as well as precise measurements and searches for new phenomena on its own using the high-intensity neutrino beam.
- The deep-underground LArTPC far detector will provide superior sensitivities to proton decay modes with kaons in the final states, modes that are favored by many Grand Unified and supersymmetric theoretical models.
- Liquid argon as a target material will provide unique sensitivity to the electron-neutrino (ν_e) component of the initial burst of neutrinos from a core-collapse supernova.
- The excellent energy and directional resolution of the LArTPC will allow novel physics studies with atmospheric neutrinos.

This section summarizes LBNE's potential for achieving its core physics objectives based on the current experimental landscape, scenarios for staging LBNE, and the technical capabilities of LBNE at each stage.

LBNE's capability to achieve the physics objectives described in this document has been subject to extensive review over a number of years. In addition to the various reviews of the LBNE Project described in Section 1.2, reviews that focused strongly on LBNE's science program include the DOE Office of Science Independent Review of Options for Underground Science in the spring of 2011 [36], the LBNE Science Capabilities Review (by an external panel commissioned by LBNE) [37] in the fall of 2011, and the LBNE Reconfiguration Review [25] in the summer of 2012.

1.3.1 Neutrino Mixing, Mass Hierarchy and CP Violation

Neutrino Mass Hierarchy: The 1,300-km baseline establishes one of LBNE's key strengths: sensitivity to the matter effect. This effect leads to a large discrete asymmetry in the $\nu_\mu \to \nu_e$ versus $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation probabilities, the sign of which depends on the mass hierarchy (MH). At 1,300 km this asymmetry is approximately $\pm 40\%$ in the region of the peak flux; this is larger than the maximal possible CP-violating asymmetry associated with $\delta_{\rm CP}$, meaning that both the MH and $\delta_{\rm CP}$ can be determined unambiguously with high confidence within the same experiment using the beam neutrinos.

In detail, the sensitivity of LBNE depends on the actual values of poorly known mixing parameters (mainly $\delta_{\rm CP}$ and $\sin^2\theta_{23}$), as well as the true value of the MH itself. The discrimination between the two MH hypotheses is characterized as a function of the *a priori* unknown true value of $\delta_{\rm CP}$ by considering the difference, denoted $\Delta\chi^2$, between the $-2\log\mathcal{L}$ values calculated for a data set with respect to these hypotheses, considering all possible values of $\delta_{\rm CP}$¶. In terms of this test statistic, the MH sensitivity of LBNE with 34 kt, and running three years each in ν and $\overline{\nu}$ modes in a 1.2-MW beam is illustrated in Figure 1.1 for the case of normal hierarchy for two different values of $\sin^2\theta_{23}$. Across the overwhelming majority of the parameter space for the mixing parameters that are not well known (mainly $\delta_{\rm CP}$ and $\sin^2\theta_{23}$), LBNE's determination of the MH will be definitive, but even for unfavorable combinations of the parameter values, a statistically ambiguous outcome is highly unlikely.

The least favorable scenario corresponds to a true value of $\delta_{\rm CP}$ in which the MH asymmetry is maximally offset by the leptonic CP asymmetry, and where, independently, $\sin^2\theta_{23}$ takes on a value at the low end of its experimentally allowed range. For this scenario, studies indicate that with a 34-kt LArTPC operating for six years in a 1.2-MW beam, LBNE on its own can (in a typical data set) distinguish between normal and inverted hierarchy with $|\Delta\chi^2| = \overline{|\Delta\chi^2|} = 25$. This corresponds to a $\geq 99.9996\%$ probability of determining the correct hierarchy. In $> 97.5\%$ of data sets, LBNE will measure $|\Delta\chi^2| > 9$ in this scenario, where measuring $|\Delta\chi^2| = 9$ with an expected value of 25 corresponds to a significance in excess of three Gaussian standard deviations.

Concurrent analysis of the corresponding atmospheric-neutrino samples in an underground detector will improve the precision with which the MH is resolved. It is important to note that for the initial stages of LBNE, a greatly improved level of precision in the determination of the MH can be achieved by incorporating constraints from NOνA and T2K data. With an initial 10-kt detector, for half the range of possible $\delta_{\rm CP}$ values, the expected significance exceeds $\overline{\Delta\chi^2} = 25$; again this corresponds to a $\geq 99.9996\%$ probability of determining the correct hierarchy. To put this in context, it is notable that even an extended NOνA program [38] at four times its nominal exposure

¶For the case of the MH determination, the usual association of this test statistic with a χ^2 distribution for one degree of freedom is incorrect; additionally the assumption of a Gaussian probability density implicit in this notation is not exact. The discussion in Chapter 4 provides a brief description of the statistical considerations.

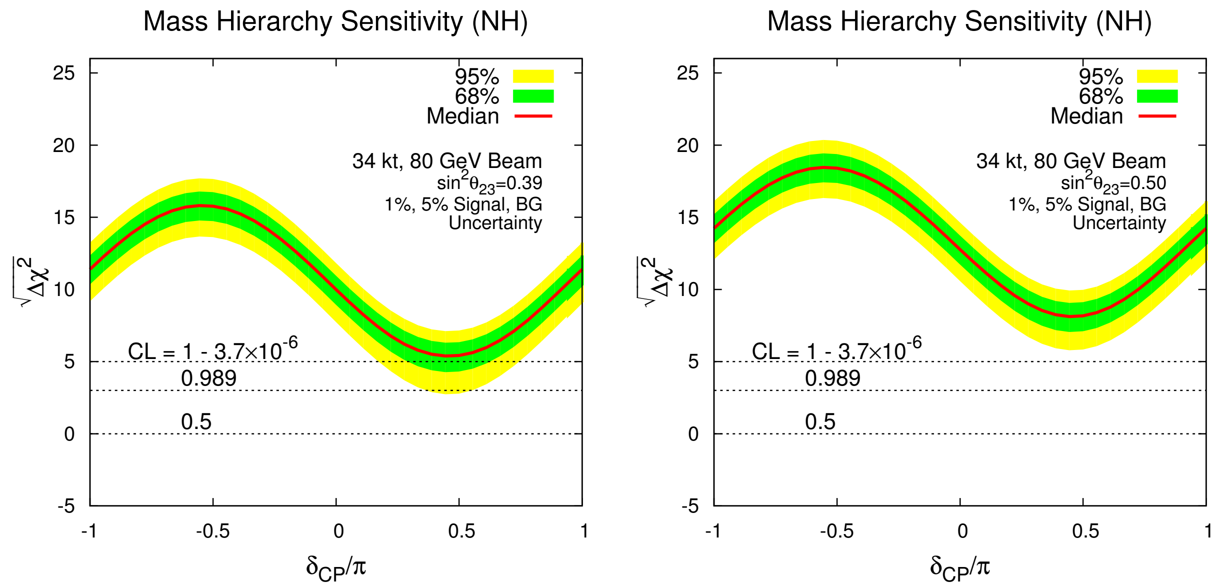

Figure 1.1: The square root of the mass hierarchy discrimination metric $\Delta\chi^2$ is plotted as a function of the unknown value of $\delta_{\rm CP}$ for the full-scope LBNE with 34 kt, 3+3 ($\nu + \overline{\nu}$) years of running in a 1.2-MW beam, assuming normal hierarchy. The plot on the left is for an assumed value of $\sin^2\theta_{23} = 0.39$ (based on global fits and assuming worst-case θ_{23} octant), while that on the right is for $\sin^2\theta_{23} = 0.5$ (maximal mixing). In each plot, the red curve represents the median experimental value expected ($\sqrt{\overline{\Delta\chi^2}}$), estimated using a data set absent statistical fluctuations, while the green and yellow bands represent the range of $\Delta\chi^2$ values expected in 68% and 95% of all possible experimental instances, respectively. For certain values of $\sqrt{\Delta\chi^2}$, horizontal lines are shown, indicating the corresponding confidence levels ($1-\alpha$ in the language of hypothesis testing) with which a typical experiment ($\beta = 0.5$) correctly determines the MH, computed according to a Bayesian statistical formulation (Section 4.3.1 for further discussion).

(of six years of operation at 700 kW), would have coverage at the $\overline{\Delta\chi^2} = 9$ level or better for only 40% of the $\delta_{\rm CP}$ range.

CP Violation and the Measurement of $\delta_{\rm CP}$: The LBNE program has two somewhat distinct objectives with regard to CP symmetry violation in the $\nu_\mu \to \nu_e$ oscillation channel. First, LBNE aims to make a precise determination of the value of $\delta_{\rm CP}$ within the context of the standard three-flavor mixing scenario described by the PMNS matrix (discussed in Section 2.2). Second, and perhaps more significantly, LBNE aims to observe a signal for leptonic CP violation, independent of the underlying nature of neutrino oscillation phenomenology. Within the standard three-flavor mixing scenario, such a signal will be observable, provided $\delta_{\rm CP}$ is not too close to either of the values for which there is no CP violation (zero and π). Together, the pursuit of these two goals provides a thorough test of the standard three-flavor scenario.

Figure 1.2 shows the expected 1σ resolution for $\delta_{\rm CP}$ as a function of exposure for a proton beam power of 1.2 MW. At this beam power, in a six-year run, a 10-kt far detector will be able to measure $\delta_{\rm CP}$ to $\pm\,20^\circ - 30^\circ$ (depending on its value), independent of other experiments. A full-scope LBNE operating with multi-megawatt beam power in a later phase, will achieve a precision better than $\pm 10°$, comparable to the current precision on the CP phase in the CKM matrix in the quark sector.

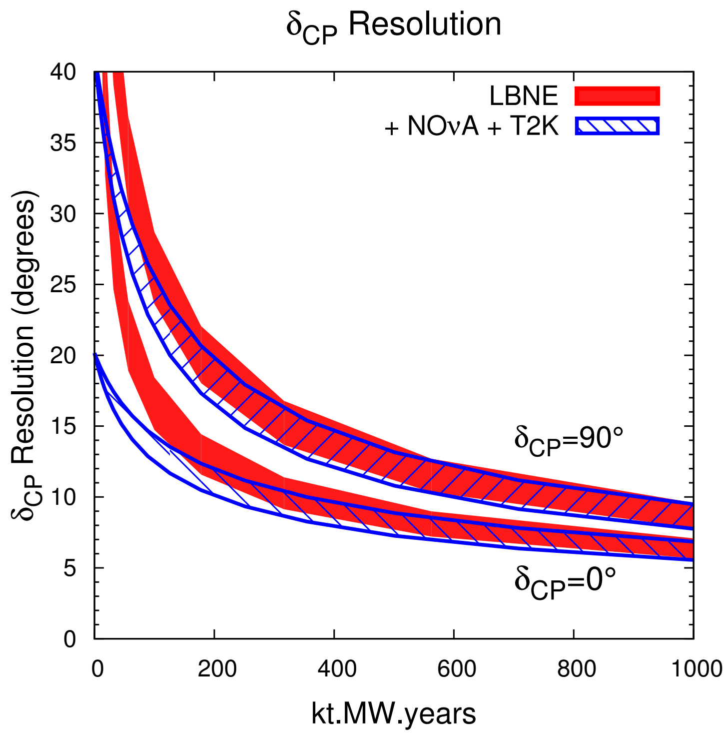

Figure 1.2: The expected 1σ resolution for $\delta_{\rm CP}$ as a function of exposure in detector mass (kiloton) $\times$ beam power (MW) $\times$ time (years). The red curve is the precision that could be obtained from LBNE alone, while the blue curve represents the combined precision from LBNE plus the T2K and NOνA experiments. The width of the bands represents variation with the range of beamline design parameters and proton energy values being considered.

LBNE with a 10-kt detector, in combination with T2K and NOνA, will determine leptonic CP violation with a precision of 3σ or greater for $\approx 40\%$ of $\delta_{\rm CP}$ values in a six-year run with 1.2-MW beam power. It is important to note that LBNE alone dominates the combined sensitivity and that T2K and NOνA have very limited sensitivity to CP violation on their own. To reach 5σ for an appreciable fraction of the range of $\delta_{\rm CP}$, the full-scope LBNE will be needed to control systematic errors while accumulating large enough samples in the far detector to reach this level of sensitivity. No experiment can provide coverage at 100%, since CP violation effects vanish as $\delta_{\rm CP} \to 0$ or π.

Determination of $\sin^2 2\theta_{23}$ and Octant Resolution: In long-baseline experiments with ν_μ beams, the magnitude of ν_μ disappearance and ν_e appearance signals is proportional to $\sin^2 2\theta_{23}$ and $\sin^2 \theta_{23}$, respectively, in the standard three-flavor mixing scenario. Current ν_μ disappearance data are consistent with maximal mixing, $\theta_{23} = 45°$. To obtain the best sensitivity to both the magnitude of its deviation from $45°$ as well as its sign (θ_{23} octant), a combined analysis of the two channels is needed [39]. As demonstrated in Chapter 4, a 10-kt LBNE detector will be able to resolve the θ_{23} octant at the 3σ level or better for θ_{23} values less than $40°$ or greater than $50°$, provided $\delta_{\rm CP}$ is not too close to zero or π. A full-scope LBNE will measure θ_{23} with a precision of $1°$ or less, even for values within a few degrees of $45°$.

1.3.2 Nucleon Decay Physics Motivated by Grand Unified Theories

The LBNE far detector will significantly extend lifetime sensitivity for specific nucleon decay modes by virtue of its high detection efficiency relative to water Cherenkov detectors and its low background rates. As an example, LBNE has enhanced capability for detecting the $p \to K^+\overline{\nu}$ channel, where lifetime predictions from supersymmetric models extend beyond, but remain close to, the current (preliminary) Super-Kamiokande limit of $\tau/B > 5.9 \times 10^{33}$ year (90% CL) from a 260-kt $\cdot$ year exposure [40]‖. The signature for an isolated semi-monochromatic charged kaon in a LArTPC is distinctive, with multiple levels of redundancy. A 34-kt LBNE far detector deep underground will reach a limit of 3×10^{34} year after ten years of operation (Figure 1.3), and would see nine events with a background of 0.3 should τ/B be 1×10^{34} year, just beyond the current limit. Even a 10-kt detector (placed underground) would yield an intriguing signal of a few events after a ten-year exposure in this scenario.

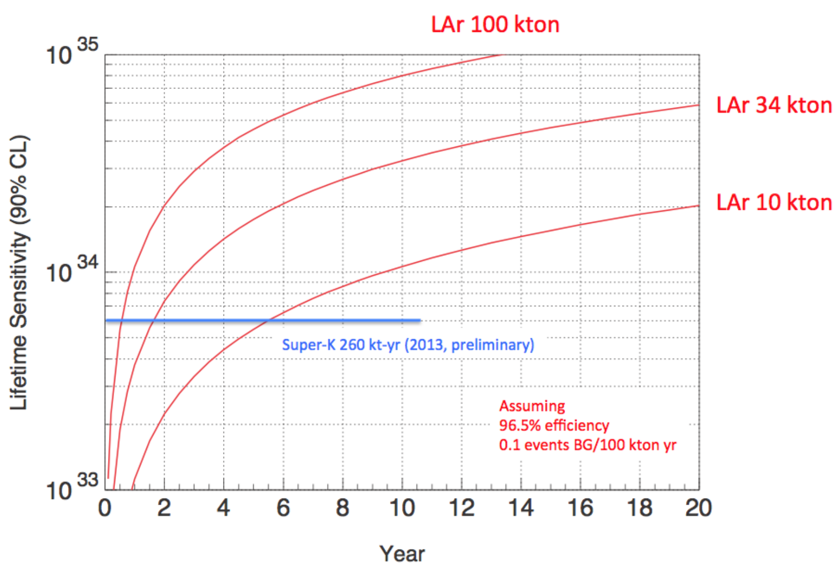

Figure 1.3: Sensitivity to the decay $p \to K^+\overline{\nu}$ as a function of time for underground liquid argon detectors with different masses.

‖The lifetime shown here is divided by the branching fraction for this decay mode, τ/B, and as such is a *partial lifetime*.

1.3.3 Supernova-Neutrino Physics and Astrophysics

The neutrinos from a core-collapse supernova are emitted in a burst of a few tens of seconds duration, with about half in the first second. Energies are in the range of a few tens of MeV, and the luminosity is divided roughly equally between the three known neutrino flavors. Currently, experiments worldwide are sensitive primarily to electron antineutrinos ($\overline{\nu}_e$), with detection through the inverse-beta decay process on free protons**, which dominates the interaction rate in water and liquid-scintillator detectors. Liquid argon has a unique sensitivity to the electron-neutrino (ν_e) component of the flux, via the absorption interaction on ^{40}Ar as follows:

$$\nu_e + {}^{40}\mathrm{Ar} \;\; \rightarrow \;\; e^- + {}^{40}\mathrm{K}^*$$

This interaction can be tagged via the coincidence of the emitted electron and the accompanying photon cascade from the $^{40}\mathrm{K}^*$ de-excitation. About 900 events would be expected in a 10-kt fiducial mass liquid argon detector for a supernova at a distance of 10 kpc. In the neutrino channel the oscillation features are in general more pronounced, since the ν_e spectrum is always significantly different from the ν_μ (ν_τ) spectra in the initial core-collapse stages, to a larger degree than is the case for the corresponding $\overline{\nu}_e$ spectrum. Detection of a large neutrino signal in LBNE would help provide critical information on key astrophysical phenomena such as

1. the neutronization burst
2. formation of a black hole
3. shock wave effects
4. shock instability oscillations
5. turbulence effects

1.3.4 Precision Measurements with a High-Intensity Neutrino Source and High-Resolution Near Detector

The near neutrino detector will provide precision measurements of neutrino interactions, which in the medium to long term are essential for controlling the systematic uncertainties in the long-baseline oscillation physics program. The near detector, which will include argon targets, will measure the absolute flux and energy-dependent shape of all four neutrino species, ν_μ, $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$ to accurately predict for each species the far/near flux ratio as a function of energy. It will also measure the four-momenta of secondary hadrons, such as charged and neutral mesons, produced

**This refers to neutrino interactions with the nucleus of a hydrogen atom in H_2O in water detectors or in hydrocarbon chains in liquid scintillator detectors.

in the neutral and charged current interactions that constitute the dominant backgrounds to the oscillation signals.

With 240,000 (85,000) ν_μ ($\overline{\nu}_\mu$) charged current and 90,000 (35,000) neutral current interactions per ton per 1×10^{20} protons-on-target at 120 GeV in the ν ($\overline{\nu}$) beam, the near detector will also be the source of data for a rich program of neutrino-interaction physics in its own right. These numbers correspond to 10^7 neutrino interactions per year for the range of beam configurations and near detector designs under consideration. Measurement of fluxes, cross sections and particle production over a large energy range of 0.5 GeV to 50 GeV (which can also help constrain backgrounds to proton decay signals from atmospheric neutrinos) are the key elements of this program. Furthermore, since the near detector data will feature very large samples of events that are amenable to precision reconstruction and analysis, they can be exploited for sensitive studies of electroweak physics and nucleon structure, as well as for searches for new physics in unexplored regions (heavy sterile neutrinos, high-Δm^2 oscillations, light Dark Matter particles, and so on).

1.4 Summary

> The LBNE physics program has been identified as a priority of the global HEP community for the coming decades. The facilities available in the U.S. are the best suited internationally to carry out this program and the substantially developed LBNE design is at the forefront of technical innovations in the field. Timely implementation of LBNE will significantly advance the global HEP program and assure continued intellectual leadership for the U.S. within this community.

This chapter has touched only briefly on the most prominent portion of the full suite of physics opportunities enabled by LBNE. The following chapters cover these in detail, as well as topics that were omitted here in the interest of brevity and focus. In Chapter 9 progress toward LBNE physics milestones is addressed, based on one potential scenario for the operation of successive stages of LBNE detector and PIP-II implementations, and the broad role of LBNE is discussed in the context of such scenarios. The present chapter concludes with a summary of its key points.

The primary science goals of LBNE are drivers for the advancement of particle physics. The questions being addressed are of wide-ranging consequence: the origin of flavor and the generation structure of the fermions (i.e., the existence of three families of quark and lepton flavors), the physical mechanism that provides the CP violation needed to generate the Baryon Asymmetry of the Universe, and the high energy physics that would lead to the instability of matter. Achieving these goals requires a dedicated, ambitious and long-term program. No other proposed long-baseline neutrino oscillation program with the scientific scope and sensitivity of LBNE is as advanced in terms of engineering development and project planning. A phased program with a far detector of even modest size in the initial stage (e.g., 10 kt) will enable exciting physics in the intermediate term, including a definitive mass hierarchy determination and a measurement of the CP phase without ambiguities, while providing the fastest route toward achieving the full range of LBNE's science objectives. Should LBNE find that the CP phase is not zero or π, it will have found strong indications ($> 3\sigma$) of leptonic CP violation. Global interest is favorable for contributions from international partners to accelerate and enhance this program, including the LBNE first-phase scope.

Implementing the vision that has brought LBNE to this point will allow the U.S. to host this world-leading program, bringing together the world's neutrino community to explore key questions at the forefront of particle physics and astrophysics. Moreover, the excitement generated by both the technical challenges of mounting LBNE and the potential physics payoffs are widely shared — among the generation of scientists who have been paving the way for these innovations, as well as the young scientists for whom LBNE will provide numerous research opportunities over the next two decades.

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