Alternatives Analysis for the Long-Baseline Neutrino Experiment

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Long-Baseline Neutrino Experiment (LBNE) Project

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Acronyms and Abbreviations

AGS	Alternating Gradient Synchotron
BNL	Brookhaven National Laboratory
CD	Critical Decision
CDR	Conceptual Design Report
CERN	European Organization for Nuclear Research
CF	Conventional Facilities
CNGS	CERN Neutrinos to Gran Sasso
CP	Charge-Parity
DocDB	Document Database (LBNE-doc-####)
DOE	Department of Energy
DUSEL	Deep Underground Science and Engineering Laboratory
EC	Executive Committee
ES&H	Environment, Safety, and Health
Fermilab	Fermi National Accelerator Laboratory
FGT	Fine-Grained Straw-Tube Tracker
FRA	Fermi Research Alliance
FSO	Fermi Site Office
JPARC	Japan Proton Accelerator Research Complex
LANL	Los Alamos National Laboratory
LAr	Liquid Argon Detector
LAr-FD	LAr Far Detector
LArM	Liquid Argon Membrane Tracker
LArTPC	Liquid Argon Time Projection Chamber
LBNE	Long-Baseline Neutrino Experiment
LOG	Laboratory Oversight Group
M&O	Management and Operating
MI	Main Injector
NSF	National Science Foundation
NuMI	Neutrinos from the Main Injector
OHEP	Office of High Energy Physics
PWG	Physics Working Group
R&D	Research and Development

SC	DOE Office of Science
SDSTA	South Dakota Science and Technology Authority
ST	Scintillator Tracker
SURF	Sanford Underground Research Facility
WCD	Water Cherenkov Detector
WC-FD	WC Far Detector
WIPP	Waste Isolation Pilot Plan

1 Introduction

On January 8, 2010, the Department of Energy (DOE) approved the Critical Decision-0 (CD-0): Mission Need for a new long-baseline neutrino experiment that would enable a world-leading program in neutrino physics. Such a program would measure fundamental physical parameters, explore physics beyond the Standard Model and better elucidate the nature of matter and antimatter.

This document presents a high-level alternative analysis to support an optimum acquisition strategy for a new project to carry out this Mission Need. The new project is referred to as the Long-Baseline Neutrino Experiment (LBNE) Project.

2 Executive Summary

The CD-0 Mission Need Statement [**1**] for LBNE calls for construction of an experiment composed of "a large detector illuminated by a distant, intense neutrino source and a much smaller detector located close to the source". A number of alternatives and variables have been carefully considered in the process of determining the complete scope required to meet this Mission Need. The selected alternatives for the CD-1 reference design and described in-depth in the Conceptual Design Report (CDR). Materials developed to support the alternatives are listed in the referenced documents.

The Mission Need Statement does not specify the location of the neutrino source or the Far Site detector; however, there are obvious candidates for each. Following the accelerator upgrades being incorporated into the Fermi National Accelerator Laboratory (Fermilab) NOνA Project[1], protons from the Fermilab Main Injector could provide an appropriate neutrino source. It has been shown that an optimum source-to-detector distance is in the range of 1,000 to 1,500 km [**2**]. Fermilab, in Batavia, IL, is 1,300 km from the Sanford Underground Research Facility (SURF, previously the Sanford Underground Laboratory at Homestake) in Lead, South Dakota, and therefore SURF is a prime candidate site for the large Far Site detector.

The DOE Office of High Energy Physics (OHEP) has advised the LBNE Project that the scope of the LBNE Project will have three main components: 1) the neutrino beamline, 2) the detectors and 3) the conventional facilities at both Fermilab and the far site to support the beamline and the detectors. The LBNE CDR in support of Critical Decision-1 (CD-1) has been developed assuming the configuration of a proton source at Fermilab (Near Site) and a Far Site detector complex at SURF. This document discusses the analysis of other alternatives and the reasons that have led to the preferred choice.

In March 2012 the LBNE Project presented a conceptual design at an independent CD-1 readiness review called by the Director of Fermi National Accelerator Laboratory (Fermilab). Chapter 4 of the current document discuss the alternatives analysis conducted up to that point, with a summary of the reference design as of that date in Section 4.10.

Also in March 2012, for budgetary reasons unrelated to the quality of the design, Dr. W.F. Brinkman, Director of the DOE Office of Science, asked Fermilab to find a path forward to reach the goals of LBNE in a phased approach or with alternative options. The Director of Fermilab formed a Steering Committee and two working groups, a Physics Working Group and an Engineering/Cost Working Group, to address this request. The Steering Committee was charged to identify viable alternatives and provide guidance to the working groups, which were in turn charged, respectively, to analyze the physics reach of various phases and alternatives on a common basis, and to provide cost estimates and analyze the feasibility of the proposed approaches with the same methodology.

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[1] The Accelerator and NuMI upgrades for the NOνA Project will result in the average beam power of 700 kW available for neutrino production.

As of June 2012, the Committee had selected a viable experimental configuration consistent with DOE budgetary guidelines, as detailed in the Steering Committee Report [**3**]. Since then the Project has redesigned portions of the project scope accordingly in preparation for a second independent CD-1 readiness review in September 2012. The alternatives analysis conducted during this reconfiguration period is discussed in Chapter 5.

3 Project Participants

The following list summarizes the institutions and facilities mentioned in this document as participants in the development of the LBNE Project.

Fermi National Accelerator Laboratory -- Day-to-day oversight of the LBNE Project is provided by DOE Office of Science (SC) Fermi Site Office (FSO). As the Management and Operating (M&O) contractor for Fermilab, Fermi Research Alliance (FRA) will be accountable to DOE for carrying out the LBNE Project. Fermilab has established the LBNE Project Management Office that will be responsible for all Research & Development (R&D); conceptual, preliminary, and final design; fabrication; installation; inspection; commissioning; and overall day-to-day management of the Project, in close cooperation and partnership with SURF for those activities occurring at the Far Site. In addition, through the conceptual design phase, Fermilab has led the liquid argon detector, beamline, and conventional facilities subprojects.

Brookhaven National Laboratory – Brookhaven National Laboratory (BNL) led the water Cherenkov detector level 2 project through the conceptual design phase and the far detector technology decision. Following the selection of the liquid argon detector as the preferred choice for the LBNE far detector, some of the BNL personnel are taking on management roles in the LBNE Project Office and in the Far Detector level 2 project.

Los Alamos National Laboratory -- Los Alamos National Laboratory (LANL) was requested by Fermilab to be responsible for the Near Detector for the LBNE Project. LANL agreed to take on this responsibility and the management of this work will take place at LANL.

Sanford Underground Research Facility ––Sanford Underground Research Facility (SURF) is managed by the South Dakota Science and Technology Authority (SDSTA), an agency of the State of South Dakota.

4 Alternatives Analysis to March 2012

4.1 Scientific Strategy

The mass differences and mixing parameters of neutrino oscillations have been now measured by several experiments each designed to measure a separate set of parameters. The entire complement of neutrino experiments to date has measured five of the mixing parameters: three angles, θ_{12}, θ_{23}, and recently θ_{13}, and two mass differences, Δm^2_{21} and Δm^2_{32}. The sign of Δm^2_{21} is known, but not that of Δm^2_{32} (mass hierarchy). The value of θ_{13} [**3**] has been determined to be much smaller than the other two mixing angles, implying that mixing is quantitatively different in the neutrino and quark sectors. With the knowledge of these parameters it is now expected to see large effects of oscillations in the mode $\nu_\mu \rightarrow \nu_e$ and its anti-matter counterpart. With an experiment using a pure muon type of neutrino beam over large distances an appearance spectrum of electron type neutrinos is expected. This spectrum is sensitive to all known parameters in the neutrino sector, and in particular the measurement of the spectrum of both neutrinos and anti-neutrinos is expected to yield the mass hierarchy and an explicit demonstration of Charge-Parity (CP) violation which has never been observed outside the quark sector.

With the facilities provided by the LBNE Project, the LBNE Science Collaboration proposes to mount a broad charge on the science of neutrinos with sensitivity to all known parameters in a single experiment. The focus of the program will be explicit demonstration of leptonic CP violation, if it exists, by precisely measuring the asymmetric oscillations of muon type neutrinos and antineutrinos into electron type neutrinos and antineutrinos.

The goal of the experiment is the most precise measurements of the 3-flavor neutrino-oscillation parameters over a very long baseline and a wide range of neutrino energies, in particular, the CP violating phase in the 3-flavor framework. The unique features of the experiment – the long baseline, the broad band beam, and the high resolution of the detector – will enable the search for new physics that manifests itself as deviations from the expected 3-flavor neutrino oscillation model.

The detector for LBNE is required to be very capable in terms of identification of charged particles such as muons and electrons. Such a detector must have a wide dynamic range in both energy and time response. The detector is also expected to be very large. And therefore, if placed underground the detector is expected to yield extraordinary sensitivity to proton decay which is one of the key goals in particle physics. LBNE intends to take advantage of this opportunity since it is scientifically coupled to possible results on super-symmetry and dark matter detection from either collider or other underground experiments.

Lastly, a sensitive study of supernova neutrinos is essential to understand the physics associated with the various stages of supernova explosions, which are crucial to the origin of heavy elements and thus of life itself. Thus such a study would be of importance to particle physics, nuclear physics and astrophysics.

Supernova neutrinos can be studied sensitively only at a large underground detector. They are a sure bonus from nature that LBNE cannot afford to miss.

The three major goals of LBNE: neutrino oscillations with a focus on CP violation, proton decay, and supernova neutrino detection place requirements on the beam, detector size, depth, and location. These requirements are balanced against the availability of sites, engineering challenges, and financial constraints. In this Alternatives Analysis these issues are discussed, with the aim of arriving at the configuration for LBNE with the broad band beam located at Fermilab, a baseline distance of 1,300 km, and the detector located at the 4850L of SURF.

4.2 The Experimental Baseline

The location of the Far Detector determines the experiment baseline, defined as the distance been the proton source and the Far Site detector, which is a key parameter in the experiment's sensitivity to neutrino oscillations. To obtain the appearance spectrum of electron neutrinos with the best physics sensitivity, the longest practical baseline length consistent with the expected energy spectrum of muon neutrinos from the available proton accelerator sources is needed.

An excellent discussion about the length of the baseline can be found in [**4**], with the highlights of the discussion summarized here. The $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of neutrino energy and baseline is shown in Figure 4-1. It is important to note that signal event rates do not drop as $1/L^2$ as one might expect. Several effects enhance the appearance event rate as a function of baseline which compensates for the drop in neutrino flux/m^2:

1) The ν_e appearance oscillation maxima occur at $L/E \sim= 515(2n\text{-}1)$ km/GeV where E is the neutrino energy in GeV and n is the number of the oscillation node. At longer baselines, the oscillations occur at higher energies as shown in Figure 4-1. Neutrino cross-sections are proportional to E to for E > 0.5 eV, therefore the appearance event rate at the oscillation maxima increases as L.

2) At longer distances the ν_e appearance spectrum occurs over a wider range of energies, this further enhances the number of ν_e neutrinos appearing when using a broad-band on-axis beam spectrum well coupled to the range of neutrino energies where oscillations occur.

3) The matter effect, assuming a normal hierarchy, enhances the appearance probability for neutrinos. If the hierarchy is inverted, the anti-neutrino appearance rate is enhanced.

The backgrounds to the oscillation drops slightly faster than $1/L^2$ because the ν_e oscillation due to the solar mass splitting reduces the beam's intrinsic background. Furthermore the background from neutral-current events – which tends to be the largest single background component – piles up at lower visible energies. The result, to first order, is the signal over the square root of the background remains the same or improves as a function of baseline. An example is shown in Figure 4-2. The expected ν_e appearance spectrum given $\sin^2(2\theta_{13}) = 0.1$ [**3**] for an identical 34-kt LAr detector placed on axis in the NuMI beamline at Soudan (L=735 km) and placed on-axis in the LBNE beam at SURF (L=1,300 km) is shown. The event rate at both baselines is similar but the S:B is worse at the shorter baseline.

More importantly, the changes in the spectrum for maximal CP violation are less distinguishable at the shorter baseline. This is driven by the fact that the impact of CP violation distorts the spectrum in predictable ways, and it is larger in the region of the secondary oscillation nodes which occur at lower energy (Figure 4-3). It is difficult to produce sufficient neutrino fluxes with energies < 1 GeV using traditional horn focused neutrino beams. The common solution to go off-axis to enhance the low energy neutrino flux results in a large loss of total flux due to the solid angle effect. The longer the baseline, the more experimentally accessible the secondary oscillation nodes are in long-baseline oscillation experiments. Figure 4-1, shows that baselines > 1,000 km are required such that the first two oscillation nodes occur at energies > 500 MeV. Below 500 MeV, Fermi motion and final state interactions in the target nucleus smear out the oscillation features.

A longer baseline significantly improves sensitivity to the mass hierarchy, as matter effects increase with the baseline. A baseline of at least 1,000 km is required to achieve 3σ sensitivity to the mass hierarchy for all possible values of the CP-violating phase given $\sin^2(2\theta_{13}) = 0.1$ [**3**]. The sensitivity to the mass hierarchy essentially plateaus for baselines above 1,500 km [**4**]. There is a significant probability that the mass hierarchy will not be resolved with baselines less than 1,000 km, this will also limit the experiment's ability to measure the CP phase, δ_{cp}. For baselines greater than 2,000 km, sensitivity to CP violation will come mainly from the lower energy nodes of oscillations since the first node will be dominated by matter effects dominating neutrino/anti-neutrino asymmetries, masking effects from the CP-violating phase. As the baseline increases, the energy of the oscillation maxima also increases. To optimize for this, the focusing configuration can be changed to provide a higher-energy neutrino spectrum, typically by increasing the separations between target and horn and between the two horns. Baselines greater than 2,000 km have also been considered for this physics program and, in principle, could have some advantages over the shorter baseline. The LBNE beam simulation with a 270 m decay pipe and the target pulled back 1.5 m from the first horn was used to study the physics capabilities of baselines greater than 2,000 km. This beam tune only covers the first oscillation node at baselines > 2,000 km which is very broad, but where matter effects dominate the CP asymmetries. The impact of different baselines on the measurement of the CP-violating phase, δ_{cp}, have been studied, as shown in Figure 4-4. LBNE has changed the beam choice for each baseline to improve the sensitivity by using off-axis beams for short baselines and the higher energy tunes for very long baselines. Baselines between 1,000 and 1,500 km have been found to have the best sensitivity both to the mass hierarchy and CP violation with practically realizable beam configurations and running conditions.

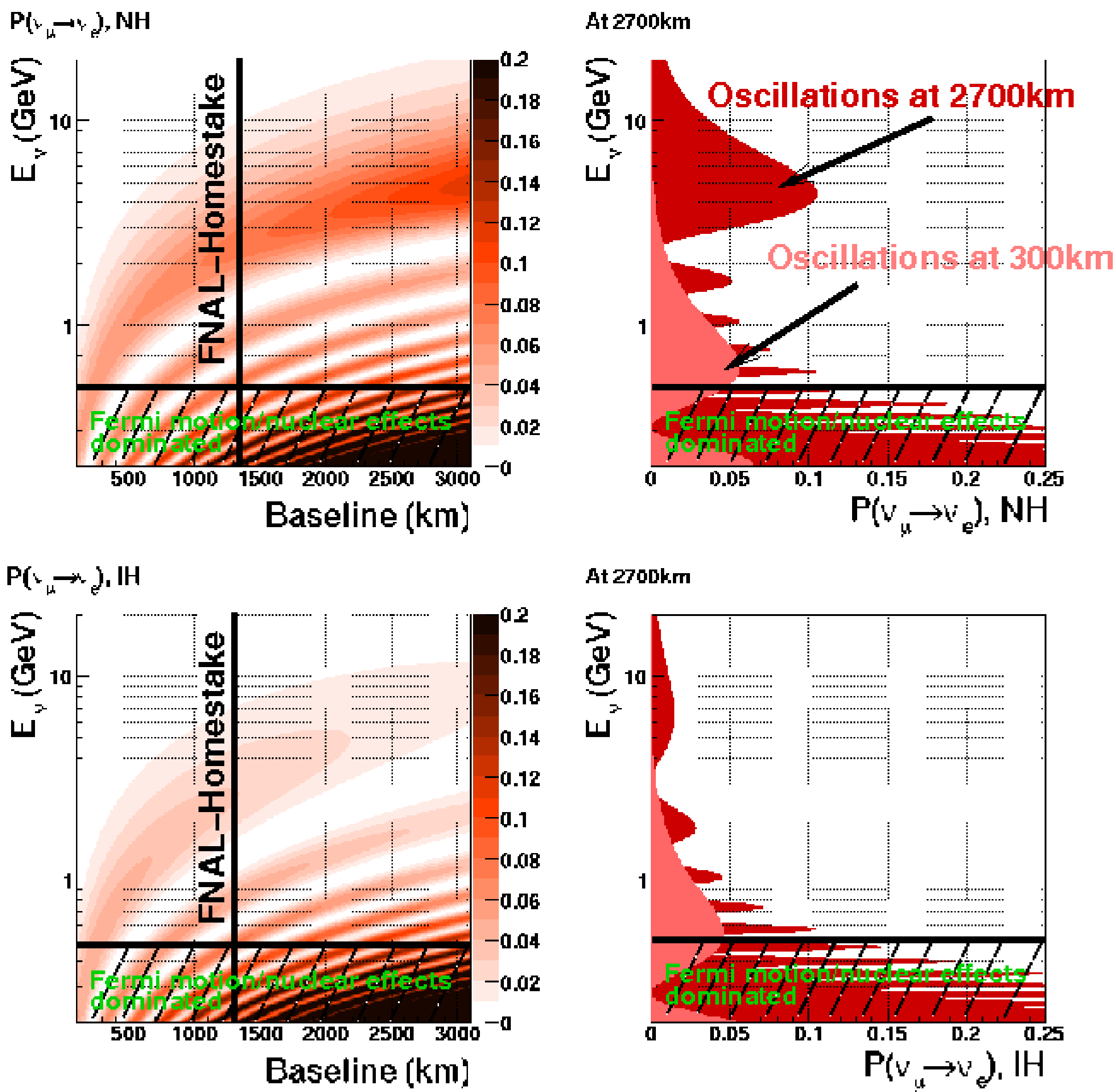

Figure 4-1: Oscillation nodes in energy versus distance from the neutrino source for neutrinos. The top set of plots is for normal hierarchy and the bottom set of plots is for inverted hierarchy. Baselines greater than 2,500 km can be created between Fermilab and Cascades, WA (2,700 km) and between Fermilab and San Jacinto, CA (2,800 km).

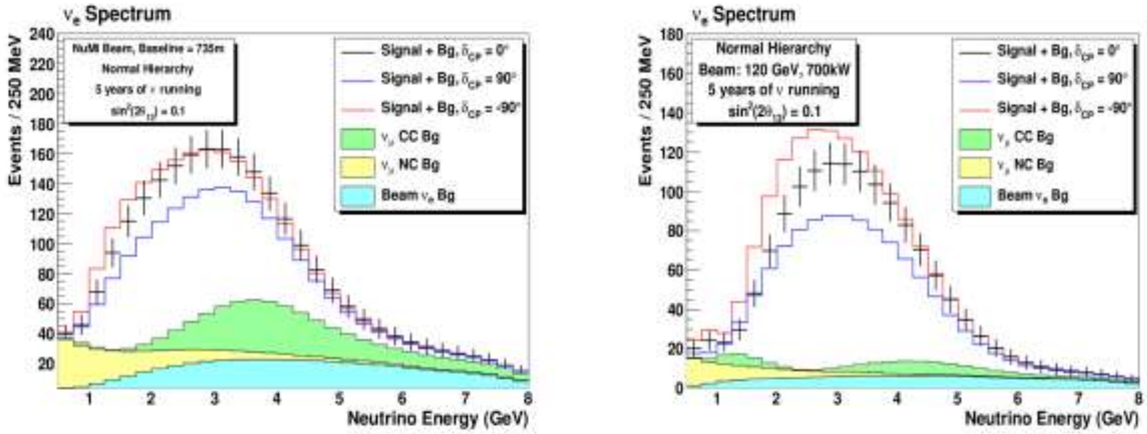

Figure 4-2: Appearance spectra in a 34-kT LAr detector located on-axis in the NuMI beamline at 735 km (left) and in the LBNE beamline at 1,300 km (right).

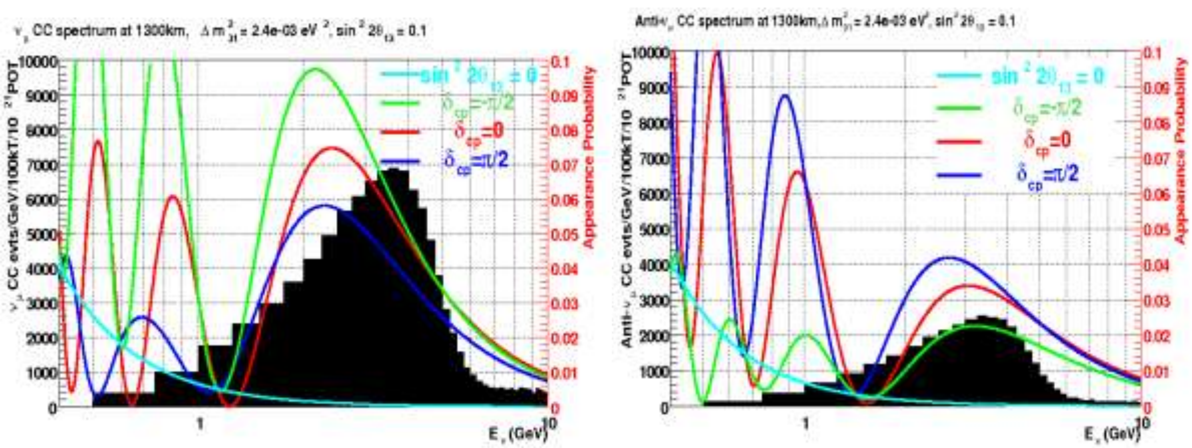

Figure 4-3: Oscillation probabilities (colored curves), given normal hierarchy and $\sin^2(2\theta_{13}) = 0.1$, at a distance of 1,300 km as a function of the CP-violating phase for neutrinos (left) and anti-neutrinos (right). The black histogram is the expected un-oscillated event rate from a candidate LBNE beam. The cyan curve shows the appearance probability from the solar oscillation term only.

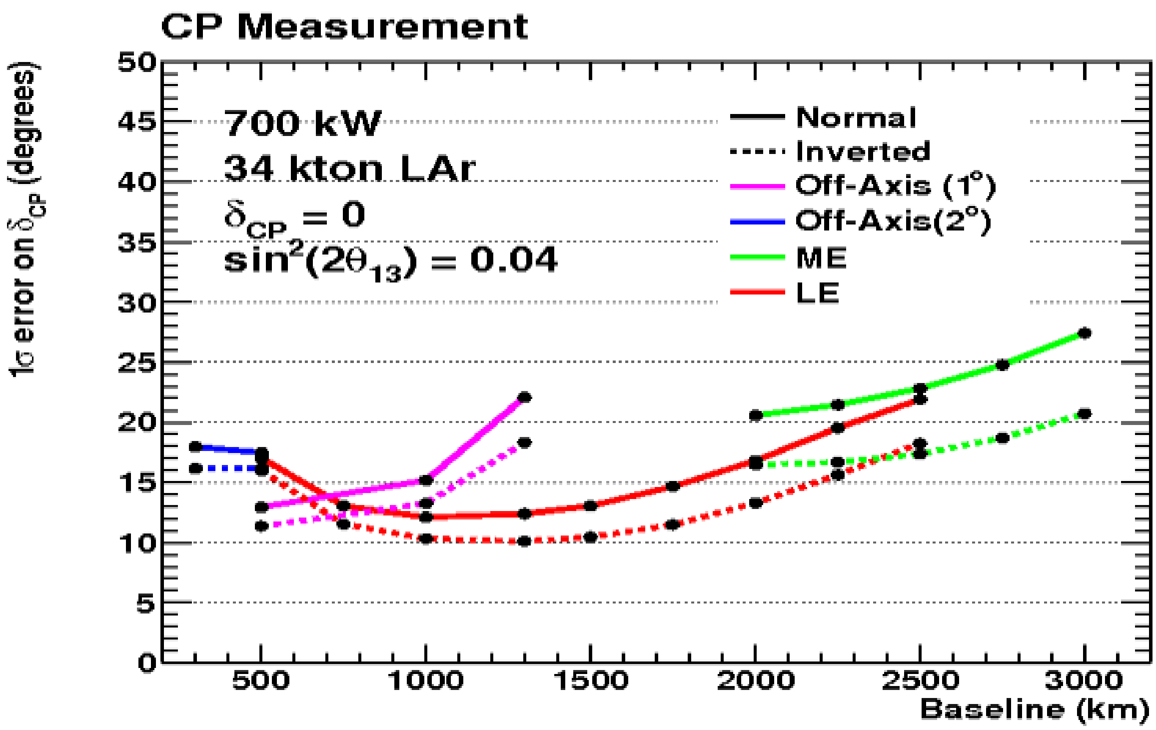

Figure 4-4: Measurement of the CP-violating phase as a function of baseline. The 1 standard deviation resolution of the value of δ_{cp} = 0 as a function of baseline is shown. Different LBNE beam tunes, are shown in different colors. For short baselines, off-axis beams are used to enhance the neutrino flux in the region of the first oscillation maximum. For baselines greater than 2,000 km, a broad-band on-axis medium energy tune from LBNE is used to cover the higher energy range where the first oscillation maximum occurs. The detector assumptions are the same at all baselines.

It is to be noted that longer baselines require longer decay pipe lengths to allow for the decay of higher energy pions. This increases the cost of the beamline. A final consideration for the length of the baseline has to do with the angle of inclination at which the neutrino beam facility would have to be constructed. Deeper inclinations directly translate into more complex construction and an increase in cost. The majority of this impact is on the conventional facilities, but a steeper slope also has an impact on component installation in the beamline, target hall, and absorber. For example, a 20% (12 degree) slope is required for a 2,600 km baseline.

4.3 The Proton Source

To create a neutrino beam, an accelerated proton beam is sent toward a target in which it can interact. When the protons strike the target, pions and kaons are produced, which subsequently decay into muons and muon neutrinos. Proton beams in the energy range of a few GeV to hundreds of GeV can be used to produce neutrino beams. At the present time, the Main Injector at the Fermilab accelerator complex can generate a 120-GeV proton beam. The existing accelerator complex can also generate lower-energy beams, which, for some detector technologies, may be desirable for limiting backgrounds.

Fermilab's NuMI beamline uses the 120-GeV proton beam from the Main Injector. NuMI was designed for a proton beam power of 400 kW and has operated with an average beam power of 350 kW since 2011.

It is to be noted that NuMI has also achieved its design goal of operating at 400kW. The NOvA Experiment, which will use the NuMI neutrino beam, requires a higher integrated proton intensity from the Main Injector than the 400 kW it can currently produce in a reasonable amount of running time. Thus the NOvA Project includes an upgrade of the Main Injector complex to produce a beam power of 700 kW, which, for the 120 GeV primary beam energy, will provide at least 6×10^{20} integrated protons on target (POT) per year. The Main Injector upgrade will be completed in 2013. By using the Main Injector complex, the LBNE beamline at Fermilab is able to exploit this investment and operate at 700 kW.

In addition to considering Fermilab as the proton source for LBNE, the Alternating Gradient Synchotron (AGS) at Brookhaven National Laboratory (BNL) was proposed at one time as a possible source for a very-long-baseline experiment [**5**] [**6**]. Substantial investment would have to be put into the AGS to achieve a comparable proton beam power to Main Injector. The construction cost of upgrading the AGS from the current operating power of 140 kW to 1 MW was estimated to be ~$350M in FY2004 dollars [**6**].

The most important LBNE physics goal is the explicit demonstration of CP violation and a measurement of the CP-violating phase δ_{CP} with a precision better than 20 degrees. This will require a total number of integrated protons with a primary beam energy of 120 GeV on the order of 70×10^{20}. Assuming the efficiency of the 700-kW accelerator complex could provide around 7×10^{20} POT per year, the LBNE integrated proton goal will be achieved in 10 years with 5 years running in neutrino mode and 5 years running in anti-neutrino mode.

4.4 The Far Detector Location

The location of the far detector must satisfy a number of constraints. First, it must be at a distance between 1,000 and 1,500 km from the neutrino source (see Section 4.3), which has been selected to be Fermilab. Second, it must be located within the United States, since currently LBNE has no foreign collaborators with territory at a suitable distance. Third, it must be in a location where the detector can be placed at a substantial depth underground to improve the performance for the accelerator-based neutrino oscillation measurements, and to enable the non-accelerator-based research of LBNE. The rock at such a location must, furthermore, be of sufficient strength and quality to allow reliable excavation of large caverns required for the massive LBNE Far Detector and yield structures that will permit reliable access to and operation of the LBNE detectors for several decades. It is desirable, although not required, that the rock be of relatively low radioactivity to improve capabilities to do utilize low-energy signatures for the non-accelerator-based physics program. Fourth, it must be in a direction from Fermilab in which it is feasible to construct a neutrino beam, given the constraints of the location of the Main Injector and other components of the Fermilab complex relative to the site boundaries.

This section first summarizes the depth requirements, which place a strong constraint on the available sites for the Far Detector. Then the characteristics of a number of potential underground sites that were identified by the NSF as part of their site selection process for the proposed Deep Underground Science and Engineering Laboratory (DUSEL) are summarized. Finally, each of these potential sites is evaluated with respect to the requirements stated above. This evaluation yields SURF, operated by the South Dakota Science and Technology Authority (SDSTA) as the clearly preferred site. Two other sites, the privately-owned Henderson Mine in Colorado and the DOE-owned Waste Isolation Pilot Plan (WIPP) in New Mexico are potential viable alternates, but each has notable disadvantages relative to SURF.

4.4.1 Depth Requirements

To optimize the impact of the Project and to allow for a broad physics program, the far detector should be located at an underground site. The depth of the installation of the detector is one of the alternatives that have been carefully considered in the development of the LBNE Conceptual Design.

The optimal installation depth for each type of detector varies for each of the physics measurements. A discussion on the depth requirements for various physics measurements for the two detector technologies are discussed in [**7**]. A summary table of this discussion is included here as Table 4-1. For long-baseline accelerator physics only, the Liquid Argon detector would have the capability of performing near the surface.

The previous analysis that produced the depth requirements did not consider external cosmic ray vetos around the detectors. For a Liquid Argon detector at a shallow depth, such vetos could be utilized to enable non-accelerator science. Such a cosmic ray veto detector has been considered for a Liquid Argon detector installation at shallow depths [**1**]. One implementation of such a veto is with scintillation detectors (liquid or solid) that penetrate into the rock at the top of the detector and perhaps at the bottom to detect muons that traverse the surrounding rock. Such muons could produce neutral particles that penetrate into the detector and produce backgrounds to proton decay. Construction of such a veto detector requires civil engineering to create space in the rock to a depth of ~7 meter beyond the detector boundaries. The technical feasibility of such construction and the efficiency with which it can detect background producing muons has not been fully established and requires high contingency. Furthermore, the muon veto only helps to reject the backgrounds to proton decay, but does not reduce the rate of spallation backgrounds that affect other low energy signatures such as supernova. The rate of spallation backgrounds is not yet firmly established for a liquid argon detector. In conclusion, a deeper deployment for either detector technology will have the best scientific program with the best detector livetime, least backgrounds across all energy scales, and the best dynamic range. The deep deployment will also simplify the design of the detectors with little need for cosmic ray veto detectors and low singles rates from muons and spallation events.

Table 4-1: Minimum depth requirements for the two detector technologies, expressed in meters-water-equivalent (mwe), for different physics measurements and the two detector technologies considered (Table is adapted from [**7**]).

Physics	**Water Cherenkov**	**Liquid Argon**
Long-Baseline Accelerator	1,000	0-1,000
$p \rightarrow K+\nu$	3,000	3,000
Day/Night 8B Solar ν	4,300	4,300
Supernova Burst	3,500	3,500
Relic supernova	4,300	2,500
Atmospheric ν	2,400	2,400

4.4.2 Candidate Underground Sites from the DUSEL Site Selection Process

The NSF engaged in a site selection process for the DUSEL Project from 2004 – 2007 that provided valuable information to LBNE in evaluating potential far detector sites [**8**]. The sites that were studied in the NSF-funded DUSEL site selection process are listed in Table 4-2. The result of the NSF-funded site selection was the selection the former Homestake Gold Mine in Lead, SD, as the preferred location for the DUSEL Project. To support the selection of the site in South Dakota, the State of South Dakota formed the South Dakota Science and Technology Authority (SDSTA) to initiate the efforts to rehabilitate the facilities and infrastructure at the former Homestake Mine and begin operations of the Sanford Laboratory (now SURF) including an early science program.

The data gathered in the during site selection process for DUSEL is summarized below in Table 4-2. The full set of information gathered by the NSF and the analysis that led to the selection of Homestake (now SURF) has not been made available to the LBNE Project. Nonetheless, the publicly-available data has proven to be valuable input to the analysis of potential sites for LBNE. Although the information gathered on each of the sites evaluated may not be current, the most important data remained relevant, such as rock type, depth, and access. It is noted that with the development of SURF at the site of the former Homestake Gold Mine by the SDSTA since the time of the NSF-funded site selection study, the condition of the former Homestake Gold Mine has changed as the site is no longer a closed mining facility and is now referred to as SURF.

Table 4-2: Sites considered by NSF for the DUSEL site selection process concluded in 2007.

Site	Distance from Fermilab (km)	Depth (mwe)	Rock type	Access	Condition
Cascades, WA	2,700	5,900-6,800	Hard rock	Horizontal	New site
Henderson Mine, Co.	1,470	3,100-6,000	Hard rock	Vertical	Commercial
Homestake Mine, SD [now SURF]	1,290	4,200-6,000	Hard rock	Vertical	Closed mine; property donated to state
Kimballton Mine, VA	820	1,900	Limestone	Horizontal	Commercial mine
San Jacinto, CA	2,600	4,000-6,000	Hard rock	Horizontal	New site
Soudan Mine, MN	735	2,200	Hard rock	Vertical	Operating lab
SNOLAB, ONT	770	5,890	Hard rock	Vertical	Commercial mine and Lab
WIPP, Carlsbad, NM	1,700	1,800	Salt bed	Vertical	Operating DOE Laboratory

Further information about the sites and the selection process can be found at http://www.dusel.org/html/designreports.html. A copy of this webpage can be found in LBNE-doc-5541.

4.4.3 Summary of the suitability of the NSF-considered Facilities for the LBNE broad physics capability

The desire to have a broad physics capability leads one to eliminate the sites at Kimballton, Soudan and Waste Isolation Pilot Plant (WIPP), based on their relatively shallow depth. Kimballton and Soudan also have too short of a baseline, restricting the ability to distinguish the matter effect from δ_{cp} effect. The baselines to Cascades and San Jacinto are too long, resulting in a technically difficult and costly beam installation and degraded resolution for measuring δ_{cp} without changes to the beam spectrum optimization. For long-baseline accelerator physics only, WIPP remains a candidate site. Henderson Mine and SURF both satisfy the depth requirement, making each of the sites capable of a broader range of physics. The more detailed analyses that were conducted to support the site selection for the LBNE Far

Detector site evaluate only a shortlist of three facilities that could meet the basic Project requirements: WIPP (for long-baseline accelerator only); Henderson Mine; and SURF.

4.4.4 Beam Design Considerations for WIPP, Henderson and SURF Candidate Sites

The WIPP and Henderson sites require aiming the beam further to the south than the direction to SURF, and given the proximity of the Main Injector to the west site boundary, space for the neutrino beamline becomes increasingly tight for beam direction farther to the south. This could result in the necessity of making a larger curvature path for the proton beamline, which in turn could either limit the maximum energy of the proton beam, or require use of superconducting magnets to be able to operate with the full 120 GeV beam energy.

To allow the maximum space for the primary beamline, the length of the MI-10 shallow neutrino beamline option was estimated, which was the shortest one under consideration. (More information about the selection of the beamline configuration is found in Chapter 4.6.) This beamline is shown in Figure 4-5, pointed towards SURF.

Figure 4-5: The shortest LBNE beamline towards SURF – MI-10 Shallow option.

A graphical technique was employed to estimate the configurations for the Henderson and WIPP, that approximated the alignment of the LBNE MI-10 shallow beamline with respect to the Main Injector onto aerial photographs using straight lines pointing at Henderson or WIPP. The Near Detector was positioned as close to the site boundary as possible, to a location that seemed to offer the most space for the proton beamline without interfering with the Main Injector. For WIPP and Henderson, only beams extracted from MI-60 were considered, since this seemed at this very conceptual level, to be the only way to fit the facilities east of the western Fermilab site boundary.

Using a circle that is tangent to the neutrino beamline and to the NuMI primary beamline, the radius was compared with the “effective” radius of the Main Injector, approximated as roughly half the distance between across the diameter between MI-60 and MI-30. Finally the dipole field required for the alternate LBNE proton beamline was scaled from the known field in the MI dipoles: 1.72 T at 150 GeV [**9**].

Figure 4-6 and Figure 4-7 show this construction for the Henderson and WIPP directions respectively, and Figure 4-8 shows the circle drawn to estimate the “effective radius” of the MI. The conclusions are summarized in the following Table 4-3. Here the beam energy has been estimated for the dipole field strengths used in the Main Injector for 120 GeV (1.38 T) and 150 GeV (1.72 T) operation.

Table 4-3: Beam energy of dipole field strengths.

	E_{max} for B=1.38 T	E_{max} for B=1.72 T	B for E=120 GeV
Henderson	115 GeV	144 GeV	1.45 T
WIPP	90 GeV	110 GeV	1.9 T

The conclusion is that a full energy beam is possible for the Henderson direction, with some margin. For the WIPP direction, the beam could be run up to about 110 GeV by running MI magnets at the strength used for 150 GeV. To get the full 120 GeV primary beam energy, higher strength magnets would be required, either specially designed conventional magnets optimized for heavy iron saturation, or superconducting ones.

It was estimated that the cost of these beamlines would be similar to the MI-60 Shallow design for the LBNE Far Site, or even slightly higher, since they combine the longer proton beamline of that solution with the penetration into the rock of the MI-10 Shallow design. This would add several tens of millions of dollars to the cost of LBNE. These solutions might also require some modest additional investments, e.g. the necessity of using Main Injector magnets without the option of recycling old main ring magnets, and additional cooling to allow the magnets to operate at higher field. In addition, there may be additional complications in extending the beamline along the NuMI direction, above the existing NuMI line before making the left bend towards Henderson or WIPP, beyond those encountered in designing the MI-60 extraction for the SURF direction.

Figure 4-6: Graphical layout for an LBNE beamline aimed at Henderson with the MI-10 Shallow configuration.

Figure 4-7: Graphical layout for an LBNE beamline aimed at WIPP with the MI-10 Shallow configuration.

Figure 4-8: Estimation of “effective radius” of Main Injector.

4.4.5 Selection of SURF as the Preferred Site

The WIPP site presents limitations: it currently does not have access to a deep enough level for LBNE. Even if it did, the salt is relatively low strength, is subject to significant levels of creep deformation, and is not expected to be stable on the decade timescale required for LBNE. The salt cannot be used as a structural element for detector construction, thereby increasing construction cost. With these considerations, it is a less favorable site than SURF or Henderson.

The NSF site selection process chose SURF over Henderson. Using funding from the NSF, the State of South Dakota, and a private donor, considerable investment has been in the SURF site, and, although the NSF has subsequently decided not to provide further funding for the DUSL project, the investment made already is of considerable value to LBNE. The site is already functioning as a laboratory, and considerable engineering effort has gone into characterizing the underground space and initiating design. In addition, access to the site for use for experimental physics has been granted by the owner (SDSTA). In selecting SURF as the preferred site, LBNE is able to take advantage of this considerable investment to lower the Project cost and schedule.

By contrast, if LBNE selected Henderson, more engineering and evaluation of the site would be required. Negotiations would need to be initiated with the owner, a private mining company, for access to the experiment, and success is not assured. Consequently, the schedule would be substantially delayed (> 1 year) and costs would increase ($10M’s).

SURF is the preferred site for the LBNE far detector. Its 1,300-km distance from Fermilab fits within the desired experimental baseline range with a reasonable beam extraction from the Main Injector. The hard-rock geologic conditions at the SURF site enable large underground openings for detectors at depth. The availability of existing drifts and infrastructure underground provide an opportunity to capitalize on previously-made investments by the State of South Dakota, the NSF, and private investment. The site is ready to accept physics experiments. An added benefit of locating at SURF is the possibility of enabling underground science through the use of common infrastructure to access the 4850L.

4.5 The Far Detector Technology and Detector Configurations

The LBNE Project developed conceptual designs for two different technologies for the far detector – water Cherenkov (WCD) and liquid argon time projection chamber (LAr TPC). The possibility of a liquid scintillator option was also raised [**7**], but it was not considered as an option for the CD-1 design or the initial configuration of the experimental program.

Studies carried out by the LBNE Science Collaboration and others [**10**] have shown that the main science goals of LBNE can be achieved in about 10 years of running using a 200-kt fiducial mass, a 34-kt LAr TPC, or a combination of a 100-kt WCD and a 17-kt LAr TPC. These three alternatives were considered for the LBNE Project.

The LBNE Project developed conceptual designs, cost estimates, and construction schedules for both water Cherenkov and liquid argon detectors. For each technology, a reference detector design was specified. For water Cherenkov, the final conceptual-level reference detector had a fiducial mass of 200-kt in a single volume, which corresponds to a detector module with a total mass of about 278 kt. For liquid argon, the reference detector had two modules, each with a fiducial mass of about 17 kT and a total mass of about 20 kt. The Water Cherenkov Detector was proposed to be sited at the 4850L of the (then) Sanford Laboratory (now SURF). The LAr TPC Detector was proposed either in a new facility constructed at the 800L or at the 4850L. Prior to finalizing the designs for the far detector technology decision, other detector configurations were explored, as well.

4.5.1 Detector Configurations

The LBNE Project studied three configurations since CD-0 and before the far detector technology decision. These are:

1. One 200-kt fiducial mass (FV) water Cherenkov detector at the 4850L.
2. Two 17-kt (FV) liquid argon detectors at the 4850L or the 800L
3. One 100-kt FV water Cherenkov detector at the 4850L and one 17-kt liquid argon detector at the 800L.

The LBNE Science Collaboration also explored a variety of detector configurations. These configurations included larger detector masses and took into account various combinations of technology, depth (for liquid argon) and energy thresholds (for water Cherenkov) via photomultiplier coverage (15% to 30%), as well as the possibility of adding gadolinium to enhance neutron capture rates [**11**] [**10**] [**12**] [**13**].

The performance of the three configurations noted above, for the primary physics measurements of LBNE are shown in Figure 4-9, Figure 4-10 and Figure 4-11.

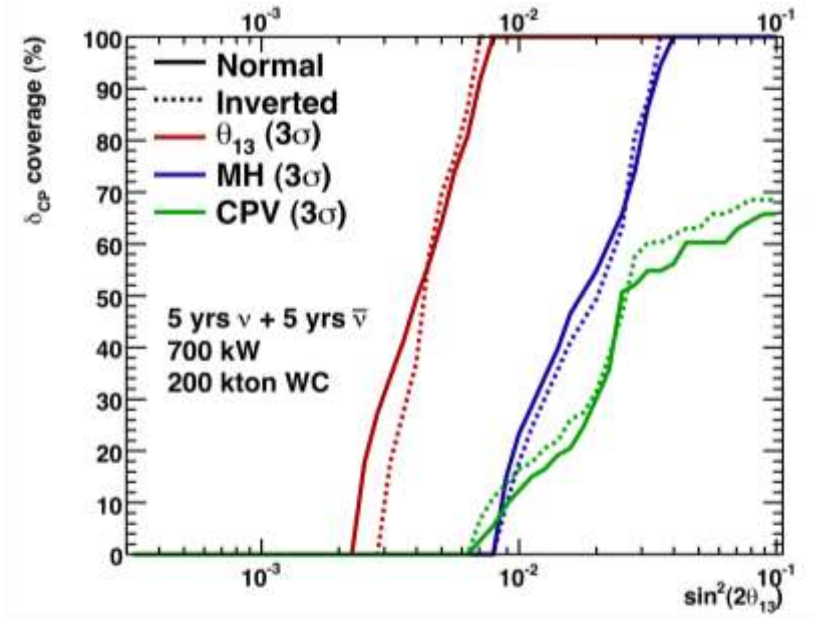

Figure 4-9: Sensitivity analysis for a water Cherenkov detector. This plot shows the sensitivity of the three primary measurements of LBNE's neutrino oscillation program for a 200-kt fiducial mass water Cherenkov detector with a 700-kW proton source and a 10-year exposure.

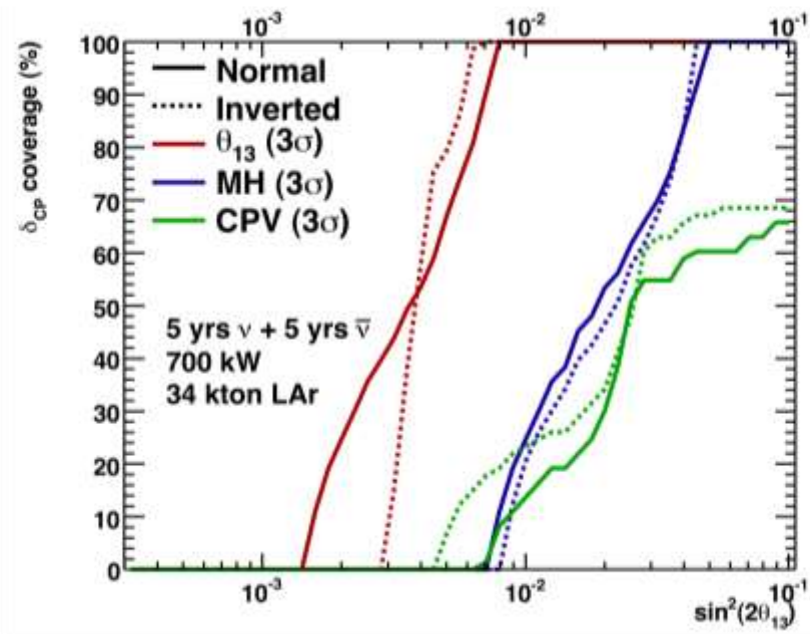

Figure 4-10: Sensitivity analysis for LAr TPC detector. This plot shows the sensitivity of the three primary measurements of LBNE's neutrino oscillation program for a 34 kt fiducial mass LAr TPC detector with a 700-kW proton source and a 10-year exposure.

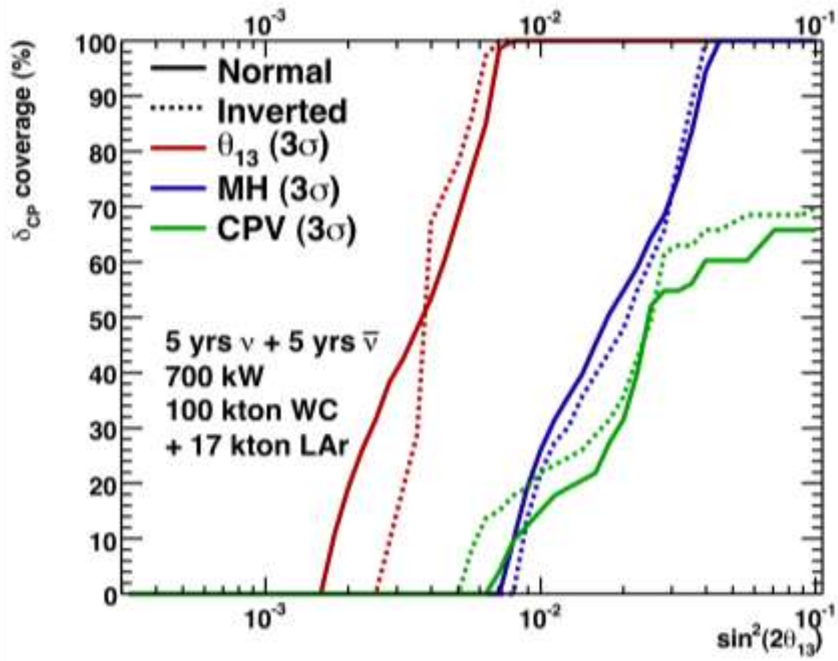

Figure 4-11: Sensitivity analysis for a hybrid detector arrangement. This plot shows the sensitivity of the three primary measurements of LBNE's neutrino oscillation program for a 100-kt fiducial mass water Cherenkov detector and a 17-kt fiducial mass LAr TPC with a 700-kW proton source and a 10-year exposure.

4.5.2 Detector Configuration and Technology Decision Process

The process by which the far detector configuration and technology were decided involved the LBNE Collaboration, the LBNE Project Manager, the Fermilab Director, and the Head of the Office of High Energy Physics. The process and final decision is summarized in a group of documents titled Documentation of the Far Detector Technology Choice [**14**]. The information is summarized here.

The decision process began with the formation of the Physics Working Group (PWG) in January 2010, which was charged to study many configurations involving WCD, LAr and combinations of the two, and included consideration of different depths for the LAr detector. In November of 2010, a document [**15**] prioritizing the physics goals of LBNE was developed and approved jointly by the Collaboration and the Project management, and was further approved by the Fermilab Director and the LBNE Federal Project Director. In January 2011, the writing of three Case Study documents was launched: one for WCD, one for LAr and one for a mixed solution. These were developed mainly by the LBNE Collaboration. In parallel, the Project organization was developing conceptual designs and cost and schedule estimates.

4.5.3 Decision Regarding the Mixed Configuration

Although the mixed configuration was generally favored as the option providing the most flexibility and broadest physics reach, it had a much higher cost than a single technology option of the same capability for the ν_e appearance measurements, due to the high fixed cost for conventional facilities and detector infrastructure specific to each technology. Therefore, the Project and the Collaboration recognized it was not a viable option for consideration. This was documented in the "Far Detector Technology Decision

General Principles" [**16**] in Assumption 2, "The decision will be between all-WCD and all-LAr. A staged implementation of both technologies is not considered to be an option within the LBNE Project as currently defined".

The decision to no longer pursue a mixed technology left three Far Detector options: a WCD at the 4850L, a LAr at the 800L, and LAr at the 4850L.

4.5.4 Decision Process and Procedures

The Project and Collaboration recognized the need for a formal procedure to decide between WCD and LAr. The policies and procedure were developed jointly by the LBNE Project and Collaboration, and documented in "Far Detector Technology Decision General Principles" [**16**] and "Procedures for LBNE Far Detector Configuration Decision." These were approved by the Collaboration Executive Committee (EC) in July 2011. The purpose of formally establishing this process was presented in in the introduction to "Far Detector Technology Decision General Principles."

It was necessary to select a specific far detector configuration in an open, objective and timely manner. The decision should be based on facts concerning the scientific capabilities, risks, and cost and schedule to implement each of the two candidate detector types. An objective process is needed to establish those facts, so that, to the greatest extent possible, all of the stakeholders agree that the information used for the decision is valid. Although the final decision is formally made by the Project Manager (as the contracted agent for the DOE through Fermilab), the goal is to reach a decision by consensus among all of the stakeholders.

The general process stated in the same document is the following:

Following a rigorous set of reviews of the science, technology, cost and schedule for each far detector, the EC, potentially augmented by additional advisors (e.g. relevant scientific or technical experts or representatives of other stakeholders) will meet to draft the far detector recommendation. The procedures for this will be defined in a later document, but will be consistent with the principles of fairness, consensus, and decisiveness established in previous EC retreats.

The last step in "Procedures for LBNE Far Detector Configuration Decision" is the following:

The Project Manager will make the formal decision, based on the advice received from the LBNE Collaboration EC, and subject to the concurrence of the Fermilab Director, the LBNE Laboratory Oversight Group, and the DOE Office of High Energy Physics.

It was agreed that the process should yield a decision in time to allow only one technology to be carried to CD-1:

Target date for the completion of the decision process is by the end of FY11. This target date will be revisited as circumstances dictate.

4.5.5 Reviews and Meetings and their Input to the Decision

The key reviews and meetings leading to the far detector decision, as outlined in the approved procedure, were: a Scientific Capabilities Review, conducted in October-November 2011 with a complete draft report delivered on 9 December; a Conceptual Design, Cost and Schedule Review, conducted 6-9 December, with a draft closeout report issued at the end of the review meeting; and a retreat of the Executive Committee 12-14 December, at which recommendations regarding the far detector choice were developed.

The Science Capabilities Review [**17**] was conducted by an external committee of six highly experienced experimental physicists, who were invited by and charged by the LBNE Co-Spokespeople. It was charged “to evaluate and compare each of the two approaches to building LBNE with respect to its capabilities to achieve the science goals of the experiment.” The full charge and the final report are available in the LBNE Document Database [**17**]. In its “Conclusions and Recommendations” the committee states:

- *In light of the presented materials the committee unanimously agrees that both technologies represent significant scientific opportunities, that either detector could be built at an acceptable level of risk, and that current knowledge supports the view that either is likely to deliver its expected performance, and that either detector would make world-leading measurements relevant to all of the major science goals.* (Italics in the original.)

The report clearly favored the LAr detector regarding CP sensitivity, and it favored it with regard to proton decay and supernova neutrino physics, particularly in terms of complementarity to Super-K. The committee report closes with the following summary of its scientific evaluation:

- The committee unanimously agrees that, that on the question of scientific capabilities, that the prospect for the LAr detector to refine our understanding of neutrino oscillations, and to be sensitive to unexpected new physics, exceeds that from the WC detector.

The LBNE Far Site Conceptual Design, Cost, Schedule and Risk Review [**18**] was conducted by an external committee of 22 experienced experimental physicists, engineers, and project controls professionals, who were invited and charged by the LBNE Project Manager and Project Engineer. The charge called for the committee to “assess the status and adequacy of the conceptual design for LBNE Water Cherenkov Detector (WCD), Liquid Argon Detector (LAr), and the associated Conventional Facilities (CF) at the Far Site (Sanford Lab).” The full charge and the final report are available in the LBNE Document Database [**18**]. The CDR review committee endorsed the viability of both detector designs and the readiness of the teams to move to the next project step.

Executive Committee Recommendation: The LBNE Executive Committee met for two and one half days in mid-December 2012 to consider these reports, as well as many other factors, in order to come to a decision on the technology choice. The committee was supplemented by four “advisors,” two from within and two from outside the collaboration, who joined the discussion. Three alternatives were explicitly considered: WCD at the 4850L depth, LAr at the 4850L depth, and LAr at the 800L depth. Although there wasn’t consensus on the detector technology, a clear consensus emerged that the experiment should, in any case, be sited at the 4850L. At the end of the second day, a final binding vote was held in which the WCD was favored by a small majority. The Project Manager as the recipient of the EC’s advice, abstained from the final vote.

As called for in the procedure, a subcommittee then drafted a written report [**19**], which was discussed and edited by the full committee. The final report was approved unanimously by the EC, and presented by Bob Svoboda at the LBNE Collaboration meeting, which began the day after the EC retreat. The main conclusions were:

- There was very strong support for both technologies. The committee feels that both technologies are viable and complementary in many aspects.
- There was a very strong preference for siting the experiment at the 4850L depth.
- Given the current state of knowledge and considering the factors listed above, the committee favored the Water Cerenkov option.

As part of this final report, the EC unanimously passed a statement strongly expressing their view that getting the science done should outweigh consideration of far detector technology in the final decision making-process:

As per the Procedures for LBNE Far Detector Configuration Decision [**16**]:

The Project Manager will make the formal decision, based on the advice received from the LBNE collaboration EC, and subject to the concurrence of the Fermilab Director, the LBNE Laboratory Oversight Group, and the DOE Office of High Energy Physics.

The Executive Committee reaffirms its commitment to the Scientific Goals of LBNE and will endorse the ultimate technology decision.

The EC preference for siting the experiment at 4850L eliminated the liquid argon detector at 800L option.

4.5.6 The Far Detector Technology Decision

The Project Manager weighed the EC recommendation to proceed with WCD against the other committee conclusions, especially the strong (unanimous) opinion of the Scientific Capabilities Review committee that the LAr detector has superior capabilities for the primary physics of LBNE. The Project Manager's decision process is documented in detail in the file titled "Procedures for LBNE Far Detector Configuration Decision" [**20**]. The final decision was for a liquid argon detector at 4850L with the statement, "a LAr TPC offers the best opportunities for LBNE to do world-leading science. It will give us the cleanest oscillation signals and ultimately provide the best chance of observing CP violation; it will produce the best limits on proton decay, relative to other operating detectors in the world; and will produce unique information about a galactic supernova, should one occur during the lifetime of the experiment, and, together with other existing or planned experiments, provide the broadest view of such a once-in-a-lifetime event. This path will bring this important detector technology to full maturity, with potential applications to future experiments. The potential for substantial international collaboration will make a stronger LBNE. Finally, the feasibility of building a large LAr TPC is supported by our recent CDR review, and the scientific advantages of this path are supported by the recent Scientific Capabilities Review."

This decision by the Project Manager was followed by a request for concurrence to the Fermilab Director on January 11, 2012, who sought the opinion of the LBNE Laboratory Oversight Group (LOG). The LOG provided their concurrence, and with that, the Director transmitted his concurrence to the Associate Director of the Office of High Energy Physics. On January 24, 2012, the Associate Director for OHEP provided his concurrence to LAr as the choice for the primary technical option to be presented as part of the CD-1 review process. DOE will formally review this decision as part of its project management process, and concur with a CD-1 Approval.

4.6 The Proton Beamline

The point at which the proton beam is extracted from the Fermilab Main Injector depends on the direction the resulting neutrino beam is to be aimed. Therefore, one needs to choose the destination of the neutrino beam before designing the extraction point and primary beamline. The proton beam for the NuMI neutrino beam is extracted from the Main Injector at MI-60 and is aimed northwest toward the Soudan Mine in northern Minnesota. For the LBNE conceptual design, the former Homestake Mine in Lead, South Dakota is chosen as the destination for the neutrino beam, setting the experiment baseline at 1,300 km. Although Lead is nearly due west of Fermilab and extraction from a different region of the Main Injector may seem more practical, the initial choice was for the LBNE beam to use the same extraction point as the NuMI beam.

As part of the Value Engineering efforts during Conceptual Design, the Project developed four different variations on the beamline configurations: extraction at MI-60 with a deep beamline; extraction at MI-60 with a shallow beamline; extraction at MI-10 with a deep beamline; and extraction at MI-10 with a shallow beamline. Cost ranges and feasibility concepts were developed for each of the options and were presented to the DOE in April 2011. The four options were reviewed extensively by the Neutrino Beamline Technical Board between March and June 2011, and in the end of June 2011 two of the four options were selected for further development and consideration. The selected options are being referred to as MI-10 Shallow and MI-60 Deep. Both options were compared with the same decay pipe length and muon range-out distance (the minimum length/distance required to achieve the physics goals). The MI-10 Shallow option presented a number of challenges, but presented a savings potential ($110M based on known costs in June 2011; $45M based on the known costs in November 2011; both estimates are in FY 2010 dollars).

The rejected MI-10 Deep concept was the most constrained real with regard to the Fermilab site boundary and did not represent a significant potential for savings in comparison with the MI-60 Deep concept. The rejected MI-60 Shallow concept represented the longest primary beamline and an engineered fill embankment with the highest apex and the largest footprint. Although there was significant savings in the conventional facilities part of the beamline facility, the technical component cost was higher because of the increased number of components.

The extraction of the beamline from MI-60 Deep is the best understood design as it mimics the design of the existing NuMI beamline and a schematic diagram is shown in Figure 4-12. After the proton beam is extracted at MI-60, about 25-ft below grade, the Beamline would continue along the Primary Beam Enclosure at a decline into and through the soil overburden and then into the underlying bedrock through the Target Hall, a 200–m long Decay Pipe, and the Absorber Hall. Downstream of the Absorber Hall, the beam would be directed through 210 meters of bedrock, allowing muons to range out before the beam enters the Near Detector Hall.

Figure 4-13 shows the design of the MI-10 Shallow concept where the proton beam is extracted at MI-10, about 25 ft below grade. The Beamline would continue along the Primary Beam Enclosure at an incline into and through the engineered fill embankment which reaches a maximum height of about 70 ft above existing grade. After reaching the apex of the embankment, the Beamline declines back into the ground and through the Target Hall, a 200–m long Decay Pipe, and the Absorber Hall. Downstream of the Absorber Hall, the Beamline is directed through 210 m (690 ft) of bedrock, allowing muons to range-out before the beam enters the Near Detector Hall.

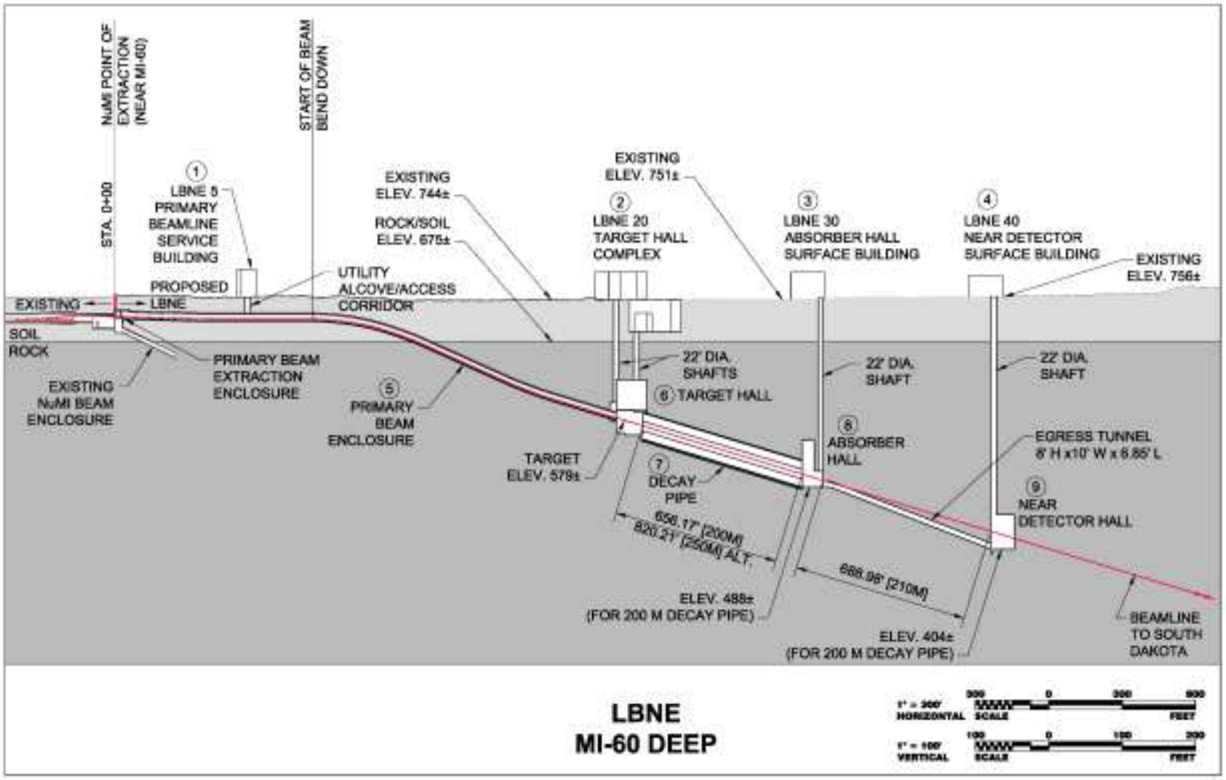

Figure 4-12: MI-60 Deep Longitudinal Section/Profile with an exaggerated vertical scale of 3 to 1.

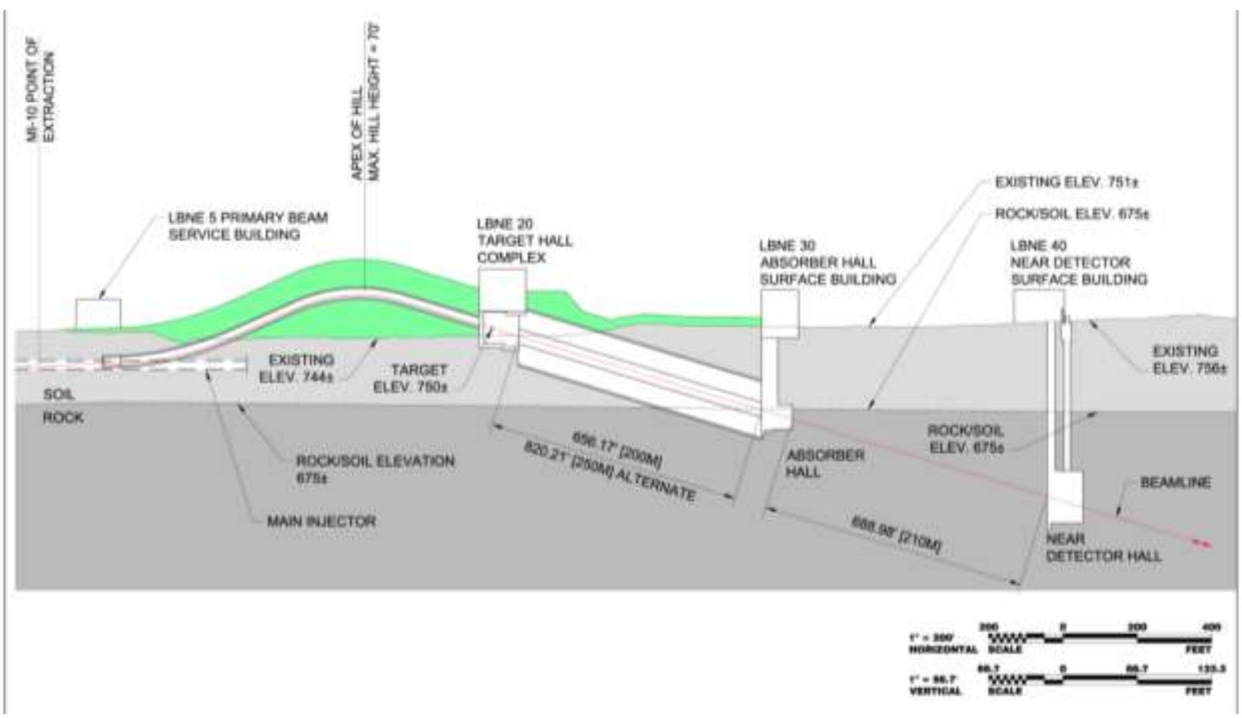

Figure 4-13: MI-10 Shallow Longitudinal Section/Profile with an exaggerated vertical scale of 3 to 1.

The radiological model in the MI-60 Deep option is such that groundwater is encouraged to migrate through the rock mass toward and into the decay region where it can be collected and transported away. In the MI-10 Shallow option, because of the presence of a local aquifer near the surface, groundwater cannot be encouraged to migrate toward or into the decay region as it would require significant regular collection. Therefore, one of the challenges of the MI-10 Shallow option is providing an adequately engineered geo-membrane barrier between the shielding and the environment. The initially proposed designs for the geo-membrane were reviewed at the Near Site Technical Review in November 2011 and determined that the design intent of the geo-membrane was feasible.

Additional issues considered in the development of the MI-10 Shallow option included:

- stability of the beamline and therefore the necessity for deep foundations into the rock to support the beamline tunnel and target hall
- impact of the man-made berm covering the beamline on the adjacent Main Injector, and therefore the required protection of the Main Injector
- muon-shine and total radiation dose at Fermilab's west boundary requiring additional shielding for the beamline facility
- understanding of the properties of the engineered geo-membrane groundwater barriers and the challenges related to installation.

After all considerations were studied, it was determined that the most critical element of the MI-10 Shallow design is the use of geo-membrane barriers in the decay and absorber regions of the beamline facility.

The Conventional Facilities team consulted with a geo-membrane expert to provide an independent review of the geo-membrane design. Plans were reviewed by Fermilab's Environment, Safety, and Health (ES&H) team. The Beamline Technical Board reviewed the technical issues, risks and cost information. Based on the assembled data and reports, the Project determined in November 2011 that the MI-10 Shallow option is the preferred configuration.

The primary reasons for this decision are as follows, and are detailed in the report on the "Decision on the LBNE Beamline Depth and Extraction Point" paper [**21**]:

1. Site boundary constraints do not prohibit the feasibility of either option.
2. Moving the majority of the facility closer to the surface makes much of the construction, installation, maintenance, operations, decommissioning and disposal of the facility and components more affordable.
3. The MI-10 Shallow configuration technical component installation is easier as it includes a shorter beamline and more straightforward magnet installation.
4. Innovative decay pipe cooling methods can be utilized in a more affordable way without introducing water cooling.
5. Locating the Target Hall above existing grade reduces the humidity and allows for the tritium mitigation to occur further downstream in the beamline facility.

The overall cost of the MI-10 Shallow configuration is understood to have a lower cost by approximately $45 million in FY 2010 dollars.

Because the MI-10 Shallow option is significantly different from the NuMI design, which was used as the basis for the design of the MI-60 Deep configuration, the project has factored the potential unknown issues into the cost, schedule and assignment of contingency.

4.7 The Neutrino Beam

There are currently three long-baseline neutrino beams operating in the world. These are the NuMI beam at Fermilab, the CNGS beam at CERN and the T2K beam at JPARC in Japan. For reference, the key parameters of these beams are presented in Table 4-4.

Table 4-4: Parameters for the three currently in-operation long-baseline neutrino beams.

Key Parameter	NuMI	CNGS	T2K
Primary beam energy	120 GeV	400 GeV	30 GeV
Beam power– initial design	400 kW	250 kW	750 kW
Beam power– current operations	350 kW	250 kW	100 kW
POT/year – current	2.5×10^{20}	4.5×10^{19}	$<<1\times10^{21}$
Beam power – future operations	700 kW	750 kW	1,666 kW
POT/year – future	6×10^{20}	1×10^{20}	2×10^{21}
Target to absorber decay distance	800 m	1,000 m	115 m
Target to near detector distance	1,200 m	N/A	280 m
Distance and angle to far detectors	735 km; 0 mrad 810 km; 14 mrad	732 km; 0 mrad	295 km; 43 mrad
Beam spectra	Broad-band; Tunable 0.5–15 GeV Off-axis, Narrow-band; 2 GeV	Broad-band 5–30 GeV, mean ~15GeV	Off-axis-Narrow-band: 0.8±0.1 GeV

For a given experiment baseline, the neutrino oscillation probability as a function of energy can be calculated. The oscillation of interest for the next generation of long-baseline experiments is $\nu_\mu \rightarrow \nu_e$ governed by the third mixing angle θ_{13}. This probability is plotted for several different baselines in Figure 4-14. The plot shows that there are two oscillation maxima in the energy region of 0.5 to 10 GeV, a range in which accelerator neutrinos are easily produced. Using magnetic focusing elements, a neutrino beam can be designed such that its energy spectrum spans the peaks of oscillation probabilities. If a neutrino detector is set on the axis of the neutrino beam with the target/horn geometry arranged to focus a broad band of mesons in the forward direction, it will see a broad-band energy spectrum of neutrinos. The focusing system can be designed to maximize the energy spectrum at the first oscillation maximum but still have significant flux covering the lower-energy second oscillation maximum. Alternatively, if the detector is set off-axis of the neutrino beam, the detected neutrinos will have a narrow-band energy spectrum; the peak energy of an off-axis beam is dependent on the off-axis angle [**22**]. The neutrino beam energy on-axis can be tuned such that the off-axis energy spectrum at the detector is matched to the first oscillation maximum, as is done for the NOvA Experiment. An additional detector could also be placed at a location that sees a narrow-band energy beam at the lower energy of the second oscillation maximum. Using the NuMI beam with this off-axis configuration was considered as an option for the next generation oscillation experiment [**4**], however, it has subsequently been rejected because it does not achieve as good experimental sensitivities as the longer-baseline broad-band beam option being developed for LBNE. A configuration with multiple off-axis angles will require multiple very large detectors operating on the surface.

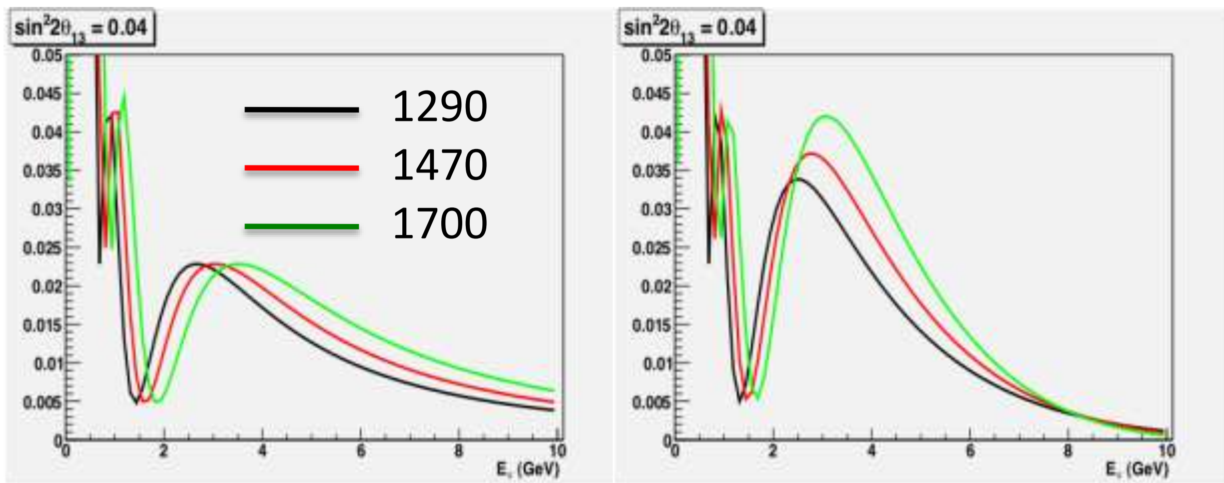

Figure 4-14: Oscillation probability for three baseline distances in km; left is for vacuum oscillations, right includes the matter effect.

There are many alternative designs for the technical elements of the LBNE neutrino beam, such as the target and horn configurations, the length and width of the decay pipe, and means and methods for mitigating and controlling radiation. The CDR reflects the Project team's selection of the preferred alternative for these elements.

4.8 The Near Detector Location

A near detector is used to measure the un-oscillated composition of the neutrino beam and thereby predict the rate of signal and background events expected at the Far Site. To make this extrapolation as accurately as possible, one aims to span the same kinematics in both the near and far detectors. It is difficult to achieve this, however, because the neutrinos are produced along the length of the decay pipe. This implies that the near detector sees a line source of neutrinos, whereas the Far Detector sees a point source. The result is a different energy spectrum observed by the near and far detectors. This difference can be reduced by locating the Near Detector as far from the end of the decay pipe as possible. However, the longer this distance is, the deeper the detector hall will have to be located. For LBNE, the plan is to locate the detector hall as far from the production source as possible but still remain on the Fermilab site. Suggestions that even farther, off-site locations may be desirable have been made, but no serious consideration has or will be given to these, due to cost considerations and political complexities that would arise.

The considerations for the Near Detector location are then (a) placement within the Fermilab site boundary, (b) accommodation of the neutrino beamline pointing at candidate Far Detector locations, and (c) creation of a sufficiently long beamline to accommodate both neutrino production and muon range-out. Before knowing if (a) and (b) can be satisfied, estimates of (c) must be made. The general scheme of neutrino production includes protons striking a roughly 1-m long graphite production target, two magnetic focusing horns, a 200-250-m long decay pipe, a charged-particle absorber, and roughly 200 m of rock to range-out muons. Simulations of 120 GeV muons, the maximum energy that can be produced by the 120 GeV Main Injector beam, show that, in addition to the absorber an additional 210m or rock is required to range out all muons [**23**]. Thus a minimum total distance of ~450 m (for a 200 m decay pipe) from the production target to the Near Detector hall is required. Such a distance can be accommodated within the Fermilab site boundary for a beam extracted from either MI-10 (the chosen alternative) of MI-60 (rejected alternative) for a beam pointing towards SURF.

4.9 The Near Detector Technology

A Near Detector is needed to measure the rate of neutrino interactions prior to oscillations and reliably predict signal and background rates expected at the far site. Because the neutrino rates are much higher at the near site, the near detector can be smaller than the far detector and still maintain adequate statistics for physics measurements. The Near Detector Complex subproject investigated a number of such near detector technology alternatives that would be compatible with the LBNE Far Detector while seeking to both optimize physics output and minimize cost. Prior to the far detector technology decision, four near detector systems were evaluated. This included two concepts for a WC Far Detector (WC-FD) option and three for a LAr Far Detector (LAr-FD):

1. Scintillator Tracker (ST) – for use with a WC-FD
2. Fine-Grained straw-tube Tracker (FGT) – containing either water targets or pressurized argon targets as appropriate for either a WC-FD or LAr-FD
3. Liquid Argon Membrane tracker (LArM) – for use with a LAr-FD
4. Liquid Argon Time-Projection Chamber (LArTPC) – for use with a LAr-FD.

Ideally, the near and far detectors should be “identical” in the sense that they employ the same detector technology (to reduce detector uncertainties) and utilize the same nuclear target (to reduce neutrino interaction uncertainties) in order to maximize the sensitivity to neutrino oscillations. Given that a LAr TPC was chosen as the reference design for the far site, the chosen reference design for the near detector is therefore also a LArTPC. This lower-cost system includes a 1.8m x 1.8-m x 4m (18 ton) volume TPC positioned inside a 0.4T dipole magnet, thus providing a liquid argon target appropriate for use with the LAr-FD. Along with its excellent resolution capability for determining energy, direction and particle identification, the LArTPC provides good containment of electromagnetic showers in the argon (140 mm radiation length). It can also fully identify muons and distinguish between μ^+ and μ^-. Gaps in the magnet steel are instrumented with scintillator planes to aid in muon identification. In addition, steel plates down-stream of the magnet, instrumented with scintillator will provide additional muon identification.

The remaining designs noted above are now considered to be alternatives, and their characteristics are summarized below:

1. A 7 ton 3.9m × 4.5m × 4.7m Scintillator Tracking (ST) detector surrounded by an electromagnetic calorimeter and positioned inside a 0.4T dipole magnet was also considered. This cost-effective option could provide good resolution (about 20%) for determining particle energies/directions and discriminate between muons and electrons. The ST could achieve μ^+/μ^- separation, but only marginal e^+/e^- separation. An additional limitation would be the inability to determine absolute neutrino flux for neutrino energies below ~5 GeV. The ST was considered to be compatible only with the WC-FD option and hence was discarded as an option given the LAr-FD selection.
2. A higher-resolution, higher cost option was considered that included a Fine-Grained straw-tube Tracker (FGT), also surrounded by a dipole magnet. An FGT could accommodate both H_2O, and D_2O targets, appropriate for use with a WC far detector, and would allow precise measurement of the absolute neutrino and antineutrino fluxes in the neutrino energy regime of interest for oscillation physics. In addition to separately measuring e^+ and e^-, this system would also be able to achieve e^+/e^- separation and therefore separately measure electron-neutrino and electron-anti-neutrino fluxes in the beam. The FGT could be compatible with a LAr-FD if equipped with the same nuclear target, i.e., by including some number of pressurized argon targets in the tracker volume. However, the particle detection and reconstruction in the FGT is quite different from that of a LArTPC, and hence some cancellations in systematic uncertainties between near and far detectors could be compromised. This option is still under active consideration.
3. A 350 ton Liquid Argon Membrane tracker (LArM) was considered that would have higher cost than a LArTPC, but provide better containment of higher energy particles. The LArM is closer to the design of the LAr-FD and consists of a 5m x 5m x 10m TPC positioned inside a ~0.4T dipole magnet. The LArM option design offered important advantages for oscillation analysis strategies that make use of identical Near and Far Detectors. Because the TPC would be of the same design, the same detection efficiencies would be anticipated. In addition, due to its larger size, it could contain more energetic hadronic showers and allow pattern-matching analyses between the near and far sites. Despite these apparent advantages this option is rejected due to its substantially higher cost compared to the chosen alternative.

4.10 Conclusion

The LBNE Project has completed the conceptual design phase, during which alternates were studied and preferred reference design choices made. These decisions range from siting and detector technologies to an innovative beamline configuration. The result is a reference configuration of:

- A preferred far detector location at SURF with an experimental baseline of 1,300 km
- A 700 kW proton beam extracted from MI-10 at Fermilab and a target above grade, with a trajectory aimed at SURF
- A 2.5-ton liquid argon TPC tracker Near Detector
- A 33-kt liquid argon TPC Far Detector at the 4850L of SURF.

With the current knowledge of the neutrino oscillation parameters – the mass differences, and the mixing angles, especially the angle θ_{13}, now determined to be approximately 9 degrees [**3**] – the above configuration for LBNE is guaranteed to result in a determination of the CP violating phase as currently understood in the 3-generation framework. If CP violation exists, and if it largely follows the 3-generation framework then the current configuration of LBNE will discover it with high degree of significance over the entire range of parameter space. Moreover, the determination from LBNE will be redundant using both the spectral distortion in each of the neutrino and anti-neutrino spectra as well as explicit demonstration in the asymmetry of neutrino versus anti-neutrino oscillations. Furthermore, LBNE will determine the mass ordering of neutrinos with high degree of significance over the entire remaining phase space.

The redundancy of measurement uniquely available to LBNE by analysis of the spectral distortion and the asymmetry will allow us to either discover or limit new physics effects that might affect oscillations.

The choice of the large liquid argon detector at the depth of 4850 ft of Sanford Underground Laboratory will allow LBNE to also fulfill the mission of sensitivity to proton decay and unique sensitivity to electron neutrinos from supernova.

5 Reconfiguration Effort Spring-Summer 2012

5.1 Introduction

The Steering Committee for the reconfiguration effort determined in their report [**24**] that to achieve all of the fundamental science goals listed in Section 4.1 a reconfigured LBNE would need both a very long baseline (>1,000 km from accelerator to detector) and a large detector deep underground. However, it is not possible to meet both of these requirements in a first phase of the experiment within the budget guideline of approximately $700M – $800M, including contingency and escalation. The committee assessed various alternatives that meet some of the requirements, including underground-detector-only alternatives (no accelerator-based neutrino beam) and a range of baselines from the existing 700-800 km available with Fermilab's NuMI beam to as far as 2,600 km. It identified three viable alternatives for the first phase of a long-baseline experiment that have the potential to accomplish important science at realizable cost.

- Using the NuMI beamline in the low energy configuration with an LArTPC detector 14 mrad off-axis at Ash River, 810 km from Fermilab,
- Using the NuMI beamline in the low energy configuration with an LArTPC detector on-axis at Soudan, 735 km from Fermilab, and
- Constructing a new low energy LBNE beamline with an LArTPC detector on-axis at SURF, 1,300 km from Fermilab

5.2 Comparison of Alternatives

To compare the alternatives, the Physics Working Group assumed the reconfigured experiment would run for five years in neutrino mode and five years in anti-neutrino mode at a beam power of 700 kW with 6×10^{20} protons-on-target accumulated per year with an LArTPC far detector and a near detector. The group assumed NOvA would run for three years in neutrino mode and three years in anti-neutrino mode (3+3) with the NuMI medium-energy (ME) beam prior to the LBNE experiment (NOvA I). An additional running of five years in neutrino mode and five years in anti-neutrino mode (5+5) with NOvA in the NuMI low-energy (LE) beam (NOvA II) is assumed when combining with the Soudan and Ash River alternatives. It was assumed 5×10^{21} protons-on-target total would be accumulated by T2K (~6 years) in neutrino-only mode.

The pros and cons of each alternative follow; no priority is implied in the ordering.

5.2.1 30-kton Detector on Surface at Ash River

The first alternative, a 30-kton surface detector at Ash River in Minnesota, would use the NuMI low-energy beam and provide an 810-km baseline.

Pros:

- Best Phase 1 CP-violation sensitivity in combination with NOvA and T2K results for the current value of θ_{13}. The sensitivity would be enhanced if the mass ordering were known from other experiments.
- Excellent (3 σ) mass ordering reach in nearly half of the CP range.

Cons:

- Narrow-band beam does not allow measurement of oscillatory signature.
- Shorter baseline risks fundamental ambiguities in interpreting results.
- Sensitivity decreases if θ_{13} is smaller than the current experimental value.
- Cosmic ray backgrounds: impact and mitigation need to be determined.
- Only accelerator-based physics.
- Limited Phase 2 path:
  - Beam limited to 1.1 MW (Project X Stage 1).
  - Phase 2 could be a 15-20 kton underground (2,340 ft) detector at Soudan.

5.2.2 15-kton Detector Underground at Soudan

The second alternative, a 15-kton underground (2,340 ft) detector at the Soudan Lab in Minnesota would use the NuMI low-energy beam and provide a 735-km baseline.

Pros:

- Broadest Phase 1 physics program:
  - Accelerator-based physics including good (2 σ) mass ordering and good CP-violation reach in half of the δCP range. CP-violation reach would be enhanced if the mass ordering were known from other experiments.
  - Non-accelerator physics including proton decay, atmospheric neutrinos, and supernovae neutrinos.
- Cosmic ray background risks mitigated by underground location.

Cons:

- Mismatch between beam spectrum and shorter baseline does not allow full measurement of oscillatory signature.

- Shorter baseline risks fundamental ambiguities in interpreting results. This risk is greater than for the Ash River option.
- Sensitivity decreases if θ_{13} is smaller than the current experimental value.
- Limited Phase 2 path:
  - Beam limited to 1.1 MW (Project X Stage 1).
  - Phase 2 could be a 30 kton surface detector at Ash River or an additional 25-30 kton underground (2,340 ft) detector at Soudan.

5.2.3 10-kton Detector on Surface at SURF

The final alternative is a 10-kton surface detector at SURF, which would require a new beamline and provide a 1,300-km baseline.

Pros

- Excellent (3 σ) mass ordering reach in the full CP range.
- Good CP violation reach: not dependent on *a priori* knowledge of the mass ordering.
- Longer baseline and broad-band beam allow explicit reconstruction of oscillations in the energy spectrum: self-consistent standard neutrino measurements; best sensitivity to Standard Model tests and non-standard neutrino physics.
- Clear Phase 2 path: a 20 – 25 kton underground (4850 ft) detector at SURF. This covers the full capability of the original LBNE physics program.
- Takes full advantage of Project X beam power increases.

Cons

- Cosmic ray backgrounds: impact and mitigation need to be determined.
- Only accelerator-based physics. Proton decay, supernova neutrino and atmospheric neutrino research are delayed to Phase 2.
- ~10% more expensive than the other two options: cost evaluations and value engineering exercises in progress.

5.3 Decision-making Process

The Steering Committee had twelve conference call meetings and had two face-to-face meetings on April 26, 2012 and May 22-23, 2012 at Fermilab. The Steering Committee organized and held a workshop on April 25-26, 2012 at Fermilab to inform the high-energy physics community, to discuss the status of the work in progress and to seek input from the community. The Physics Working Group and the Engineering/Cost Working Group enlisted the necessary experts from Fermilab, other national laboratories, universities and the LBNE and other neutrino experiment collaborations to carry out the studies. Each working group provided a report of its analysis [**25**] [**26**].

5.4 The Preferred First-Phase Alternative

While each of these first-phase alternatives is more sensitive than the others in some particular physics domain, the Steering Committee in its discussions strongly favored the alternative to build a new beamline to SURF with an initial 10-kton LArTPC detector on the surface. The physics reach of this first phase is very strong; it would determine the mass hierarchy and explore the CP-violating phase δ_{cp}, and measure other oscillation parameters: θ_{13}, θ_{23}, and Δm^2_{32}.

Moreover this alternative is seen by the Steering Committee as a start for a long-term world-leading program that would achieve the full goals of LBNE in time and allow probing the Standard Model most incisively beyond its current state.

5.5 Deficiencies in Preferred First-Phase Alternative

5.5.1 Loss of Underground Physics Program

Although the preferred alternative has the required very long baseline, the major limitation of the preferred alternative is that the underground physics program including proton decay and supernova collapse cannot start until later phases of the project. Placing a 10 kton detector underground instead of the surface in the first phase would allow such a start, and increase the cost by about $135M.

The deep site at 4850 ft is strongly favored for this program, providing improved cosmogenic background rejection for astrophysical neutrino and proton decay studies, as well as the possibility for shared infrastructure with a broader underground program. At the proposed deep site, the LBNE program will be enriched by additional sensitivity to proton decay and atmospheric and supernova neutrino physics.

5.5.2 Lowered Precision

The LBNE collaboration has examined strategies to maintain the initial scientific performance without a full near detector complex. Although detailed evaluation must await full simulations, the conclusion is that there are viable strategies that will be adequate for the initial period of LBNE running. However, a complete LBNE near detector system will be required in a later stage to achieve the full precision of the experiment. Studies will continue as the design of LBNE is developed.

5.6 Cost Estimates

Cost estimates were evolved from the original LBNE reference design. Costs include a far LArTPC detector, a new beamline for the SURF alternative (~$400M), investment in the NuMI beamline for extended running with the low-energy configuration at 700 kW for the Soudan and Ash River alternatives (~$40M), project management (~10% of the total cost), escalation and contingency. For a near detector, construction of a muon-monitoring system for the SURF alternative, and use of the MINERvA, MINOS near detector or NOvA near detector for the Soudan and Ash River alternatives is assumed.

5.7 Conclusion

Cost estimates were done at a preliminary level, and evaluations and value engineering exercises showed that the preferred alternative is ~15% more expensive than the other two.

Preference for this first-phase alternative was driven by the scientific advantages of a longer distance baseline between the neutrino source and detector afforded by siting the detector at SURF. This alternative requires a new neutrino beamline to meet the necessary beam directional, energy, and long-term operability requirements needed to initiate and sustain the LBNE program. It provides the best opportunity to realize a timely, cost-effective and scientifically capable LBNE, and provides a solid foundation for cost effectively extending scientific reach should additional funds become available.

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