LBNE Reconfiguration

Steering Committee
Interim Report

June 5, 2012

Content

Executive Summary

Introduction

The Department of Energy (DOE) Office of Science (SC) High Energy Physics (HEP) is planning investments in the next generation neutrino experiment, Long-Baseline Neutrino Experiment (LBNE).

In light of the current budget climate, on March 19th, Dr. W.F. Brinkman, Director of the DOE Office of Science, asked Fermilab to find a path forward to reach the goals of the LBNE in a phased approach or with alternative options. His letter notes that this decision is not a negative judgment about the importance of the science, but rather it is a recognition that the peak cost of the project cannot be accommodated in the current budget climate, or that projected for the next decade. Pier Oddone, 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 is charged to provide guidance to the working groups, to identify viable options and to write the report to the DOE. The Physics Working Group is charged to analyze the physics reach of various phases and alternatives on a common basis, and the Engineering/Cost Working Group is charged to provide cost estimates and to analyze the feasibility of the proposed approaches with the same methodology. Dr. Brinkman's letter to Pier Oddone is given in *Appendix A*, and the membership of the Steering Committee, the committee's ex-officio members and the membership of the working groups are listed in *Appendix B*.

The Steering Committee had eight 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. *Appendix C* gives the agenda for the workshop. The Physics Working Group and the Engineering/Cost Working Group enlisted the necessary experts from Fermilab, other national laboratories, universities and neutrino experiment collaborations to carry out the studies. Each working group provided a report of their analysis and their reports are given in *Appendices D and E*. Meeting agendas and minutes of the Steering Group and the working groups, and the workshop presentations are posted on the LBNE reconfiguration webpage (http://www.fnal.gov/directorate/lbne_reconfiguration/).

The Steering Committee wishes to thank the Physics Working Group, the Engineering/Cost Working Group and many experts who participated in the studies, whose work is the foundation of this report. The committee would also like to thank those who provided their input to this process via presenting at the workshop or writing letters to the committee.

Neutrinos and LBNE

The discovery that neutrinos spontaneously change type – a phenomenon called neutrino oscillation – was one of the most revolutionary particle-physics discoveries of the last several decades. This discovery was unexpected by the very successful Standard Model of particle physics. It points to new physics phenomena at energies much higher than those that can directly be discovered at particle colliders, and it raises other challenging questions about the fundamental workings of the universe.

Neutrinos are the most elusive of the known fundamental particles. To the best of our knowledge, they interact with other particles only through the weak interactions. For this reason, neutrinos can only be observed and studied via intense neutrino sources and large detectors. Particle accelerators, nuclear reactors, cosmic ray air showers, and neutrinos originating in the sun and in supernovae provide important neutrino sources, and have all played critical roles in discovering neutrinos and their mysterious properties. These discoveries led to the 1988 Nobel Prize in Physics (Leon Lederman, Melvin Schwartz and Jack Steinberger), the 1995 Nobel Prize in Physics (Frederick Reines), and the 2002 Nobel Prize in Physics (Raymond Davis and Masatoshi Koshiba).

The experimental achievements of the past 15 years have been astonishing. A decade ago, the space of allowed oscillation parameters spanned many orders of magnitude. Within the three-neutrino picture, allowed regions have now shrunk to better than the 10% precision level for most of the parameters. By the end of this decade, invaluable new information is expected from the current generation of neutrino-oscillation experiments, namely the long-baseline beam experiments NOvA, T2K, MINOS, ICARUS and OPERA and the reactor experiments Double Chooz, Daya Bay and RENO. These experiments will measure the known oscillation parameters much more precisely, and may provide nontrivial hints regarding the neutrino mass hierarchy. However, it is unlikely that these experiments will be able to determine the ordering of the neutrino masses unambiguously, nor provide any significant information regarding possible violation of CP-invariance in the lepton sector. Nor is it expected that they will be able to test definitively the standard three-neutrino paradigm. That will be the task of next-generation experiments.

Future opportunities for testing the paradigm and probing new physics using next-generation neutrino-oscillation experiments are broad and exciting. The focus for the U.S. has been the Long Baseline Neutrino Experiment (LBNE), which would employ a 700 kW beam from Fermilab and a large liquid argon time-projection chamber at the Homestake mine in South Dakota, 1,300 km away. With the 1,300 km baseline, a broad-band neutrino beam designed specifically for this purpose, and the highly capable detector, LBNE would measure many of the oscillation parameters to high precision and, in a single experiment, test the internal consistency of the three-neutrino oscillation model. Placed deep underground, the detector would also allow for a rich physics program beyond neutrino-oscillation studies. It would include a high-sensitivity search for proton decay, and high-sensitivity studies of neutrinos coming from supernovae within our galaxy.

The LBNE would answer a number of important scientific questions:

1. Is there CP violation in the neutrino sector? The existence of matter this late in the universe's development requires CP violation at an early stage, but the amount seen in the quark sector is much too small to account for the matter that we observe in the universe. CP violation in the lepton sector may provide the explanation.
2. Is the ordering of the neutrino mass states the same as that of the quarks, or is the order inverted? In addition to being an important question on its own, the answer has a major impact on our ability to determine whether the neutrino is its own antiparticle. If true, it could reflect physics at energy scales much greater than those probed at the LHC.
3. Is the proton stable? Proton decay would require violation of baryon number conservation, and such violation is needed to account for the matter-antimatter asymmetry in the universe. The answer will provide clues to the unification of the forces of nature.
4. What physics and astrophysics can we learn from the neutrinos emitted in supernova explosions?

The importance of these questions and the unique ability of LBNE to address them led to strong support by the scientific community for LBNE. LBNE was a feature of the plan proposed by the Particle Physics Project Prioritization Panel (P5) of the High Energy Physics Advisory Panel (HEPAP) in 2008 and was a key element of the strong endorsement for underground physics by the National Research Council, in July, 2011. The importance of LBNE to U.S leadership in neutrino physics was also recognized in the report of the DOE-sponsored workshop on Fundamental Physics at the Intensity Frontier, held in December 2011.

A very strong collaboration formed around LBNE with the participation of 65 institutions from 5 countries including 6 U.S. national laboratories.

Interim Conclusions

To achieve all of the fundamental science goals listed above, a reconfigured LBNE would need 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 options that meet some of the requirements, and identified three viable options for the first phase of a long-baseline experiment that have the potential to accomplish important science at realizable cost. These options are (not priority ordered):

- Using the existing NuMI beamline in the low energy configuration with a **30 kton** liquid argon time projection chamber (LAr-TPC) **surface detector** 14 mrad off-axis at Ash River in Minnesota, **810 km** from Fermilab.

- Using the existing NuMI beamline in the low energy configuration with a **15 kton** LAr-TPC **underground (at the 2,340 ft level) detector** on-axis at the Soudan Lab in Minnesota, **735 km** from Fermilab.

- Constructing a new low energy LBNE beamline with a **10 kton** LAr-TPC **surface detector** on-axis at Homestake in South Dakota, **1,300 km** from Fermilab.

The committee looked at possibilities of projects with significantly lower costs and concluded that the science reach for such projects becomes marginal.

We list pros and cons of each of the viable options below (not priority ordered).

- 30 kton surface detector at Ash River in Minnesota (NuMI low energy beam, 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 (3σ) mass ordering reach in nearly half of the δ_{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: o Beam limited to 1.1 MW (Project X Stage 1). o Phase 2 could be a 15-20 kton underground (2,340 ft) detector at Soudan.

- 15 kton underground (2,340 ft) detector at the Soudan Lab in Minnesota (NuMI low energy beam, 735 km baseline)

Pros	• Broadest Phase 1 physics program: o Accelerator-based physics including good (2σ) mass ordering and good CP-violation reach in half of the δ_{CP} range. CP-violation reach would be enhanced if the mass ordering were known from other experiments. o 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: o Beam limited to 1.1 MW (Project X Stage 1). o 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.

- 10 kton surface detector at Homestake (new beamline, 1,300 km baseline)

Pros	• Excellent (3σ) mass ordering reach in the full δ_{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 the Homestake mine. 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.

While each of these first-phase options is more sensitive than the others in some particular physics domain, the Steering Committee in its discussions strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface. The physics reach of this first phase is very strong; more over this option is seen by the Steering Committee as a start of 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. Ultimately this option would exploit the full power provided by Project X. At the present level of cost estimation, it appears that this preferred option may be ~10% more expensive than the other two options, but cost evaluations and value engineering exercises are continuing.

In the next few months the LBNE collaboration and external experts will be studying the operation of LAr-TPCs on the surface to verify that the cosmic ray backgrounds are manageable. The operation on the surface may require shorter drift times than required for underground operations and the localization of the event in the TPC coincident with the ten microsecond-long beam from Fermilab. The Phase 1 experiment will use the existing detectors (MINOS near detector, MINERvA, and NOvA near detector) as near detectors for the two NuMI options, and use muon detectors to monitor the beam for the Homestake option. The Physics working group is currently studying the impact of near detectors on the physics reach.

Although the preferred option has the required very long baseline, its major limitation of the preferred option 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.

Establishing a clear long-term program will make it possible to bring the support of other agencies both domestic and foreign. The opportunities offered by the beam from Fermilab, the long baseline and ultimately underground operation are unique in the world. Although the contributions from other agencies could substantially reduce the cost to the DOE or enhance the science capabilities for the first phase of the project, they are not taken into account in the present cost estimates.

Long Baseline Neutrino Program in the U.S.

1. Introduction

The discovery that neutrinos spontaneously change type – a phenomenon called neutrino oscillation – was one of the most revolutionary particle physics discoveries of the last several decades. This discovery was unexpected by the very successful Standard Model of particle physics. It points to new physics phenomena at energies much higher than those that can directly be discovered at particle colliders, and raises other challenging questions about the fundamental workings of the universe.

Neutrinos are the most elusive of the known fundamental particles. To the best of our knowledge, they interact with other particles only through the weak interactions. For this reason, neutrinos can only be observed and studied via intense neutrino sources and large detectors.

With the advent of the first nuclear reactors in the 1940's it was realized that they could serve as intense neutrino sources, many orders of magnitude greater than what can be obtained from naturally radioactive substances. Frederick Reines captured the reactor neutrinos through the reaction: (anti)neutrino + proton $\rightarrow$ neutron + positron in 1956, and was awarded the 1995 Nobel Prize in Physics. The observation of neutrinos was a pioneering contribution that paved the way for the "impossible" neutrino experiments. One such experiment attempted to capture neutrinos, originating in the sun or in supernovae. Solar neutrinos were first detected by Raymond Davis with a detector of 600 tonnes of fluid placed in the Homestake mine, but at a rate substantially below what was expected. Supernova neutrinos (SN1987A) were observed by Kamioka (Japan) and IMB (U.S.) research teams. The oscillation of atmospheric neutrinos was observed by the Super-Kamiokande experiment in 1998 and the oscillation of solar neutrinos as the explanation of the solar neutrino deficit was conclusively established by the Sudbury Neutrino Observatory in Canada in 2001. These observations were rewarded with the 2002 Nobel Prize in Physics (Raymond Davis and Masatoshi Koshiba). Particle accelerators can also produce intense neutrino sources. In 1962 using accelerators at Brookhaven National Laboratory Leon Lederman, Melvin Schwartz and Jack Steinberger showed that more than one type of neutrino exists by first detecting interactions of the muon neutrino, which earned them the 1988 Nobel Prize in Physics. The first detection of tau neutrino interactions was announced in 2000 by the DONUT collaboration at Fermilab, making it the latest particle of the Standard Model to have been observed. It eluded direct observation five years longer than the top quark, the heaviest known elementary particle, discovered in 1995 by the CDF and DZero collaborations at Fermilab.

In the late 1990s the discovery that neutrinos oscillate and therefore must have non-zero masses moved the study of neutrino properties to the forefront of experimental and theoretical particle physics. Experiments with solar, atmospheric, reactor and accelerator neutrinos established that neutrinos have mass, and that neutrino flavor eigenstates (ν_e, ν_μ or ν_τ) are different from neutrino mass eigenstates (ν_1, ν_2 or ν_3), that is, neutrinos mix or oscillate. A neutrino produced with a well-defined flavor is a coherent superposition of mass eigenstates and has a non-zero probability to be detected as a neutrino with a different flavor. This oscillation, or flavor-changing, probability depends on the neutrino energy, the distance traversed between the neutrino source and the detector ("baseline"), the neutrino mass differences, and the elements of the neutrino mixing matrix, which relates neutrinos with a well-defined flavor and neutrinos with a well-defined mass.

Oscillation Parameters

Almost all neutrino data to date can be explained assuming that neutrinos interact as prescribed by the Standard Model, there are only three neutrino mass eigenstates, and the mixing matrix is unitary. Under these circumstances, it is customary to parameterize the mixing matrix with three mixing angles (θ_{12}, θ_{13}, and θ_{23}) and three CP-violating phases (δ, ξ, and ζ). ξ and ζ, the so-called Majorana phases, are only physical if the neutrinos are Majorana fermions, and have essentially no effect on flavor-changing phenomena. In order to relate the mixing elements to experimental observables, it is necessary to define the neutrino mass eigenstates or to "order" the neutrino masses. This is done in the following way: $m_2^2 > m_1^2$ and $\Delta m^2_{21} < |\Delta m^2_{31}|$. In this case, $m_3^2 > m_2^2$ ($m_3^2 < m_2^2$) characterizes a normal (inverted) neutrino mass hierarchy.

The astonishing experimental achievements of the past 15 years have filled in the three-flavor neutrino picture. A decade ago, the space of allowed oscillation parameters spanned many orders of magnitude. Allowed regions have now shrunk to better than the 10% precision level for most of the oscillation parameters. Table 1 summarizes our current knowledge of neutrino oscillation (mixing) parameters from a fit to experimental data, including measurements of θ_{13} from the Daya Bay reactor experiment. Indications by T2K, MINOS and Double Chooz experiments in 2011 pointed to $\sin^2 2\theta_{13}$ around 0.08. In combination, these results excluded $\sin^2 2\theta_{13} = 0$ at more than three standard deviations. Early 2012, the Daya Bay collaboration announced five standard deviation evidence that $\sin^2 2\theta_{13}$ is not zero. This result was immediately followed by the RENO result with an independent five standard deviation evidence of non-zero $\sin^2 2\theta_{13}$. It is evident that our knowledge of the smallest of the neutrino mixing angles is quickly evolving. The fact that it is non-zero permits experimental sensitivity to the CP-violating phase angle δ.

Table 1. Best fit values of parameters in the neutrino mixing matrix and comparison to the equivalent values in the quark mixing matrix.

Parameter	Neutrino mixing matrix	Quark mixing matrix
θ_{12}	34 ± 1^{o}	13.04 ± 0.05^{o}
θ_{23}	43 ± 4^{o}	2.38 ± 0.06^{o}
θ_{13}	9 ± 1^{o}	0.201 ± 0.011^{o}
Δm^2_{21}	$+ (7.58 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2_{32}\rvert$	$(2.35 \pm 0.12) \times 10^{-5}$ eV^2 (sign unknown)	$m_3 >> m_2$
δ_{CP}	Unknown	67 ± 5^{o}

We have virtually no information concerning the CP-violating phase (δ) and the mass hierarchy. The primary goal of accelerator-based neutrino oscillation experiments is to measure these unknown parameters, the CP violation and the mass hierarchy, and to test whether the standard three-massive-neutrinos paradigm is correct and complete. This will be achieved not simply by determining all of the parameters, but by "over-constraining" the parameter space in order to identify potential inconsistencies. This is not an easy task, and the data collected thus far, albeit invaluable, allow for only the simplest consistency checks. In the future, precision measurements will require a new generation of improved neutrino oscillation experiments.

As demonstrated in Table 1, the pattern of mixing and mass is significantly different between neutrinos and quarks. Another goal of future neutrino experiments is to understand the relationship between the quark and lepton mixing matrices and the organizing principle responsible for the observed pattern of neutrino mixing.

Large, qualitative modifications to the standard paradigm are allowed while still being consistent with existing data. Furthermore, there are several hints in the world neutrino data that point to a neutrino sector that is more complex than the one outlined above. Possible surprises include new "sterile" states that manifest themselves only by mixing with the known neutrinos, and new weaker-than-weak interactions.

Origin of Neutrino Mass

Neutrino masses are at least six orders of magnitude smaller than the electron mass. We don't know why neutrino masses are so small or why there is such a large gap between the neutrino and charged fermion masses. We suspect, however, that this may be Nature's way of telling us that neutrinos might acquire their masses differently.

This suspicion is only magnified by the possibility that massive neutrinos, unlike all other fermions in the Standard Model, may be Majorana fermions. Neutrinos are the only electrically neutral fundamental fermions and hence need not be distinct from their antiparticles. Determining the nature of the neutrino would not only help guide theoretical work related to uncovering the origin of neutrino masses, but could also reveal that the conservation of lepton number is not a fundamental law of Nature. The most promising avenue for learning the fate of lepton number is to look for neutrinoless double-beta decay, a lepton-number violating nuclear process.

Small neutrino masses can be explained by a seesaw mechanism which appears to be the simplest and most appealing way to understand small neutrino masses. It introduces three (as yet unobserved) right-handed neutrinos with heavy masses to the Standard Model, with at least one mass required by data to be close to the energy scale of conventional grand unified theories ($\sim 10^{16}$ GeV). This may be a hint that new physics scales implied by neutrino masses and grand unification of forces are the same.

Questions for Next-Generation Neutrino Oscillation Experiments

The main goal of next-generation neutrino oscillation experiments is to answer the following questions:

- Do the interactions of neutrinos violate charge-parity (CP) symmetry? The preponderance of matter over antimatter in the universe could not have developed without a violation of this symmetry. CP violation has already been seen in quarks, but at a level insufficient to explain the observed cosmic matter-antimatter asymmetry. CP violation in neutrinos may be the missing ingredient.
- Does the neutrino mass spectrum resemble the spectra of the quarks and the charged leptons (normal mass hierarchy), or is it inverted (inverted mass hierarchy)? In other words, is Δm^2_{31} positive (normal) or negative (inverted)? The answer to this question will shed light on the origin of the masses of all elementary particles. If the spectrum is found to be inverted it will also provide clues to whether neutrinos are their own antiparticles, which would shed light on the evolution of the early universe.
- What is the organizing principle responsible for the observed pattern of neutrino masses and lepton mixing?

- Are there new neutrino-like particles that are not predicted by the Standard Model? Do the known neutrinos participate in new, non-Standard-Model interactions? Are there other surprises in the neutrino sector?

Precision neutrino oscillation measurements are required to address these fundamental questions. That can only be achieved as the result of significant investments in intense, well-characterized neutrino sources and massive high-precision detectors.

2. Opportunities for Neutrino Programs in the World

Worldwide there are multiple existing and planned neutrino programs using accelerator-based long- and short-baseline experiments at surface and underground sites, and reactor-based neutrino, atmospheric neutrino and neutrinoless double-beta decay experiments at underground sites.

For neutrino oscillation measurements, by the end of this decade, we anticipate invaluable new information from the current generation of neutrino oscillation experiments, namely the accelerator-based long-baseline experiments NOvA, T2K, MINOS, ICARUS and OPERA and the reactor experiments Double Chooz, Daya Bay and RENO. In the language of the standard paradigm, these experiments will measure θ_{13}, θ_{23}, and $|\Delta m^2_{31}|$ much more precisely, and may provide nontrivial hints regarding the neutrino mass hierarchy. While the possibility of surprises cannot, and certainly should not, be discarded, it is expected that the neutrino data accumulated until the end of the decade will not be able to definitively test the standard three-neutrino paradigm, nor determine the ordering of neutrino masses, nor observe CP-invariance violation in the lepton sector. That will be the task of next-generation experiments.

Future opportunities for testing the paradigm and probing new physics for next-generation neutrino oscillation experiments are broad and exciting. The focus for the U.S. has been the Long Baseline Neutrino Experiment (LBNE), which would employ a 700 kW beam from Fermilab and a large liquid argon time projection chamber at the Homestake mine in South Dakota, 1,300 km away. The chosen 1,300 km baseline is nearly ideal for this physics. It is long enough that LBNE could unambiguously separate the CP-conserving neutrino-antineutrino difference due to the matter effect from a true CP-violating asymmetry. It is short enough that significant numbers of both neutrino and antineutrino events could be collected to explicitly measure a CP-violating difference between their oscillation probabilities, if one exists. The neutrino energies required for this baseline are in the range where it is straightforward to produce a high-power broad-band beam that will allow observation of full oscillation patterns. In addition the detector, if placed underground, would allow for a rich physics program beyond neutrino oscillation studies. This would include a high-sensitivity search for proton decay, which probes the grand unification scale of $\sim 10^{16}$ GeV, and high-sensitivity studies of neutrinos coming from supernovae within our galaxy.

Around the world, a number of ambitious proposals are being discussed. In Japan planning is underway for a scheme to increase the power of the T2K beam to 1.7 megawatts. A proposed new experiment in Japan is Hyper-Kamiokande, a much larger version of the existing Super-K water Cherenkov detector. Ideas have been floated in Japan for large liquid argon detectors, possibly sited on Okinoshima island halfway between Japan and Korea. In Europe the LAGUNA study is exploring a host of options for future long-baseline programs. These could be based on the existing CERN neutrino beam capability, or much more challenging concepts including beta beams or a neutrino factory. Various large detector options are being discussed, as well as a variety of sites, including

Pyhasalmi Finland (2,300 km from CERN), Frejus (130 km from CERN), and a site in Umbria off-axis from the existing CNGS (CERN Neutrinos to Gran Sasso) beam. The European study includes investigation of possible staging options for these major initiatives.

Of these proposed next-generation experiments, the plans for LBNE are the best developed, including robust designs for the neutrino beamline and the detectors and well-developed cost and schedule estimates. The scientific and technical designs and the project plan have been thoroughly reviewed internally by the LBNE Project and by Fermilab, and found to be nearly at the CD-1 level. However, the LBNE project cost, in particular, the yearly cost, is too high and cannot be accommodated in the current budget climate. We are, therefore, in the process of finding a path forward to reach the goals of the LBNE in a phased approach or with alternative options.

3. Opportunities for Neutrino Programs at Fermilab

3.1 Current and Near Future Programs

Fermilab operates diverse and intense neutrino beams. The neutrino beamline from the 120 GeV Main Injector (NuMI) operates at 350 kW with a tunable neutrino beam covering from 0.5 GeV to 10 GeV, and the neutrino beamline from the 8 GeV Booster accelerator (BNB) operates with a low-energy neutrino beam covering from 0.2 GeV to 1 GeV. These beams are unmatched in the world today.

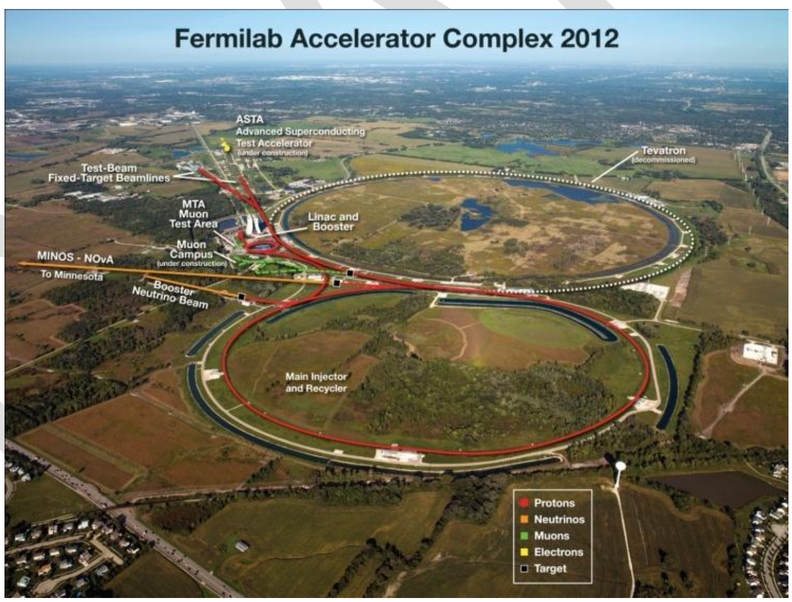

Figure 1. Fermilab's accelerator facility consists of a 400 MeV linear accelerator, 8 GeV Booster accelerator and 120 GeV Main Injector synchrotron. The complex delivers proton beams to a variety of target stations: 8 GeV protons to the Booster Neutrino Beam target and 120 GeV protons to the NuMI target, a fixed-target experiment and a test-beam facility.

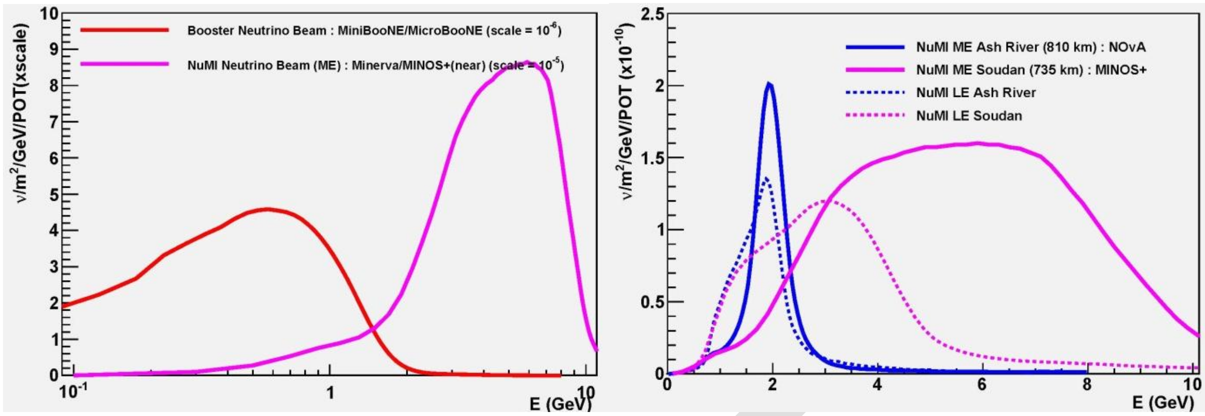

Figure 2. (Left) Energy distributions of neutrinos from the 8 GeV Booster and the 120 GeV Main Injector; (Right) Energy distributions of neutrinos from the 120 GeV Main Injector at Soudan (MINOS) and Ash River (NOvA) for low-energy and medium-energy target options.

Fermilab is transforming its accelerator facilities to meet the challenges of the Intensity Frontier era. These transformations, which include upgrades for the NOvA experiment and the Proton Improvement Plan, make the best use of assets freed up by the end of Tevatron collider operations and provide a platform for even longer-term accelerator development. The existing Fermilab accelerator complex, including the Main Injector synchrotron, Recycler storage ring and NuMI neutrino beamline and target, is being upgraded to supply 700 kW proton beams for NOvA, a second-generation long-baseline (810 km) neutrino experiment, and the existing long-baseline (735 km) MINOS experiment starting in 2013.

The Proton Improvement Plan is a program of equipment refurbishment and replacements to enhance the reliability and capability of the accelerator complex for high proton throughput that will deliver 33 kW of proton-beam power at 8 GeV simultaneous with NOvA and MINOS+ operations. The Proton Improvement Plan, which will be completed in 2016, will support the operation through 2025 of a suite of neutrino experiments (NOvA, MINOS+, MINERvA, and MicroBooNE), muon experiments (Mu2e and muon g-2), and proton experiment (SeaQuest) at the Intensity Frontier and the test-beam facility for detector R&D.

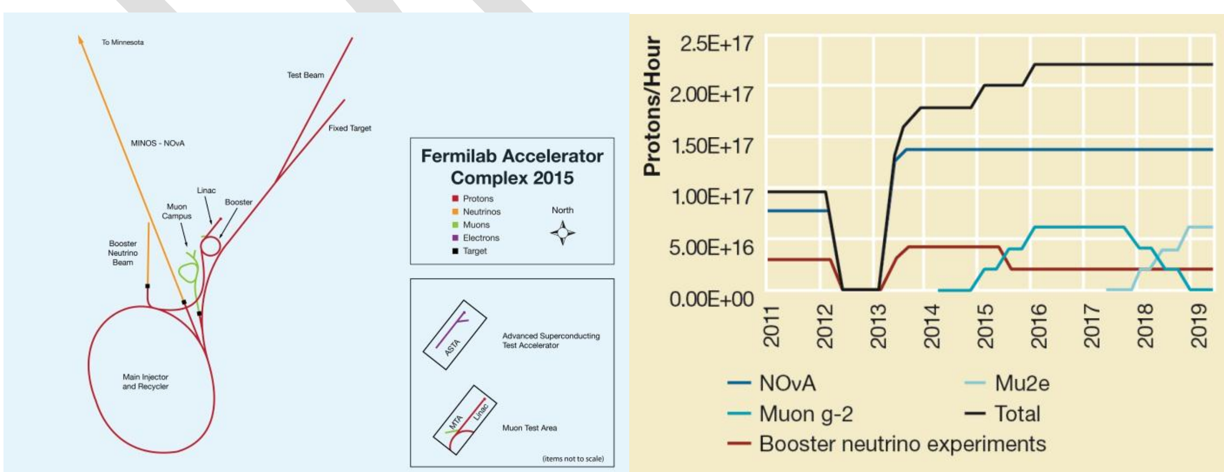

Figure 3. Layout of the accelerator complex (left) and the total number of protons needed for Fermilab's NOvA neutrino experiments and Muon g-2 and Mu2e experiments through 2020 (right).

Fermilab's intense beams of accelerator-generated neutrinos and associated experiments address the following questions:

- Does the neutrino mass spectrum resemble the spectra of the quarks and the charged leptons, or is it inverted? NOvA, which will start taking data in 2013, is the only near-term experiment worldwide that can address this question, and its sensitivity will be enhanced by combining with T2K results. The combined sensitivity, however, is not guaranteed to discover the mass hierarchy.

- NOvA can also independently confirm, using a different approach, recent results from experiments using the Daya Bay and RENO nuclear reactors that point to a high value for a parameter, θ_{13}. The specific value of θ_{13} influences the rest of the worldwide neutrino physics program. Because accelerator beam experiments are sensitive to the product of θ_{13} and θ_{23}, NOvA will make precise measurements of θ_{23} and could establish for the first time non-maximal mixing due to this parameter.

- Are there new neutrino-like particles that are not predicted by the Standard Model? Do the known neutrinos participate in new, non-Standard-Model interactions? Are there other surprises in the neutrino sector? MiniBooNE, having just completed its run, is showing evidence that suggests that these neutrino-like particles, called sterile neutrinos, may exist. MicroBooNE, under construction, will explore this evidence in a new way and help develop the liquid-argon technology on which LBNE will depend. MINOS+, the next stage of the successful MINOS experiment that precisely measured the neutrinos' mass differences, will constrain or find evidence for non-standard neutrino interactions and physics.

- What are the rates of interaction of neutrinos with various nuclei? The interaction rates of neutrinos with the nuclei used in targets that produce them are currently poorly known. The operating MINERvA experiment measures the rates that other experiments must know before they can deduce neutrino oscillation probabilities.

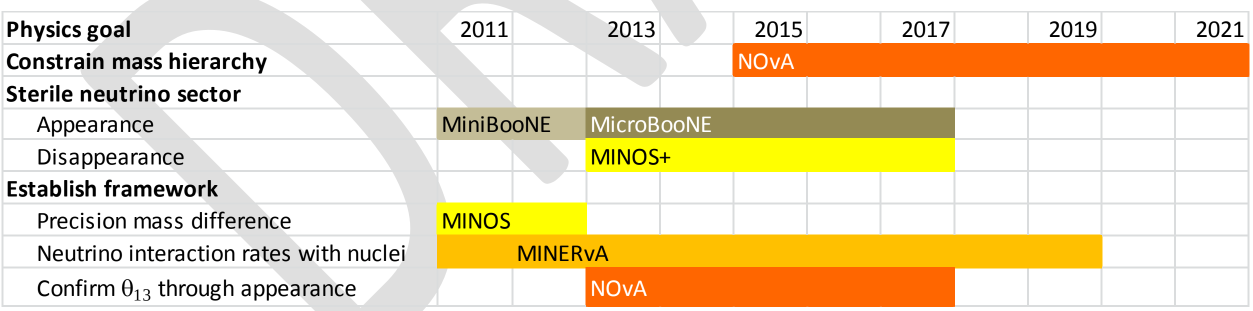

Figure 4. Timelines of Fermilab neutrino experiments and their physics goals in the next ten years

3.2 Longer Term Programs

Next-generation neutrino experiments and an Intensity Frontier accelerator facility will be needed in the 2020s and 2030s to assure continued U.S. leadership at the Intensity Frontier where some of the most important new discoveries are expected in the coming decades.

Long Baseline Neutrino Experiment (LBNE)

The Long Baseline Neutrino Experiment (LBNE) is the next major planned neutrino program in the U.S. The experiment as currently envisioned comprises a new 700 kW beamline at Fermilab, whose spectrum is optimized for this physics and which is upgradeable to handle more than 2 MW of beam power from the future Project X; a near detector complex to fully characterize the unoscillated beam; and a large far detector at the Homestake mine in South Dakota, at a baseline of 1,300 km, to make precision measurements of neutrino oscillation phenomena and enable a broad program of non-accelerator-based physics.

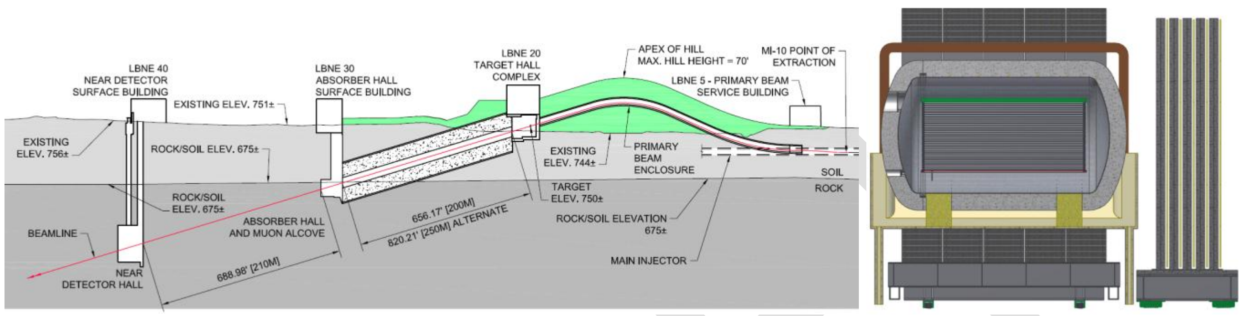

Figure 5. Layout of the LBNE beamline (left) and the near detector (right).

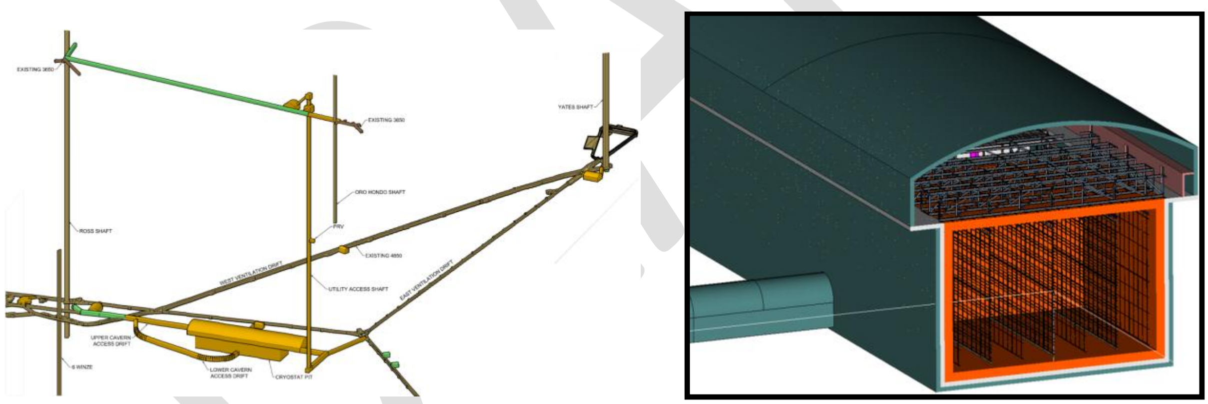

Figure 6. Layout of the underground facility at Homestake (left) and the LAr-TPC far detector (right).

The LBNE would answer a number of important scientific questions:

1. Is there CP violation in the neutrino sector? The existence of matter this late in the universe's development requires CP violation at an early stage, but the amount seen in the quark sector is much too small to account for the matter that we observe in the universe. CP violation in the lepton sector may provide the explanation.
2. Is the ordering of the neutrino mass states the same as that of the quarks, or is the order inverted? In addition to being an important question on its own, the answer has a major impact on our ability to determine whether the neutrino is its own antiparticle. If true, it could reflect physics at energy scales much greater than those probed at the LHC.

3. Is the proton stable? Proton decay would require violation of baryon number conservation, and such violation is needed to account for the matter-antimatter asymmetry in the universe. The answer will provide clues to the unification of the forces of nature.
4. What physics and astrophysics can we learn from the neutrinos emitted in supernova explosions?

LBNE would be well suited for this physics with its long distance and versatile and massive far detector. Such massive detectors are crucial for collecting sufficient event samples over such long distances. Extensive design work and physics sensitivity studies were done over the past few years for two detector options for LBNE: a 200-kton single-module water Cherenkov detector and a 34-kton dual-module liquid argon time projection chamber (LAr-TPC). Although a configuration with both technologies would be preferable for physics, the cost was prohibitive. After an extensive decision-making process, the LAr-TPC option was selected.

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.

A phased approach or alternatives to LBNE will be discussed in Section 4.

A phased approach to Project X

Project X is a U.S.-led accelerator initiative with strong international participation that aims to realize a next-generation proton source that will dramatically extend the reach of intensity frontier research. The state of the art in superconducting radio frequency has advanced to a point where it can be considered and implemented as the core enabling technology for a next-generation multi-megawatt proton source. By reliably delivering unprecedented beam power and flexible beam timing configurations among simultaneous experiments, and allowing a broad range of experiments to develop and operate in parallel, Project X would establish the world-leading program at the intensity frontier in 2020s and beyond.

Project X has leadership potential in the future landscape of more than five-megawatt proton sources with kinetic energies of 3, 8, and 120 GeV. Notable in the Project X program is the deep reach in neutrino physics. The direct scope of Project X includes 2 – 2.4 MW of beam power at 60 – 120 GeV for LBNE and 50 – 190 kW at 8 GeV, corresponding to three times the initial beam power of the LBNE and three to 12 times the beam power delivered to the MiniBooNE experiment. This extraordinary beam power is particularly important to long-baseline experiments in which the sensitivity is ruled by the product of beam power and detector mass. Project X beam intensities allow the long-baseline oscillation physics program to be accomplished much faster with high precision and flexibility.

Figure 7 presents the layout of Project X and beam power for long baseline neutrino programs from the Main Injector for three neutrino facilities in the next couple of decades: the current Main Injector capability (350kW at 120 GeV), the ongoing accelerator upgrade (700kW at 120 GeV) and Project X (2.3MW at 120 GeV).

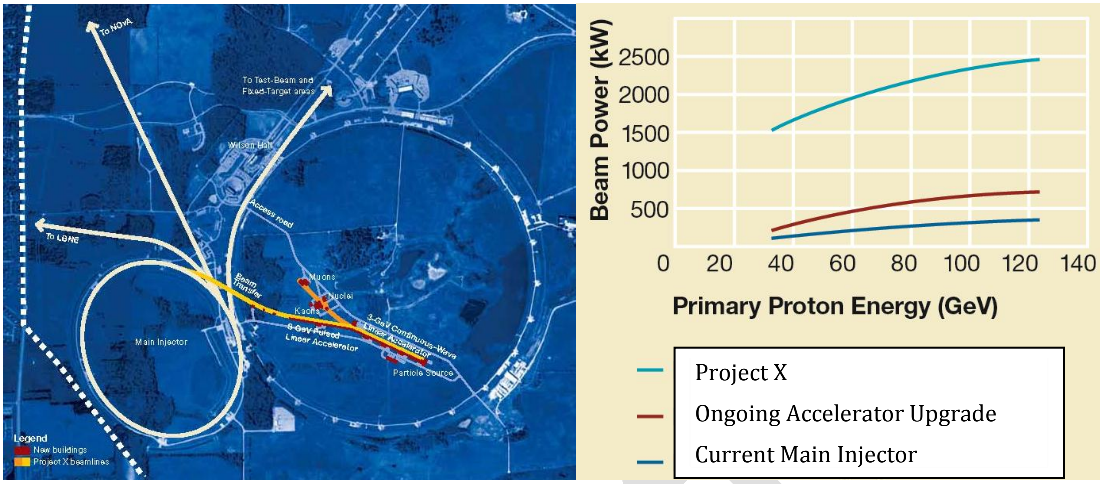

Figure 7. Layout of Project X (left) and beam power from the Main Injector for three neutrino facilities: the existing NuMI beam, the ongoing accelerator upgrade and Project X (right).

Fermilab has developed a phased approach for Project X, leveraging existing accelerator assets at the Fermilab accelerator facility. The first stage, Stage 1, at approximately one-third of the full project cost, would replace the front end of the 50-year old injectors at Fermilab, provide a 1.1-megawatt beam to LBNE and support other world-leading experiments (e.g., muon and electric dipole moment experiments and energy applications) beginning in the 2020s. Phase 1 would be built in such a way as to accommodate subsequent expansion to the full facility in an efficient and straightforward manner. The various phases of Project X and LBNE could be interleaved as demonstrated in Figure 8. The phased approach to both LBNE and Project X offers great flexibility and resiliency relative to both funding changes and physics discoveries.

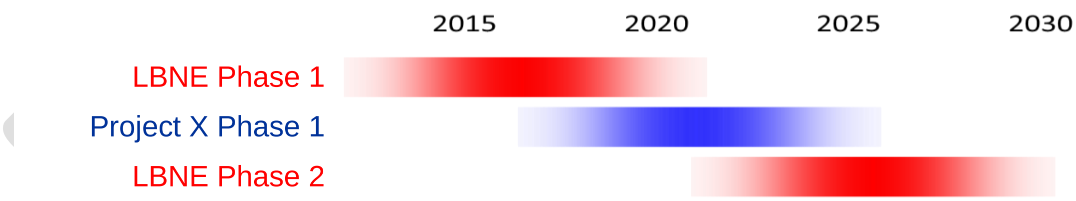

Figure 8. Potential timeline for various phases of LBNE and Project X.

4. Reconfigured LBNE

Studies focus on the comparison of physics capabilities and estimated costs of a LAr-TPC detector at the Homestake location with a LAr-TPC detector placed in the NuMI low energy beam at the Soudan and Ash River locations. The beam and detector configurations under consideration include

- Using the NuMI beamline in the low energy configuration with a LAr-TPC detector 14 mrad off-axis at Ash River, 810 km from Fermilab,
- Using the NuMI beamline in the low energy configuration with a LAr-TPC detector on-axis at Soudan, 735 km from Fermilab, and

- Constructing a new low energy LBNE beamline with a LAr-TPC detector on-axis at Homestake, 1,300 km from Fermilab

Physics Studies

We assume the reconfigured LBNE Phase 1 experiment will run for 5 years in neutrino mode and 5 years in anti-neutrino mode at a beam power of 700 kW with 6 x 10^{20} protons-on-target accumulated per year with a LAr-TPC far detector and a near detector. We assume NOvA will run for 3 years in neutrino mode and 3 years in anti-neutrino mode (3+3) with the NuMI medium-energy (ME) beam prior to the LBNE Phase 1 experiment (NOvA I). An additional running of 5 years in neutrino mode and 5 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 options. We assume 5 x 10^{21} protons-on-target total accumulated by T2K (~6 years) in neutrino only mode.

Table 2 and Figure 9 summarize the oscillation measurements with various configurations as a function of LAr-TPC detector mass, where we assume $\sin^2 2\theta_{13} = 0.092 \pm 0.006$ (or $\theta_{13} = 0.154 \pm 0.005$) and that nature has chosen the normal hierarchy but that this is not known *a priori*. Non-accelerator physics capabilities with various configurations as a function of LAr-TPC detector mass are presented in Figure 10. Physics capabilities are described in more detail in *Appendix D* (Physics Working Group Report).

*Table 2. Summary of the oscillation measurements with various configurations given $\theta_{13} = 8.8^o$, $\theta_{23} = 40^o$, and $\Delta m^2_{31} = +2.27 \times 10^{-3} eV^2$. The values for the fraction of δ_{CP} for which the mass hierarchy (MH) or CP violation (CPV) are determined with 3σ sensitivity are given in the first 2 columns. All correlations and uncertainties on the known mixing parameters, as well as the uncertainty in the mas hierarchy, are included. *These measurements are for the combination of neutrino and anti-neutrino running.*

Configuration		MH* fraction of δ (3σ)	CPV* fraction of δ (3σ)	σ(δ_{CP})* δ=0, π/2 (deg.s)	σ(θ_{13})* δ=π/2 (deg.s)	σ(θ_{23}) ν (deg.s)	σ(θ_{23}) anti–ν (deg.s)	σ(Δm^2_{31}) ν ($10^{-3}eV^2$)	σ(Δm^2_{31}) anti–ν ($10^{-3}eV^2$)
Soudan	10kt	0.00	0.00	27, 36	0.70	1.3	1.6	0.045	0.065
	15kt	0.17	0.05	23, 30	0.60	1.1	1.3	0.036	0.055
	30kt	0.34	0.18	16, 24	0.45	0.80	0.97	0.028	0.040
Ash River	10kt	0.28	0.00	23, 48	0.60	1.3	1.8	0.058	0.080
	15kt	0.37	0.10	19, 40	0.50	1.0	1.5	0.048	0.069
	30kt	0.47	0.27	18, 29	0.40	0.74	1.1	0.035	0.050
Homestake	5kt	0.66	0.00	25, 41	0.60	0.92	1.4	0.035	0.055
	10kt	0.81	0.27	17, 30	0.40	0.69	0.97	0.025	0.040
	15kt	0.95	0.43	15, 25	0.30	0.52	0.80	0.020	0.030
	20kt	1.00	0.50	13, 21	0.25	0.46	0.63	0.018	0.026
NOvA (6yrs) + T2K (6yrs)		0.00	0.00	22, 65					
NOvA I+II (16yrs) + T2K (6yrs)		0.25	0.11	18, 47					
NOvA I+II + T2K + Soudan	10kt	0.38	0.21	16, 30					
	15kt	0.38	0.23	14, 26					
	30kt	0.45	0.29	12, 21					
NOvA I+II + T2K + Ash River	10kt	0.40	0.23	14, 34					
	15kt	0.45	0.25	13, 30					
	30kt	0.50	0.55	13, 25					
NOvA I + T2K + Homestake	5kt	1.00	0.33	15, 31					
	10kt	1.00	0.45	12, 25					
	15kt	1.00	0.53	12, 24					

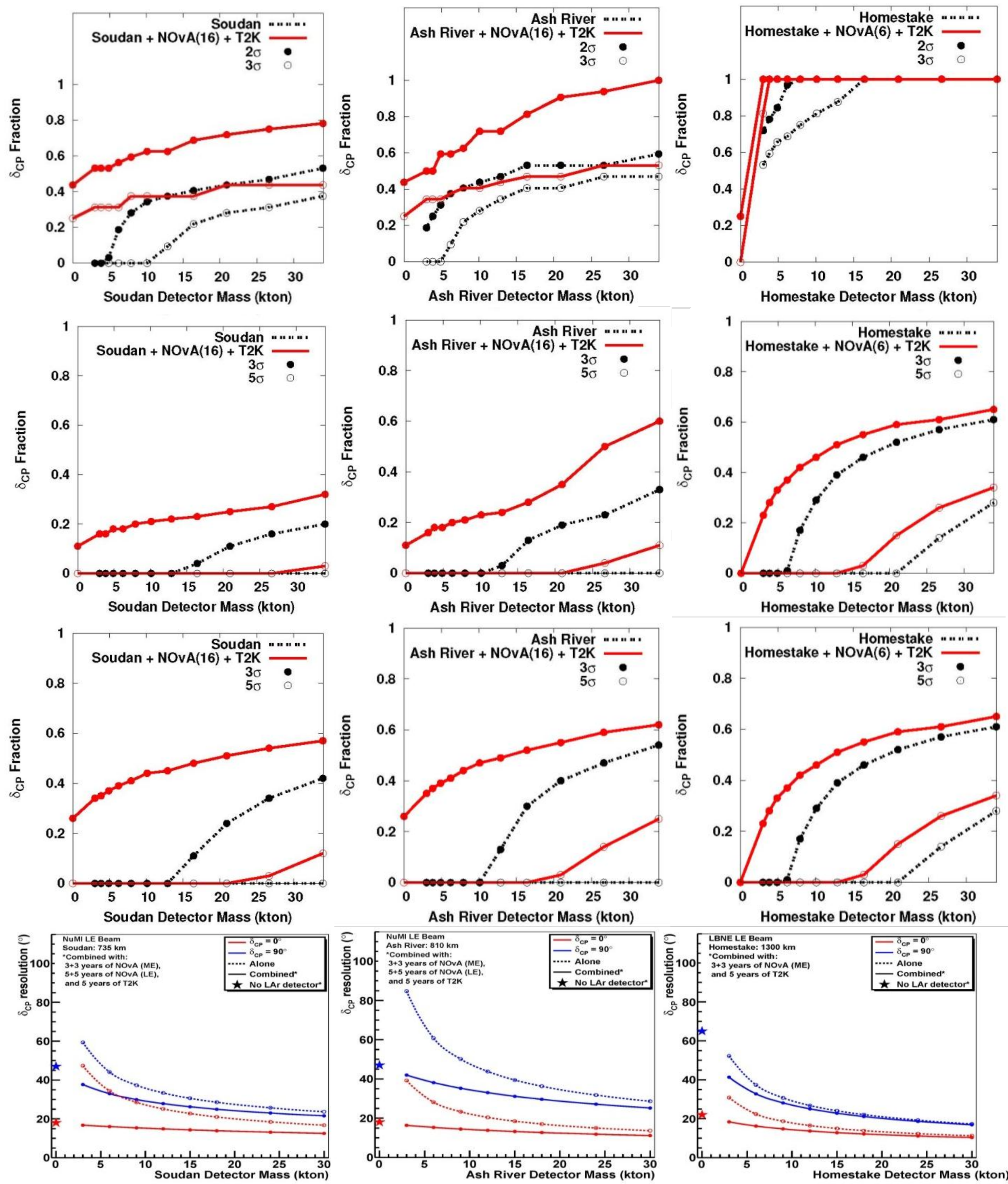

*Figure 9. The plots from top to bottom: the fraction of δ_{CP} values for which **the mass hierarchy** can be resolved at 2/3σ (solid/open points), **CP violation** can be resolved at 3/5σ (solid/open points), and **CP violation** can be resolved at 3/5σ (solid/open points) when the mass ordering is known, and **the 1σ resolution on the measurement of δ_{CP}** for δ_{CP} = 0 (red), π/2 (blue) as a function of LAr-TPC detector mass after running for 10 years. For the resolution (bottom), a tight external constraint on θ_{13} = 0.154 ± 0.005 is included and the mass hierarchy is assumed to be known. The plots from left to right are for Soudan, Ash River and Homestake from the experiment alone and the combination with T2K and NOvA.*

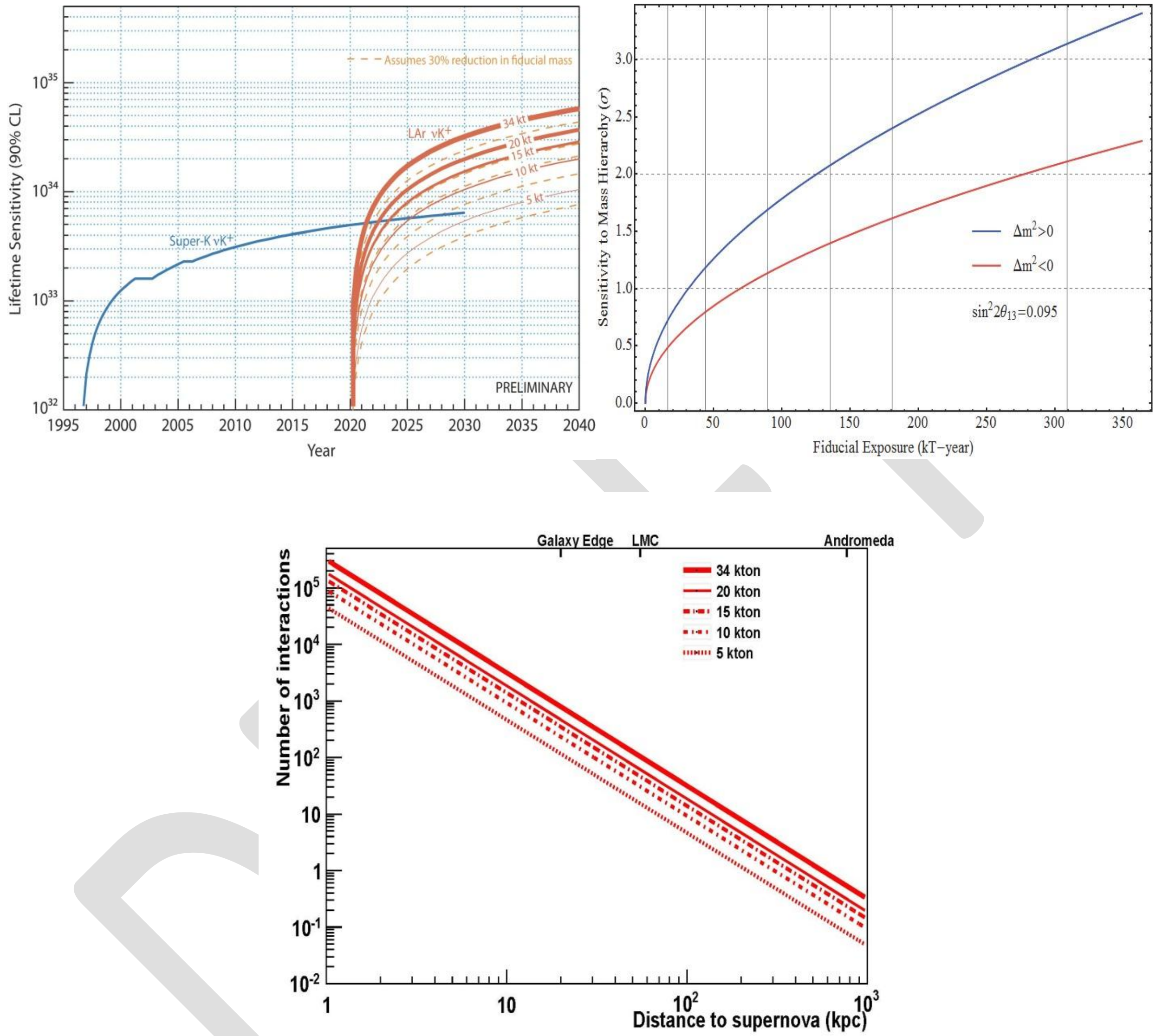

Figure 10. (Top-left) The 90% CL proton lifetime limit in the proton decay mode, $p \rightarrow K\nu$, in units of years as a function of time for Super-Kamiokande compared to different LAr-TPC masses at the Homestake 4850 ft level starting in 2020. The dashed lines show the limit for the Soudan 2340 ft level option, representing about 30% reduction in fiducial due to its shallower location. (Top-right) The mass hierarchy sensitivity from atmospheric neutrinos as a function of fiducial exposure or LAr-TPC mass x running time. The sensitivities for the Homestake option and the Soudan option are similar. (Bottom) The number of neutrinos from a supernova as a function of distance to the supernova for various LAr-TPC detector masses. Core collapses are expected to occur a few times per century, at a most-likely distance of about 10-15 kpc. The sensitivities for the Homestake option and the Soudan option are similar.

Cost Estimates

Cost estimates were evolved from the original LBNE reference design. Costs include a far LAr-TPC detector, a new beamline for the Homestake option (~$400M), investment in the NuMI beamline for extended running with the low energy configuration at 700 kW for the Soudan and Ash River options (~$30M), project management (~10% of the total cost), escalation and contingency. For a near detector for Phase 1, we assume that we will build a muon monitoring system for the Homestake option and use the MINERvA, MINOS near detector or NOvA near detector for the Soudan and Ash River options. A complete LBNE near detector system will be required to achieve the ultimate precision of the experiment, and must be provided in a later phase. For surface detectors, cosmic ray backgrounds could be an issue (studies are being done) and in that case we might need a top veto system, photon detectors, or modification in a far detector with shorter drift length. These are not included in the current cost estimates. Cost estimates are still very preliminary and evaluations and value engineering exercises are in progress.

Figure 11 summarizes the total cost as a function of the LAr-TPC far detector mass for various options. Cost estimates are described in more detail in *Appendix E* (Engineering/Cost Working Group Report).

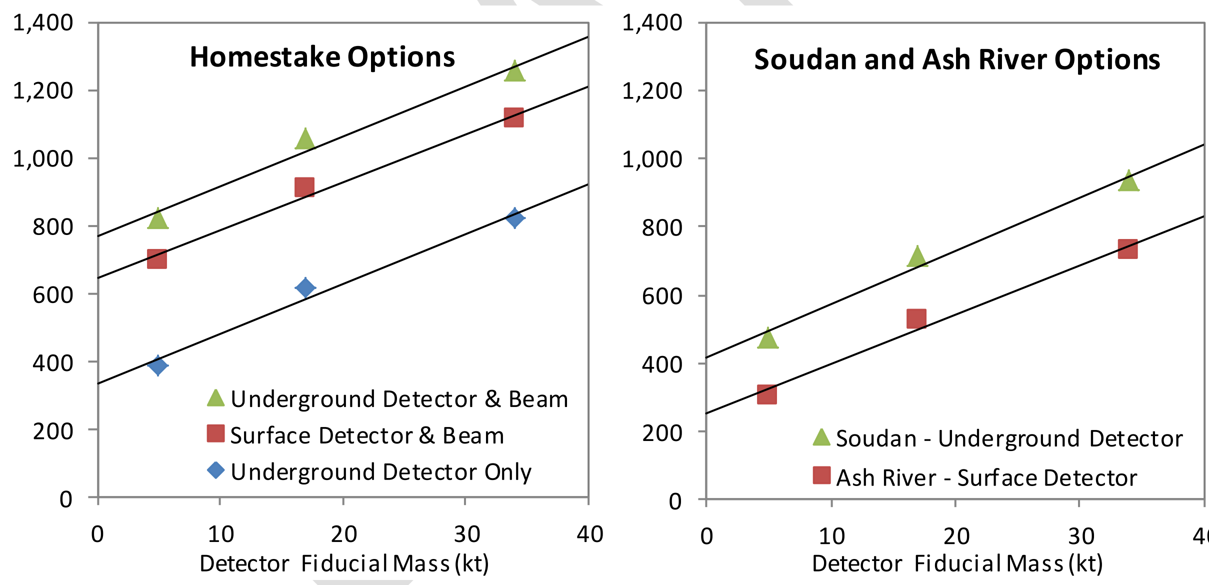

Figure 11. Cost estimates ($M), including contingency and escalation, as a function of LAr-TPC detector mass at Homestake (left) and Soudan and Ash River (right). Straight lines are linear fits.

5. Interim Conclusions: Viable Options for Reconfigured LBNE Phase 1

To achieve all of the fundamental science goals listed above, a reconfigured LBNE would need 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 options that meet some of the requirements, and identified three viable options for the first phase of a long-baseline experiment that have the potential to accomplish important science at realizable cost. These options are (not priority ordered):

- Using the existing NuMI beamline in the low energy configuration with a **30 kton** liquid argon time projection chamber (LAr-TPC) **surface detector** 14 mrad off-axis at Ash River in Minnesota, **810 km** from Fermilab.

- Using the existing NuMI beamline in the low energy configuration with a **15 kton** LAr-TPC **underground (at the 2,340 ft level) detector** on-axis at the Soudan Lab in Minnesota, **735 km** from Fermilab.

- Constructing a new low energy LBNE beamline with a **10 kton** LAr-TPC **surface detector** on-axis at Homestake in South Dakota, **1,300 km** from Fermilab.

The committee looked at possibilities of projects with significantly lower costs and concluded that the science reach for such projects becomes marginal.

Table 3. Summary of the oscillation measurements using accelerator neutrinos and the non-accelerator based physics reach with various configurations. For the oscillation measurements, we assume θ_{13} = 8.8°, θ_{23} = 40°, and Δm^2_{31} = +2.27 x $10^{-3}eV^2$. All correlations and uncertainties on the known mixing parameters, as well as the uncertainty in the mass hierarchy, are included. The numbers shown in parentheses indicate the expected results when combined with NOvA and T2K data.

Phase 1 Option		15 kton Soudan (underground)	30 kton Ash River (surface)	10 kton Homestake (surface)
Phase 1 Science Capabilities assuming 6 x 10^{21} protons on target or 10 years with 700 kW	Mass Hierarchy: fraction of δ_{CP} at 3σ	0.17 (0.38)	0.47 (0.50)	0.81 (1.00)
	CP Violation: fraction of δ_{CP} at 3σ	0.05 (0.23)	0.27 (0.55)	0.27 (0.45)
	Resolution of δ_{CP} δ = 0, 90°	23°, 30° (14°, 26°)	18°, 29° (13°, 25°)	17°, 30° (12°, 25°)
	Proton Decay p → Kν 90% CL in 10 years	1 x 10^{34} years	No	No
	Number of observed neutrinos from a supernova explosion at a distance of 10 kiloparsecs	1,300	No	No
	Atmospheric neutrinos Mass Hierarchy in 10 years	1.5 σ	No	No
	Precision Measurements: $\sigma(\theta_{13})$ for δ=π/2 Neutrino $\sigma(\theta_{23})$ Anti neutrino $\sigma(\theta_{23})$ Neutrino $\sigma(\Delta m_{31}^2)$ ($10^{-3}eV^2$) Anti neutrino $\sigma(\Delta m_{31}^2)$ ($10^{-3}eV^2$)	 0.60° 1.1° 1.3° 0.036 0.055	 0.40° 0.74° 1.1° 0.035 0.050	 0.40° 0.69° 0.97° 0.025 0.040
Phase 1 Risks	Work in progress	Geotechnical studies for the underground detector	Cosmic ray backgrounds in a surface detector	Cosmic ray backgrounds in a surface detector

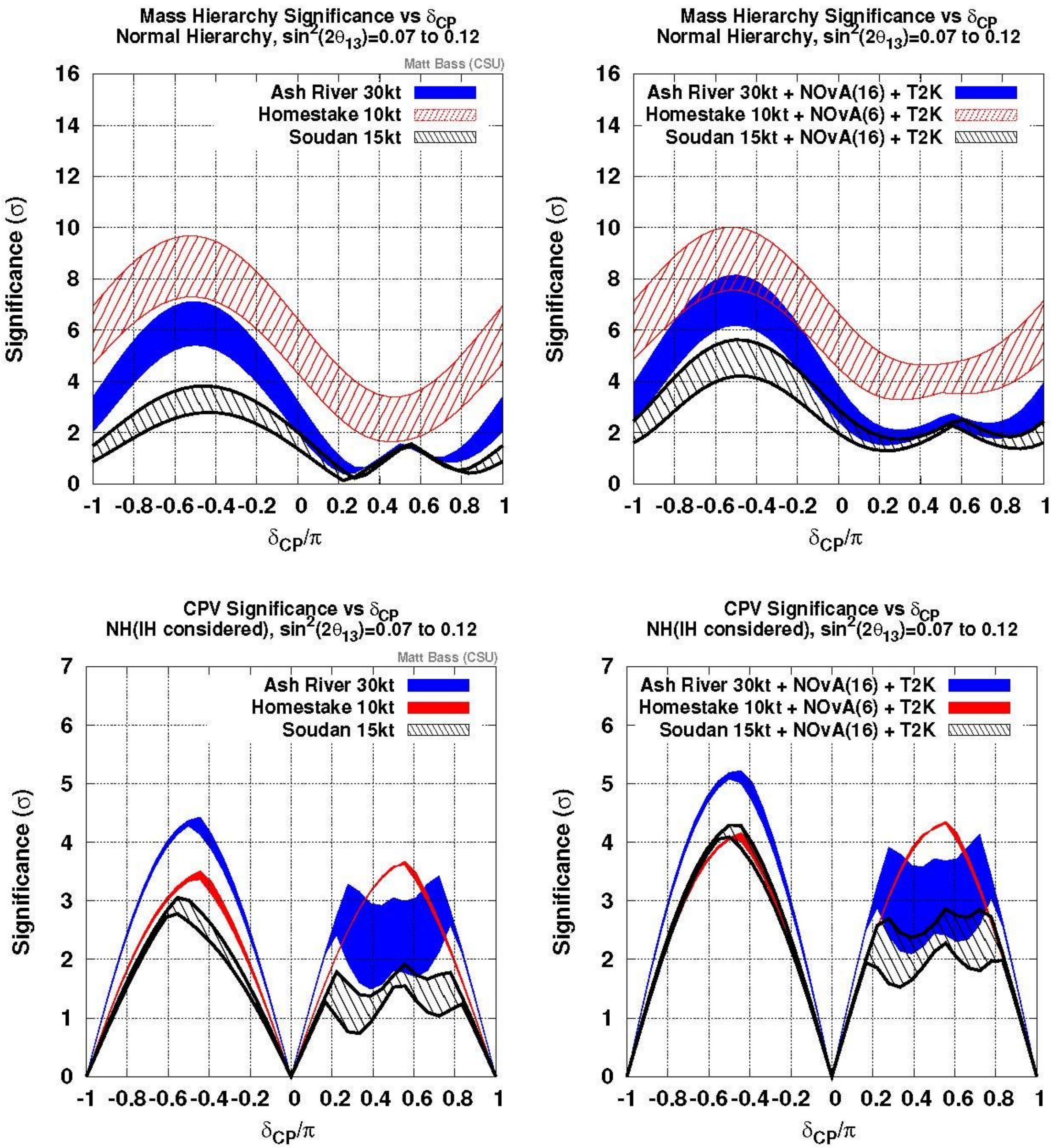

Figure 12. The significance with which the mass ordering (top) and CP violation (bottom) is resolved with a 10 kton surface detector at Homestake (red), a 30 kton surface detector at Ash River (blue), and a 15 kton underground detector at Soudan (black) as a function of the unknown CP violating phase δ_{CP}. The sensitivities are measured with the experiment alone (left) and combined with NOvA running with the ME beam for 3+3 years and T2K for all three options and additional NOvA running the LE beam for 5+5 years for the Ash River and Soudan options (right). If the mass ordering is known, the CP violation significance in the positive δ_{CP} region with the Ash River option (blue) and the Soudan option (black) will look like that in the negative δ_{CP} region. The bands cover ±2σ of the current measurement of $\sin^2 2\theta_{13}$.

We list pros and cons of each of the viable options below (not priority ordered).

- 30 kton surface detector at Ash River in Minnesota (NuMI low energy beam, 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 (3σ) mass ordering reach in nearly half of the δ_{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.

- 15 kton underground (2,340 ft) detector at the Soudan Lab in Minnesota (NuMI low energy beam, 735 km baseline)

Pros	• Broadest Phase 1 physics program:
	  ○ Accelerator-based physics including good (2σ) mass ordering and good CP-violation reach in half of the δ_{CP} 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.

- 10 kton surface detector at Homestake (new beamline, 1,300 km baseline)

Pros	• Excellent (3σ) mass ordering reach in the full δ_{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 the Homestake mine. 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.

While each of these first-phase options is more sensitive than the others in some particular physics domain, the Steering Committee in its discussions strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface. The physics reach of this first phase is very strong; more over this option is seen by the Steering Committee as a start of 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. Ultimately this option would exploit the full power provided by Project X. At the present level of cost estimation, it appears that this preferred option may be ~10% more expensive than the other two options, but cost evaluations and value engineering exercises are continuing.

In the next few months the LBNE collaboration and external experts will be studying the operation of LAr-TPCs on the surface to verify that the cosmic ray backgrounds are manageable. The operation on the surface may require shorter drift times than required for underground operations and the localization of the event in the TPC coincident with the ten microsecond-long beam from Fermilab. The Phase 1 experiment will use the existing detectors (MINOS near detector, MINERvA, and NOvA near detector) as near detectors for the two NuMI options, and use muon detectors to monitor the beam for the Homestake option. The Physics working group is currently studying the impact of near detectors on the physics reach.

Although the preferred option has the required very long baseline, its major limitation of the preferred option 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.

Establishing a clear long-term program will make it possible to bring the support of other agencies both domestic and foreign. The opportunities offered by the beam from Fermilab, the long baseline and ultimately underground operation are unique in the world. Although the contributions from other agencies could substantially reduce the cost to the DOE or enhance the science capabilities for the first phase of the project, they are not taken into account in the present cost estimates.

Appendix A: Brinkman Letter to Oddone

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

March 19, 2012

Dr. Pier Oddone
Director
Fermilab
Wilson and Kirks Road
Batavia, IL 60510-5011

Dear Pier,

Thank you for your recent presentation on the status and plans for the Long Baseline Neutrino Experiment (LBNE). The project team and the scientific collaboration have done an excellent job responding to our requests to assess the technology choices and refine the cost estimates for LBNE. We believe that the conceptual design is well advanced and the remaining technical issues are understood.

The scientific community and the National Academy of Sciences repeatedly have examined and endorsed the case for underground science. We concur with this conclusion, and this has been the motivator for us to determine a path forward as quickly as possible following the decision of the National Science Board to terminate development of the Homestake Mine as a site for underground science.

We have considered both the science opportunities and the cost and schedule estimates for LBNE that you have presented to us. We have done so in the context of planning for the overall Office of Science program as well as current budget projections.

Based on our considerations, we cannot support the LBNE project as it is currently configured. This decision is not a negative judgment about the importance of the science, but rather it is a recognition that the peak cost of the project cannot be accommodated in the current budget climate or that projected for the next decade.

In order to advance this activity on a sustainable path, I would like Fermilab to lead the development of an affordable and phased approach that will enable important science results at each phase. Alternative configurations to LBNE should also be considered. Options that allow us to independently develop the Homestake Mine as a future facility for dark matter experiments should be included in your considerations.

A report outlining options and alternatives is needed as soon as practical to provide input to our strategic plan for the Intensity Frontier program. OHEP will provide additional details on realistic cost and schedule profiles and on the due date for the report.

Thank you,

W. F. Brinkman
Director, Office of Science

Appendix B: Steering Committee and Working Group Membership

Steering Committee	
Young-Kee Kim, FNAL (Chair)	LBNE LOG (Lab Oversight Group) member
James Symons, LBNL	LBNE LOG (Lab Oversight Group) member
Steve Vigdor, BNL	LBNE LOG (Lab Oversight Group) member
Bob Svoboda, UC Davis	LBNE co-spokesperson
Kevin Lesko, LBNL	SURF (Sanford Underground Research Facility) head
Gary Feldman, Harvard	NOvA co-spokesperson
Mel Shochet, U.Chicago	Physics working group chair, Former HEPAP chair
Mark Reichanadter, SLAC	Engineering/Cost working group chair DOE DUSEL review committee co-chair
Charlie Baltay, Yale	P5 chair
Jon Bagger, JHU	Former HEPAP deputy chair
Ann Nelson, UW, Seattle	HEPAP member

Steering Committee: Ex-officio members	
Andy Lankford, UC Irvine	HEPAP chair, DUSEL NRC study chair
Steve Ritz, UC Santa Cruz	PASAG (Particle Astrophysics Scientific Assessment Group) chair, Fermilab PAC member
Jay Marx, Caltech	DOE DUSEL review committee co-chair
Pierre Ramond, U. Florida	DPF chair
Harry Weerts, ANL	DOE Intensity Frontier Workshop co-chair
JoAnne Hewett, SLAC	DOE Intensity Frontier Workshop co-chair
Jim Strait, FNAL	LBNE Project Manager Engineering/Cost working group deputy chair
Pier Oddone, FNAL	Director, Fermilab
Susan Seestrom, LANL	LBNE LOG (Lab Oversight Group) member

Physics Working Group	Engineering / Cost Working Group
Mel Shochet, U.Chicago (chair)	Mark Reichanadter, SLAC (chair)
Mary Bishai, BNL	Jim Strait, FNAL (deputy chair)
Ed Blucher, UChicago	Bruce Baller, FNAL
Steve Brice, FNAL	Mike Headley, SURF
Milind Diwan, BNL	Marvin Marshak, U. Minnesota
Bonnie Fleming, Yale	Chris Mauger, LANL
Gil Gilchriese, LBNL	Elaine McCluskey, FNAL
Bill Marciano, BNL	Vaia Papadimitriou, FNAL
Mark Messier, Indiana	Bob O'Sullivan, FNAL
Stephen Parke, FNAL	Jeff Sims, ANL
Gina Rameika, FNAL	Additional invitation to
Kate Scholberg, Duke	Tracy Lundin (FNAL)
Jenny Thomas, UCL	Jeff Dolph (BNL)
Charlie Young, SLAC	Jim Stewart (BNL)
Sam Zeller, FNAL	Joel Sefcovic (FNAL)

Appendix C: Agenda of the Workshop on April 25-26, 2012

April 25 (day 1)

- Plenary session (chair: Bob Wilson)
  - 10:30 am Welcome – Pier Oddone (5')
  - 10:35 am Introduction – Young-Kee Kim (30' + 5')
  - 11:10 am Physics Working Group: Introduction + Summary of Initial Studies – Mel Shochet / Gina Rameika (40'+10')
  - 12:00 pm Lunch (60')
- Plenary session (chair: Brajesh Choudhary)
  - 1:00 pm Engineering / Cost Working Group: Introduction – Mark Reichanadter or Jim Strait (10' + 5')
  - 1:15 pm Beamline including Conventional Facilities: assumptions and cost estimates - Vaia Papadimitriou (30' + 15')
  - 2:00 pm Near Detector including Conventional Facilities: assumptions and cost estimates - Christopher Mauger (15' + 5')
  - 2:20 pm Conventional Faclities for the Far Detector: assumptions and cost estimates - Tracy Lundin (30' + 15')
  - 3:05 pm Far Detector: assumptions and cost estimates – Bruce Baller (25' + 10')
  - 3:40 pm Coffee Break (30')
- Plenary session (chair: Kevin Lesko)
  - 4:10 pm Community voice: moderated discussion focusing on NuMI options (60')
    - This session is organized by MINOS + NOvA co-spokespersons
  - 5:10 pm Community voice: open mikes – up to 2 slides / 5' each (60')
    - If you want to sign up for a time slot, please send an email to Jon Bagger, Steve Vigdor and Mary-Ellyn McCollum (bagger@jhu.edu, vigdor@bnl.gov, mccollum@fnal.gov).
- Reception (6:30 – 8:30 pm) – Wilson Hall 2nd floor North Crossover

April 26 (day 2)

- Plenary session (chair: Jon Rosner)
  - 8:00 am Neutrino reach – Mary Bishai (30' + 10')
  - 8:40 am Proton decay and cosmic neutrino reach – Kate Scholberg (30' + 10')
  - 9:20 am Community voice: LBNE collaboration (60')
    - This session is organized by LBNE co-spokespersons
  - 10:20 am Coffee Break (30')
- Plenary session (chair: Shekhar Mishra)
  - 10:50 am Community voice: open mikes – up to 2 slides / 5' each (60')
    - If you want to sign up for a time slot, please send an email to Jon Bagger, Steve Vigdor and Mary-Ellyn McCollum (bagger@jhu.edu, vigdor@bnl.gov, mccollum@fnal.gov).
  - 11:50 am Community voice: moderated discussion – moderator: Charlie Baltay (40')
  - 12:30 pm Wrap-up (15') – Young-Kee Kim

Appendix D

Physics Working Group Report to the LBNE Reconfiguration Steering Committee

DRAFT

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(Dated: June 4, 2012)

This document summarizes the physics capabilities of a long baseline neutrino experiment employing a liquid argon detector and fed by an intense beam from Fermilab. The locations considered for the detector are at the Homestake mine in South Dakota, the Soudan mine in Minnesota, and the Ash River, Minnesota site of the NOvA detector. The experimental reach as a function of detector mass is given for the neutrino mass hierarchy and CP violation phase as well as for proton decay, atmospheric neutrino studies, and neutrinos from supernova explosions.

CONTENTS

I. INTRODUCTION

Four years ago, HEPAP's P5 subpanel laid out a plan to maintain the United States as a world leader in high energy physics. Central to that plan was a world-class neutrino program utilizing a large underground detector in South Dakota fed by an intense neutrino source at Fermilab. Such an experiment would answer a number of important scientific questions. (1) Is there CP violation in the neutrino sector? The existence of matter this late in the universe's development requires CP violation, but the effect seen in the quark sector is much too small. The answer may be neutrino CP violation, and the proposed project would be the first to have the sensitivity needed to observe it. (2) Is the ordering of the neutrino mass states the same as that of the quarks, or is the order inverted? In addition to being an important question on its own, it has a major impact on our ability to determine whether the neutrino is its own antiparticle, which if true could reflect physics at energy scales much greater than those probed at the LHC. (3) Is the proton stable? The answer will provide clues to the unification of the forces of nature. (4) What physics and astrophysics can we learn from the neutrinos emitted in supernova explosions?

The proposed experiment would have addressed all of these questions, but its cost was found to be too large. We were asked to propose options for staging the program in a way that is both affordable and effective in doing the science. Here we provide the data needed to assess the reach of each option for the above scientific questions.

II. CONFIGURATIONS

During the committee's deliberations, the following detector configurations were considered.

Config. Number	Beam	Baseline	Off-axis angle	Location	Depth	Detector
1	NuMI LE	735km	0	Soudan	0	LAr 5, 10, 15, 34 kt
2	NuMI LE	735km	0	Soudan	2300ft	LAr 5, 10, 15, 34 kt
3	NuMI ME	810km	14mrad	Ash River	0	LAr 5, 10, 15, 34 kt
4	NuMI LE	810km	14mrad	Ash River	0	LAr 5, 10, 15, 34 kt
5	NuMI ME	810km	14mrad	Ash River	0	TASD 14 (NOνA), 40kt
7	LBNE LE	1300km	0	Homestake	0	LAr 5, 10, 15, 34 kt
8	LBNE LE	1300km	0	Homestake	4850ft	LAr 5, 10, 15, 34 kt

TABLE I. Configurations considered by the LBNE Reconfiguration Physics Working Group. NuMI LE (ME) refers to the low-energy (medium-energy) tunes of the existing NuMI beamline. LBNE LE is the low-energy tune of a new proposed beam-line from Fermilab aimed at the Homestake Mine in South Dakota. LAr refers to a Liquid Argon Time-Projection Chamber, and TASD refers to a Totally Active Scintillator Detector.

III. LONG-BASELINE PHYSICS

Although the Standard Model of particle physics presents a remarkably accurate description of the elementary particles and their interactions, it is known that the current model is incomplete and that a more fundamental underlying theory must exist. Results from the last decade, that the three known types of neutrinos have nonzero mass, mix with one another and oscillate between generations, implies physics beyond the Standard Model [1].

The three-flavor-mixing scenario for neutrinos can be described by three mixing angles (θ_{12}, θ_{23} and θ_{13}) and one CP-violating phase (δ_{CP}). The probability for neutrino oscillation also depends on the difference in the squares of the neutrino masses, $\Delta m^2_{ij} = m^2_i - m^2_j$; three neutrinos implies two independent mass-squared differences (Δm^2_{21} and Δm^2_{32}).

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}. The value of θ_{13} has been determined to be much smaller than the other two mixing angles which are both large [2] [3], implying that mixing is qualitatively different in the neutrino and quark sectors. Table II summarizes the current values of the neutrino oscillation parameters obtained from a global fit to experimental data [4] and the measurement of θ_{13} from the Daya Bay reactor experiment [2]. A comparison to the equivalent mixing parameter values in the quark CKM matrix is also shown [5].

TABLE II. Best fit values of the neutrino mixing parameters in the PMNS matrix and comparison to the equivalent values in the CKM matrix

Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12}	$34 \pm 1°$	$13.04 \pm 0.05°$
θ_{23}	$43 \pm 4°$	$2.38 \pm 0.06°$
θ_{13}	$9 \pm 1°$	$0.201 \pm 0.011°$
Δm^2_{21}	$+(7.58 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2_{32}\rvert$	$(2.35 \pm 0.12) \times 10^{-3}$ eV^2	$m_3 >> m_2$
δ_{CP}	no measurement	$67 \pm 5°$

Assuming a constant matter density, the oscillation of $\nu_\mu \to \nu_e$ in the Earth for 3-generation mixing is described approximately by the following equation [6]

$$\begin{aligned}
P(\nu_\mu \to \nu_e) \approx & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta) \\
& +\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)
\end{aligned} \tag{1}$$

where $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31}L/4E$, $\hat{A} = 2VE/\Delta m^2_{31}$, $V = \sqrt{2}G_F n_e$, n_e is the density of electrons in the Earth, L is the distance between the neutrino source and the detector in km, and E is the neutrino energy in GeV. Recall that $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$. For antineutrinos, the second term in Equation 1 has the opposite sign, and the matter potential also has the opposite sign. The second term is proportional to the following CP violating quantity:

$$J_{CP} \equiv \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\cos\theta_{12}\cos\theta_{23}\cos^2\theta_{13}\sin\delta_{CP} \tag{2}$$

Equation 1 is an expansion in powers of α. The $\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ oscillation probabilities from the approximate formula given in Equation 1 as a function of neutrino energy and baseline are shown in Figure 1 for both the normal mass hierarchy ($m_1 < m_2 < m_3$) and inverted mass hierarchy ($m_3 < m_1 < m_2$) . There are two very different oscillation scales driven by the two independent mass-squared differences (Δm^2_{21} and Δm^2_{32}). The maximal oscillation

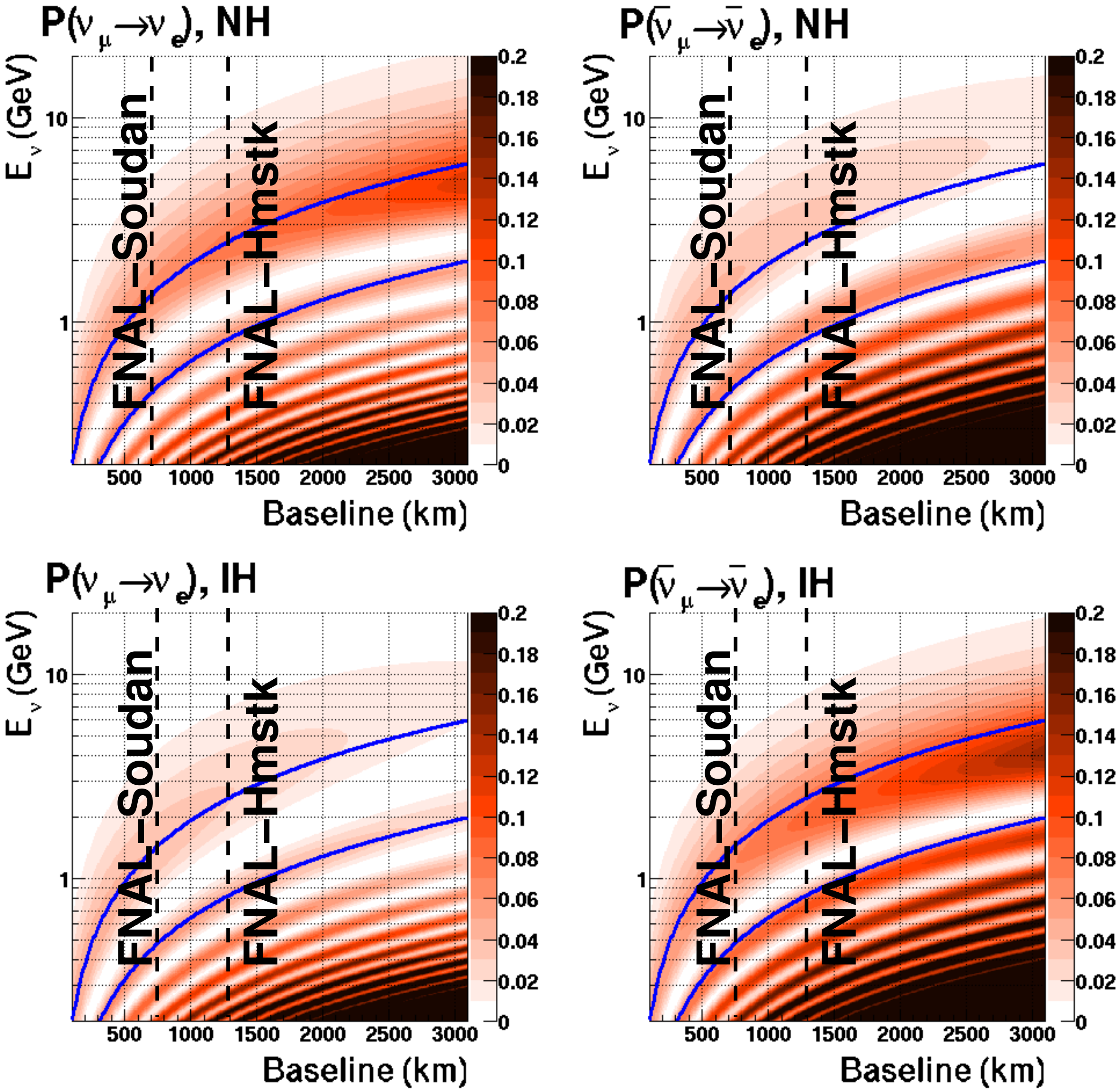

FIG. 1. The $\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ oscillation probability vs neutrino energy and baseline with $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$ for normal hierarchy (top) and inverted hierarchy (bottom). The solid blue lines correspond to the locations of the 1^{st} and 2^{nd} oscillation maxima in vacuum.

probabilities occur at:

$$\begin{aligned} L/E_n^\nu \text{ (km/GeV)} &= (2n-1)\frac{\pi}{2}\frac{1}{(1.267 \times \Delta m^2 \text{ (eV}^2))} \\ &\approx (2n-1) \times 500 \text{ km/GeV for } \Delta m^2_{32} \text{ (atmospheric)} \\ &\approx (2n-1) \times 15,000 \text{ km/GeV for } \Delta m^2_{21} \text{ (solar)} \end{aligned} \tag{3}$$

where E_n^ν is the neutrino energy at the maximum of oscillation node n. The oscillations of $\nu_\mu \to \nu_e$ in long baseline accelerator neutrino experiments are driven primarily by the atmospheric mass scale. The 1^{st} and 2^{nd} nodes are indicated as solid blue lines in Figure 1. The approximate formula given in Equation 1 is useful for understanding important features of the appearance probability shown in Figure 1:

1. The first three terms in the equation control the matter induced enhancement for normal mass ordering ($m_1 < m_2 < m_3$) or suppression for the inverted mass ordering ($m_3 < m_1 < m_2$) which dominates in the region of the

first oscillation node (largest E_ν).

2. The second and third terms control the sensitivity to CP and the value of δ_{cp} at the second oscillation node.

3. The last term controls the sensitivity to Δm^2_{21} and the solar oscillation parameters at the higher order oscillation nodes (largest L/E).

4. The first term (last term) is also proportional to $\sin^2\theta_{23}$ ($\cos^2\theta_{23}$), and therefore is sensitive to whether θ_{23} is above or below 45°.

The large non-zero value of θ_{13} indicates that measurement of the spectrum of oscillated $\nu_\mu \rightarrow \nu_e$ events over a large range of L/E in a single experiment will allow us access to all of the parameters in Equation 1 with good systematics control. Figure 1 demonstrates that the longer the experimental baseline the more oscillation nodes and the larger the range of L/E values are accessible.

The signature of CP violation is a difference in the probabilities for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions. The CP asymmetry $\mathcal{A}_{cp}$ is defined as

$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{\mathrm{P}(\nu_\mu \rightarrow \nu_e) - \bar{\mathrm{P}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{\mathrm{P}(\nu_\mu \rightarrow \nu_e) + \bar{\mathrm{P}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}\right] \tag{4}$$

The observed asymmetry $\mathcal{A}$ is a combination of both the CP asymmetry and the asymmetry due to the matter effect. Figure 2 shows the maximal possible CP asymmetry in vacuum ($\delta_{cp} = -\pi/2$) and the asymmetry from the matter effect alone as a function of energy and baseline. The CP asymmetry arising from non-zero/π values of δ_{cp} is dominant in the L/E regions of the secondary oscillation nodes and is constant as a function of baseline, whereas the asymmetry due to the matter effect dominates the L/E region of the first oscillation node and increases with longer baselines.

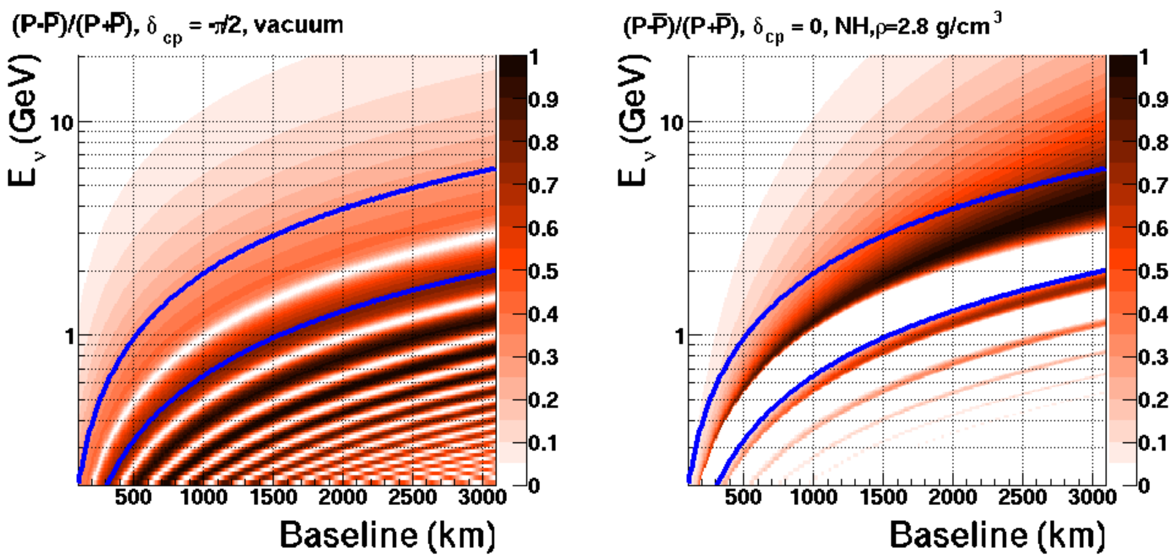

FIG. 2. The asymmetry, $\mathcal{A}_{cp}$, for maximal CP violation in vacuum (left) and arising from the matter effect only (right) as a function of energy and baseline. An average earth density of $\rho = 2.8$ g/cm^3 is assumed for the matter effect.

Observations of $\nu_\mu \rightarrow \nu_e$ oscillations of a beam (composed initially of muon neutrinos, ν_μ) over a long baseline and a wide range of neutrino energies are thus the key to unambiguously determining the mass hierarchy (the sign of Δm^2_{32}), and the unknown CP-violating phase δ_{cp}. The study of $\nu_\mu \rightarrow \nu_e$ oscillations can also help determine the θ_{23} quadrant since the first and fourth terms in Equation 1 are proportional to $\sin^2\theta_{23}$ and $\cos^2\theta_{23}$ respectively.

The study of the disappearance of ν_μ probes $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$. Non-standard physics can manifest itself in differences observed in higher precision measurements of ν_μ and $\bar{\nu}_\mu$ disappearance over long baselines and in observing deviations from the 3-flavor model in $\nu_\mu \rightarrow \nu_e$ oscillations. The precision with which we know the current set of neutrino oscillation parameters ensures that the compelling physics program outlined is feasible with the combination of a long baseline, very large detector mass, and a wide-band beam with beam energies matched to the baseline as summarized in Equation 3.

The primary scientific goals of the next generation of long baseline neutrino experiments is to carry out the most precise measurements of the three-flavor neutrino-oscillation parameters over a very long baseline and a wide range of neutrino energies, in particular, the CP-violating phase in the three-flavor framework. Precision measurements of the 3-flavor neutrino oscillation parameters will also enable the search for new physics that manifests itself as deviations from the expected three-flavor neutrino-oscillation model.

A. The Neutrino Beams

The three beam configurations under consideration are the 1) LBNE beam-line in the low energy configuration on-axis with a detector at Homestake Mine (1300km), 2) the NuMI beam-line in the low energy configuration with a detector on-axis at Soudan Mine (735km), and 3) the NuMI beam-line in the medium energy configuration with a detector 14mrad off-axis at Ash River (810km). The neutrino beam-line parameters used in the GEANT3 simulation for each of these options are summarized in Table III.

TABLE III. The NuMI and LBNE neutrino beam configurations used in this study

	LBNE LE [a]	NuMI LE	NuMI ME
Primary beam	120 GeV p^+	120 GeV p^+	120 GeV p^+
Beam power	708 kW	708 kW	708 kW
POT/yr	6.0×10^{20}	6.0×10^{20}	6.0×10^{20}
Target material	graphite	graphite	graphite
Target cross-section	circular d=1.2cm	rectangular w=0.64cm h=2cm	rectangular w=0.64cm h=2cm
Target length	2 interaction lengths	2 interaction lengths	2 interaction lengths
Focusing horns (1/2)	NuMI, 250kA	NuMI, 185 kA	NuMI, 200 kA
Horn separation	6m	10m	23m
Target-Horn 1 distance	30cm	45cm	135 cm
Decay pipe	4m diameter, 280m long Evacuated/He filled	2m diameter, 677m long He filled	2m diameter, 677m long He filled

[a] The LBNE decay pipe in the conceptual design has a length between 200 and 250m and is filled with air.

All the beam-line designs considered can be operated in neutrino or anti-neutrino mode by reversing the horn current to charge select positive or negative hadrons. The ν_μ and $\bar{\nu}_\mu$ charged current spectra at each candidate far detector location are shown in Figure 3 with the ν_e appearance probability curves overlaid. We note that there is a small ν_e beam contaminant of order 1% from μ and Ke3 decays. There is also a wrong-sign ν_μ contaminant in each beam ($\approx 10\%$) from decays of unfocused hadrons. The numbers of expected neutrino and anti-neutrino events at the three potential sites are given in Table IV.

TABLE IV. Number of events per 100kT.MW.yrs (1 MW.yr= 1×10^{21} protons-on-target) for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$, normal mass ordering in the visible energy range 0.5 to 20 GeV. CC refers to charged-current interactions, and NC to neutral-current interactions. The ν_μ CC unosc. rates are the estimated event rates without oscillations, the ν_μ CC osc. rates are the event rates with $\nu_\mu \to \nu_\mu$ oscillations. ν_e beam refers to the ν_e contaminant in the beam. The first 6 columns of numbers are for neutrino beams, and the last 6 columns are for anti-neutrino beams.

Expt	ν_μ CC Unosc.	ν_μ CC Osc.	ν_μ NC	ν_e beam CC	$\nu_\mu \to \nu_e$ CC	$\nu_\mu \to \nu_\tau$ CC	$\bar{\nu}_\mu$ CC Unosc.	$\bar{\nu}_\mu$ CC Osc.	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam CC	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	$\bar{\nu}_\mu \to \bar{\nu}_\tau$ CC
Ash River 810km	18K	7.3K	3.6K	330	710	38	7.1K	2.5K	1.8K	110	210	
Soudan 735km	73K	49K	15K	820	1500	166	27K	18K	13K	285	495	54
Hmstk 1300km	29K	11K	5.0K	280	1300	130	11K	3.8K	3.0K	86	273	46

B. The LAr-TPC Neutrino Detector

Neutrino events detected in experiments like LBNE are often categorized according to the particle mediating the interaction. The term (used below, and throughout this document) "neutral current process" (NC) refers to an interaction which is mediated by the neutral boson Z^0. Similarly, a "charged current" (CC) interaction involves a postive or negative charged W boson. The flavor of a neutrino in a CC interaction is tagged by the flavor of the emitted lepton: e, μ, or τ tag for a ν_e, ν_μ, or ν_τ interaction respectively. A "quasi-elastic" (QE) event is a CC event in which

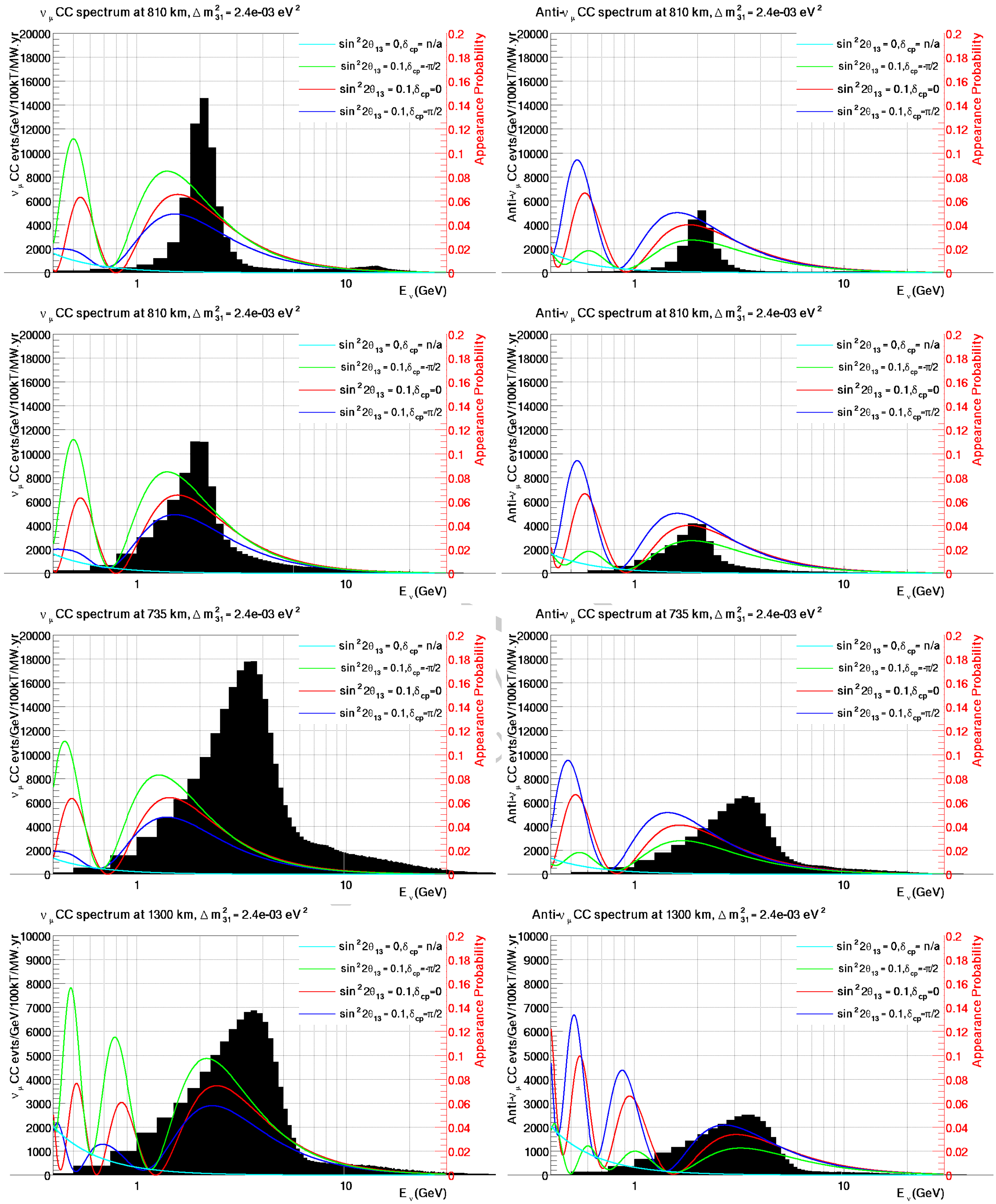

FIG. 3. The un-oscillated ν_μ CC spectra at the 3 candidate locations (black histograms) with the ν_e appearance probability curves for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$ (red) $\pi/2$ (blue) $-\pi/2$ (green) with normal mass ordering. The curve in cyan shows the contribution from the fourth term of Equation 1 which is driven by the solar oscillation and is independent of $\sin^2 2\theta_{13}$ and δ_{cp}. The figures are from top to bottom: NuMI ME at Ash River, NuMI LE at Ash River, NuMI LE at Soudan, and the LBNE beam at Homestake. The left set of figures is for neutrino running and the right set of figures is for anti-neutrino running.

the scattering of the neutrino is almost elastic with only a charged lepton and a nucleon or nucleons emerging from the target nucleus. The charged lepton in QE events carries most of the energy of the neutrino, and as a result, QE interactions have the best neutrino-energy resolution. Final State Interactions (FSI) inside the nucleus will alter the expected nucleon types and spectrum, and a measurement of this effect is an important goal of the Near Detector. CC and NC interactions of neutrinos with energies > 1 GeV are inelastic and the target nucleus disintegrates producing multiple hadrons.

The cross-section of $\nu/\bar{\nu}$ CC and NC interactions [7] for different event categories is shown in Figure 4.

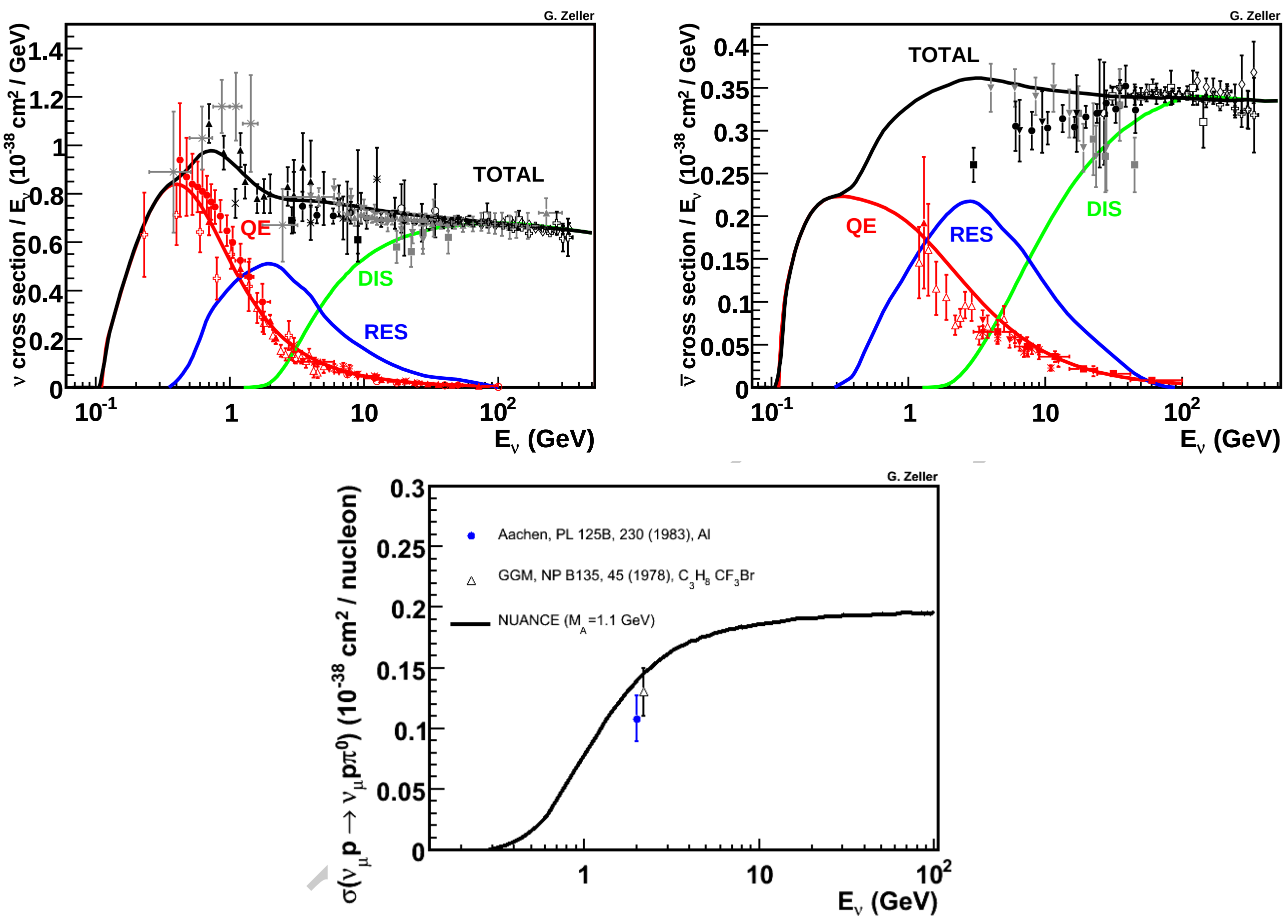

FIG. 4. Neutrino charged-current interaction cross-sections divided by neutrino energy for neutrinos (top-left), and anti-neutrinos (top-right) for an isoscalar target plotted as a function of neutrino energy. Also shown are the contributions to the total cross section from quasi-elastic scattering (red), resonance production (blue), and deep inelastic scattering (green) processes. Example predictions for each are provided by the NUANCE generator [8]. Note that the quasi-elastic scattering data and predictions have been averaged over neutron and proton targets and hence have been divided by a factor of 2 for the purposes of this plot. On the bottom are existing measurements of the cross section for the NC process, $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$, as a function of neutrino energy. The Gargamelle measurement comes from a more recent re-analysis of this data [9]. Also shown is the prediction from [8]. All three Plots are from [7].

A substantial component of the background for ν_e CC interactions comes from NC interactions where a π^0 is produced. The π^0 decays to two γs which shower electromagnetically and fake electrons. NC interactions where a charged pion is produced are also the predominant background for ν_μ CC interactions where the pion fakes a muon. Therefore to study neutrino flavor oscillations with high precision, the LBNE Far Detector has to have high efficiency and high purity $e/\mu/\gamma$ and $\pi/K/p$ separation.

A massive liquid argon TPC (LArTPC) has been chosen as the Far Detector technology for the LBNE project [10]. TPCs are the detectors of choice for low-rate, large-volume, high-precision particle physics experiments due to their excellent 3D position resolutions and particle identification in large volumes. In addition to detailed event topologies and measurements of particle kinematics, dE/dx measurements allow TPCs to unambiguously distinguish electrons, muons, photons, kaons, pions and protons over a wide range of energies. Examples of how event topologies can be used to identify ν_e/ν_μ CC and ν NC events in a LAr-TPC are shown in Figure 5. The expected signal efficiencies and

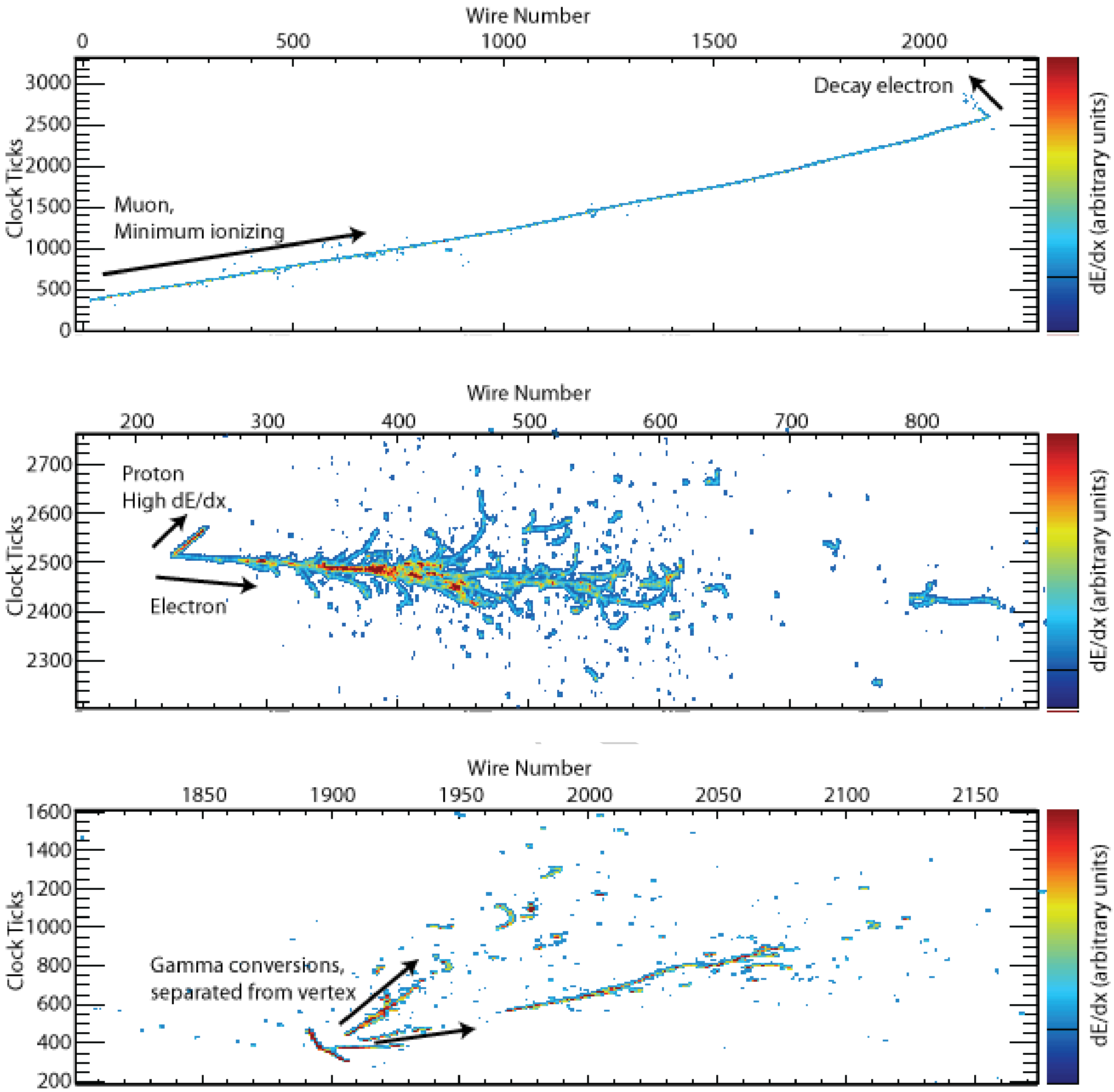

FIG. 5. Examples of neutrino beam interactions in an LArTPC obtained from a GEANT4 simulation [11]. A CC ν_μ interaction with a stopped μ followed by a decay Michel electron (top), a QE ν_e interaction with a single electron and a proton (middle), an NC interaction which produced a π^0 that then decayed into two γ's with separate conversion vertices (bottom).

background mis-identification rates as well as the energy resolution for different event types are summarized in Table V. The performance parameters were derived from several visual scan studies carried out using GEANT4 simulation of LAr-TPC as shown in Figure 5, from studies of the ICARUS detector performance [12–14] and from automated reconstruction used in the LAr detector proposal for a detector at a 2km baseline in the T2K experiment [16].

The performance parameters summarized in Table V were implemented into the GLoBES software package [17]. The expected spectrum of ν_e or $\overline{\nu}_e$ oscillation events from a parameterized implementation of a 34-kton LArTPC running with 5 years of neutrino and 5 years of anti-neutrino 700kW beam assuming $\sin^2(2\theta_{13}) = 0.1$ and normal mass ordering is shown in Figure 6. The expected spectrum of ν_μ or $\overline{\nu}_\mu$ oscillation events is shown in Figure 7.

The GLoBES experimental assumptions for the NOνA and T2K experiments used in this study were obtained from references [18, 19] and [20–22] respectively. The assumptions for the NOνA experiment are summarized in Table VI.

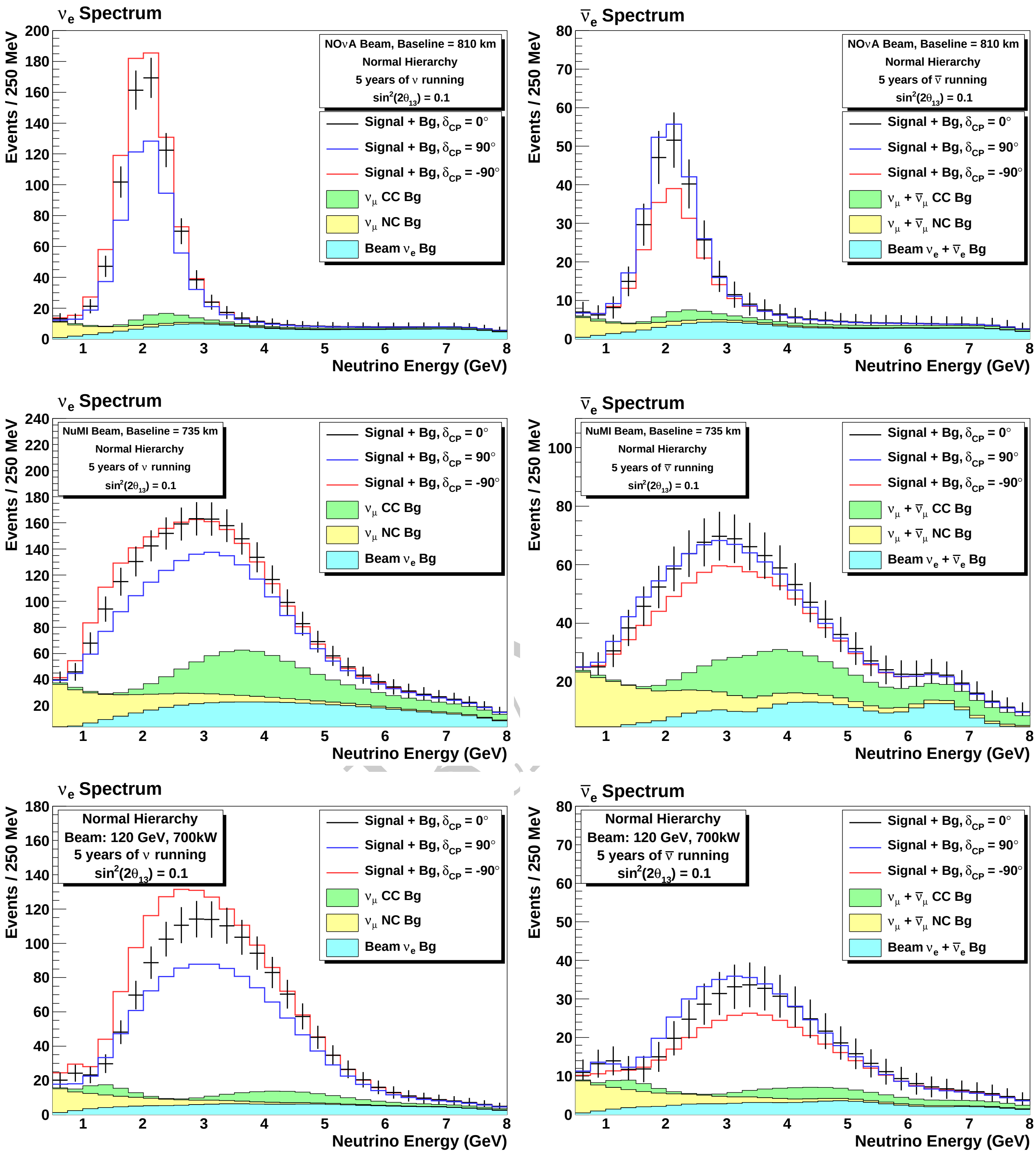

FIG. 6. The expected spectrum of ν_e or $\overline{\nu}_e$ oscillation events in a 34-kton LArTPC for 5 years of neutrino (left) and anti-neutrino (right) running with a 700 kW beam assuming $\sin^2(2\theta_{13}) = 0.1$ and normal mass ordering. Backgrounds from intrinsic beam ν_e (cyan), ν_μ NC (yellow), and ν_μ CC (green) are displayed as stacked histograms. The points with error bars are the expected total event rate for $\delta_{cp} = 0$; the red (blue) histogram is the total expected event rate with $\delta_{cp} = -\pi/2(+\pi/2)$. The figures are from top to bottom: NuMI ME at Ash River, NuMI LE at Soudan and the LBNE beam at Homestake.

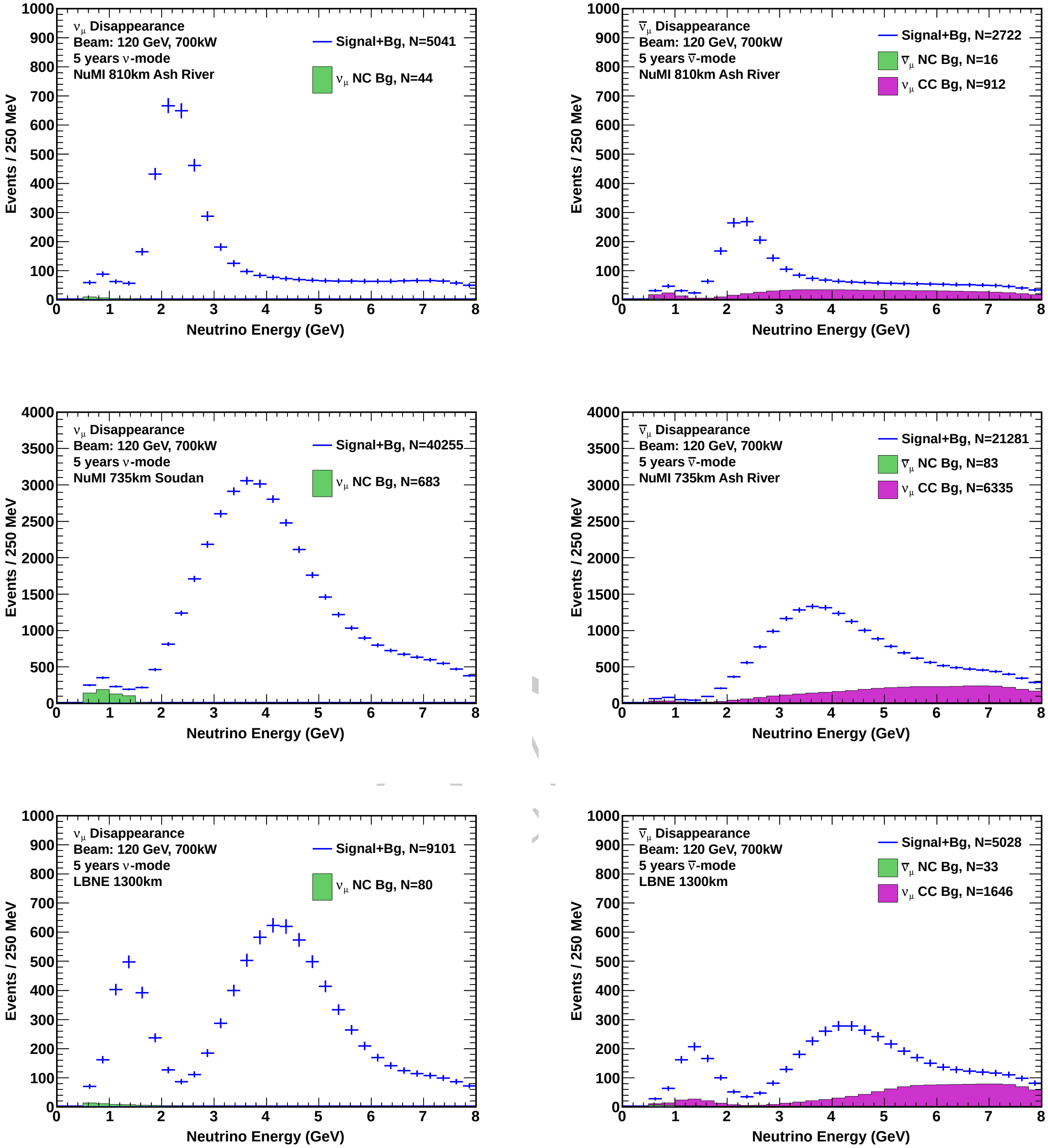

FIG. 7. The expected spectrum of ν_μ or $\overline{\nu}_\mu$ oscillation events in a 34-kton LArTPC for 5 years of neutrino (left) and anti-neutrino (right) running with a 700 kW beam. The points with error bars are the expected total event rate for $\Delta^2 m_{32} = 2.35$ and $\sin^2 2\theta_{23} = 0.1$. Backgrounds from NC and the wrong sign ν are displayed. The figures are from top to bottom: NuMI ME at Ash River, NuMI LE at Soudan and the LBNE beam at Homestake.

TABLE V. Estimated range of the LAr-TPC detector performance parameters for the primary oscillation physics. The expected range of signal efficiencies, background levels, and resolutions from various studies (middle column) and the value chosen for the baseline LBNE neutrino-oscillation sensitivity calculations (right column) are shown. * For atmospheric neutrinos this is the mis-identification rate for < 2 GeV events, the mis-identification rate is taken to be 0 for > 2 GeV.

Parameter	**Range of Values**	**Value Used for LBNE Sensitivities**
Identification of ν_e CC events		
ν_e CC efficiency	70-95%	80%
ν_μ NC mis-identification rate	0.4-2.0%	1%
ν_μ CC mis-identification rate	0.5-2.0%	1%
Other background	0%	0%
Signal normalization error	1-5%	1%
Background normalization error	2-10%	5%
Identification of ν_μ CC events		
ν_μ CC efficiency	80-95%	85%
ν_μ NC mis-identification rate	0.5-10%	0.5%
Other background	0%	0%
Signal normalization error	1-5%	5%
Background normalization error	2-10%	10%
Identification of ν NC events		
ν NC efficiency	70-95%	90%
ν_μ CC mis-identification rate	2-10%	10% *
ν_e CC mis-identification rate	1-10%	10% *
Other background	0%	0%
Signal normalization error	1-5%	
Background normalization error	2-10%	
Neutrino energy resolutions		
ν_e CC energy resolution	$15\%/\sqrt{E(GeV)}$	$15\%/\sqrt{E(GeV)}$
ν_μ CC energy resolution	$20\%/\sqrt{E(GeV)}$	$20\%/\sqrt{E(GeV)}$
E_{ν_e} scale uncertainty		
E_{ν_μ} scale uncertainty	1-5%	2%

TABLE VI. Detector efficiencies and background rejection assumptions for NOνA used in sensitivity calculations.

Parameter	**Value Used (NOνA)**
Identification of ν_e CC events	
ν_e CC efficiency	26% (ν) 41% ($\bar{\nu}$)
ν_μ NC mis-identification rate	0.28% (ν) 0.88% ($\bar{\nu}$)
ν_μ CC mis-identification rate	0.13%
Other background	0%
Signal normalization error	5%
Background normalization error	10%
Identification of ν_μ CC events	
ν_μ CC efficiency	100% (QE only)
ν_μ NC mis-identification rate	0.1%
Other background	0%
Signal normalization error	2%
Background normalization error	10%

C. Mass Hierarchy and CP Violation Sensitivity

The long baseline physics capabilities of a LAr-TPC far detector in the proposed LBNE project is described in detail in [23]. In these sections we will focus on the comparison of physics capabilities of a LAr-TPC at Homestake with a LAr-TPC detector placed in the NuMI beam at the Soudan and Ash River locations.

We use the GLoBES software package to estimate the significance, σ, with which we can 1) exclude the opposite mass hierarchy, and 2) exclude $\delta_{cp} = 0$ or π (CP violation). A True appearance event spectrum is generated for a given value of $\delta_{cp}, sign(\Delta m^2_{31})$ as shown in Figure 6. A minimum χ^2 fit is performed to the given hypothesis. The minimization accounts for the correlations between the different mixing parameters which are included with Gaussian constraints based on the best fit uncertainties as summarized in Table II. The disappearance experiment as shown in Figure 7 is included in the minimization and helps to constrain the atmospheric parameters. The normalization uncertainties on the signal and background listed in Table V are included as nuisance parameters. θ_{13} is constrained using the projected accuracy expected from the final run of the current reactor experiments (3%). When estimating the sensitivity to the mass hierarchy, the χ^2 minimization is performed over all values of δ_{cp}. The opposite mass hierarchy is included in the minimization when estimating the χ^2 to determine whether CP is violated ($\delta_{cp} \neq 0$ or π). The significance with which we can exclude the opposite mass hierarchy and determine whether $\delta_{cp} \neq 0$ or π is defined as $\sigma = \sqrt{\chi^2}$. The significance as a function of δ_{cp} is shown in Figure 8 for three different LAr-TPC masses, 10, 15, and 34 kT placed at Soudan, Ash River, and Homstake. No constraints from other experiments are included.

The relatively poor performance for $\delta_{cp} > 0$ for the Minnesota sites is due to the inability to determine the mass hierarchy with those experiments alone. Sensitivity to the hierarchy depends strongly on the baseline and the energy spread of the beam. The very long baseline to Homestake makes the problem easier. For the shorter baseline to the Minnesota sites, it is more difficult, especially for $\delta_{cp} > 0$ where the CP and matter effects are of opposite sign. The situation is significantly improved if results from the T2K experiment in Japan are included in a global analysis. T2K's short baseline greatly reduces the matter effect. This allows the two effects to be separated in the global analysis. However it must be remembered that success depends on understanding in detail the systematics of several experiments and their correlations. The significance of the hierarchy measurement when results from a 15 kt LAr-TPC are combined with the NOνA, and T2K experiments is shown in Figure 9. For the combinations with a LAr-TPC at the Minnesota site the NOνA experiment is assumed to run concurrently for a total of 16 yrs. We use a 6 year run when combining NOνA results with the experiment at Homestake. A total of 5×10^{21} integrated protons on target is assumed for the T2K experiment. The significance with which CP violation is resolved with a LAr-TPC at Ash River Soudan, and Homestake when combined with NOνA and T2K running is also shown in Figure 9. The opposite mass hierarchy is considered when estimating the CP violation significance with different experimental combinations.

In Figure 10, the significance with which CP violation is resolved for 50% of δ_{cp} values as a function of exposure in kt.yrs with a LAr-TPC at Homestake , Ash River, and Soudan is shown. The sensitivity of the NOνA experiment (estimated using the GLoBES package) with increasing exposure is also displayed for reference.

D. Precision Measurement of Neutrino Mixing Parameters

One of the primary scientific goals of the LBNE experiment is to carry out the most precise measurements of the three-flavor neutrino-oscillation parameters. The precision with which the values of δ_{cp} and $\sin^2 2\theta_{13}$ can be determined in the $\nu_\mu \rightarrow \nu_e$ appearance mode as a function of exposure in yrs and mass is shown in Figures 11, and 12 respectively. It is to be noted that for measurements of δ_{cp}, the resolution is limited by the degeneracy between δ_{cp} and other mixing parameters such as θ_{13}, θ_{23} and the mass ordering. External constraints on θ_{13} from the reactor experiments improves the δ_{cp} resolution from the NuMI options for values of δ_{cp} in the vicinity of $|\pi/2|$ (maximal CP violation). LBNE-Homestake provides enough internal constraints on the other mixing parameters and the mass ordering that the impact of degeneracies is much less pronounced. Its to be noted that Figures 11 and 12 assume the mass ordering is resolved for all values of δ_{cp}.

The precision with which the values of $\sin^2 2\theta_{23}$ and $|\Delta m^2_{31}|$ can be determined from a joint fit to the $\nu_\mu \rightarrow \nu_\mu$ disappearance mode and $\nu_\mu \rightarrow \nu_e$ appearance mode as a function of exposure in years and mass is shown in Figures 13, and 14 respectively. The measurements from neutrino and anti-neutrino running in the ratio 1:1 are combined. The current best measurements of $|\Delta m^2_{32}|$ for neutrinos and anti-neutrinos measured separately are from the MINOS experiment [24] utilizing only the signal in the disappearance mode.

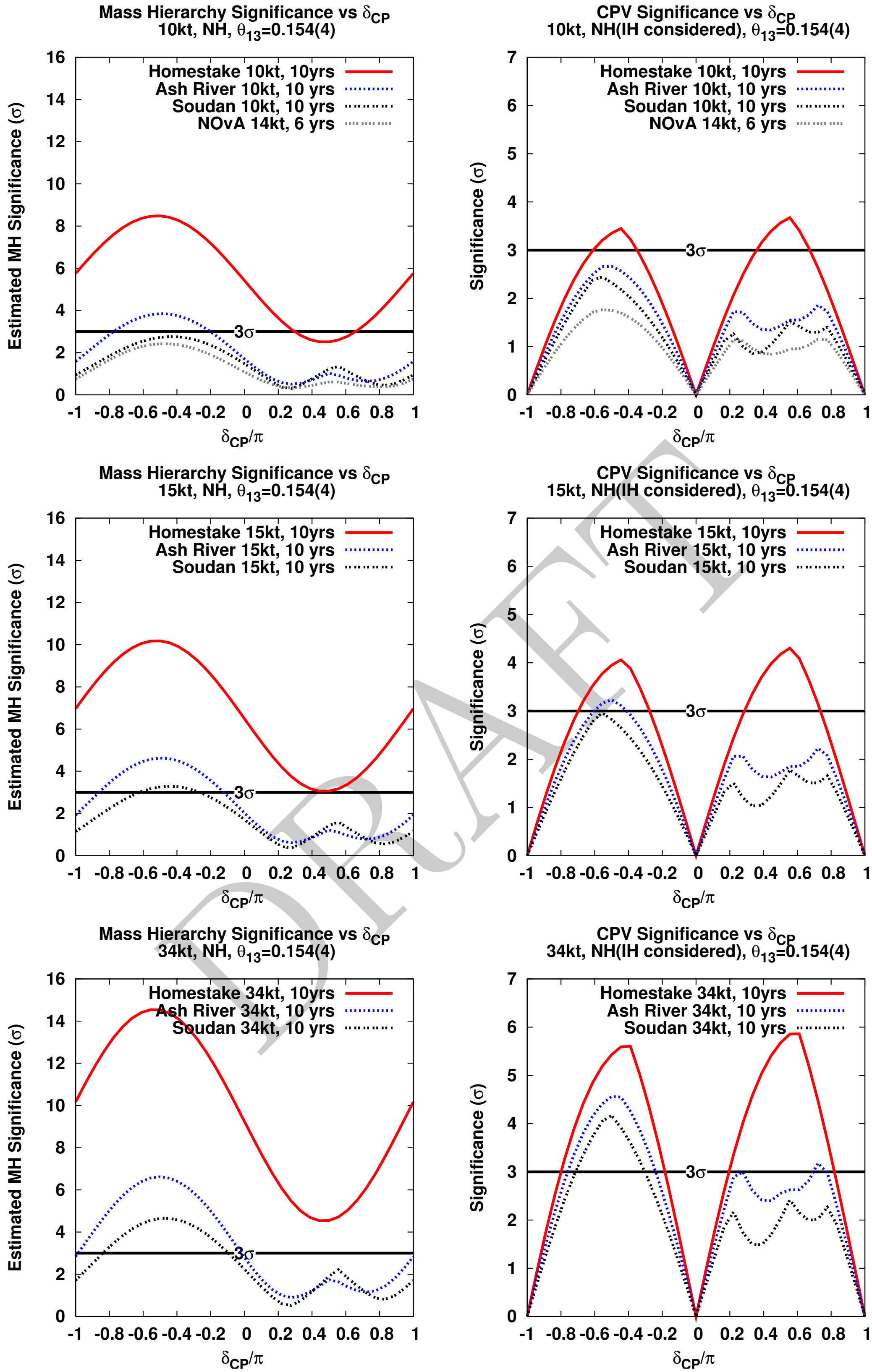

FIG. 8. The significance with which the mass ordering (left) and CP violation ($\delta_{cp} \neq 0, \pi$) is resolved (right) with a LAr-TPC at Homestake (red), Ash River (blue-dashed), Soudan (black-dashed) as a function of the unknown CP violating phase δ_{cp}. The sensitivity of the NOνA experiment with 14 kt of a totally active liquid scintillator detector (TASD) at Ash River is shown in gray. The plots are from top to bottom: 10kt, 15kt and 34kt. The significance is calculated using the current constraints on the mixing parameters from the global fit as shown in Table II. θ_{13} is constrained using the projected accuracy expected from the current reactor experiments (3%). The opposite mass hierarchy is considered when calculating the CP violation significance. There is no T2K constraint on the mass hierarchy. An exposure of 5 yrs neutrino running combined with 5 yrs of anti-neutrino running in a 700kW beam is assumed. The NuMI LE beam is used at Soudan and at Ash River.

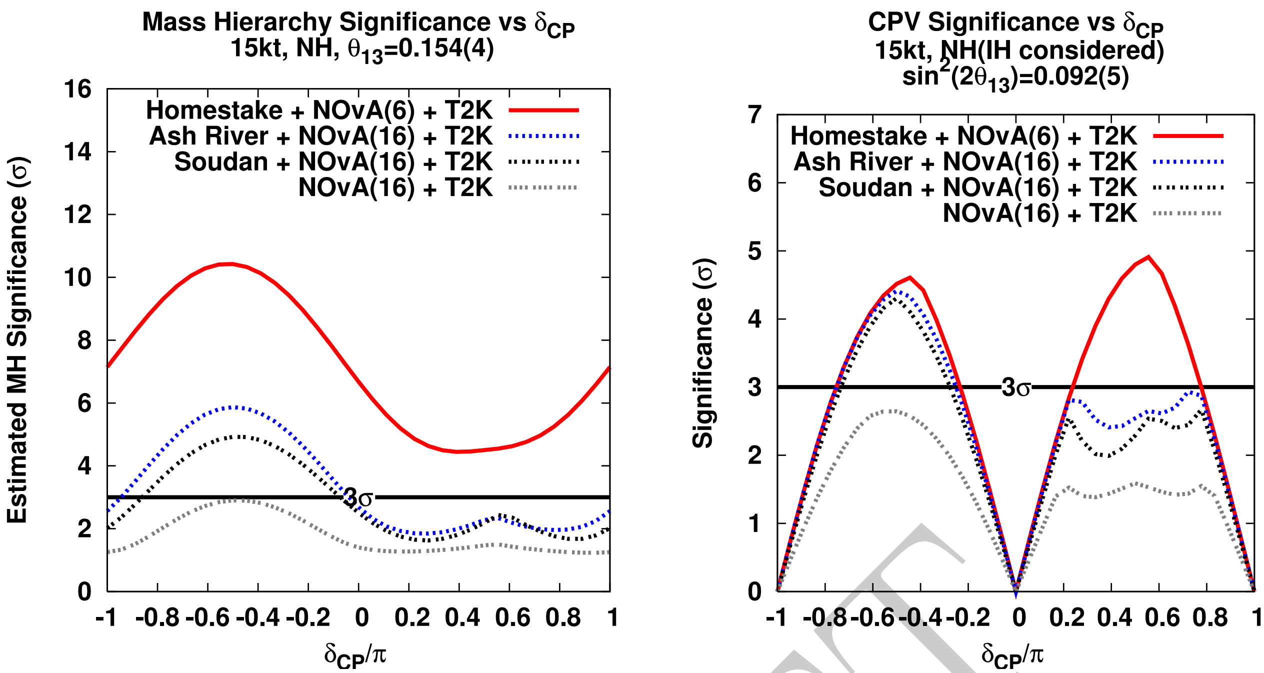

FIG. 9. The significance with which the mass ordering (left) and CP violation (right) is resolved when a 15 kT LAr-TPC at Homestake (red), Ash River (blue-dashed), Soudan (black-dashed) is combined with NOνA running with the ME beam for 3+3 years (I), the LE beam for 5+5 yrs (II) and T2K (5×10^{21} protons-on-target). The significance just from NoVA I+II combined with T2K is shown as gray-dashed line.

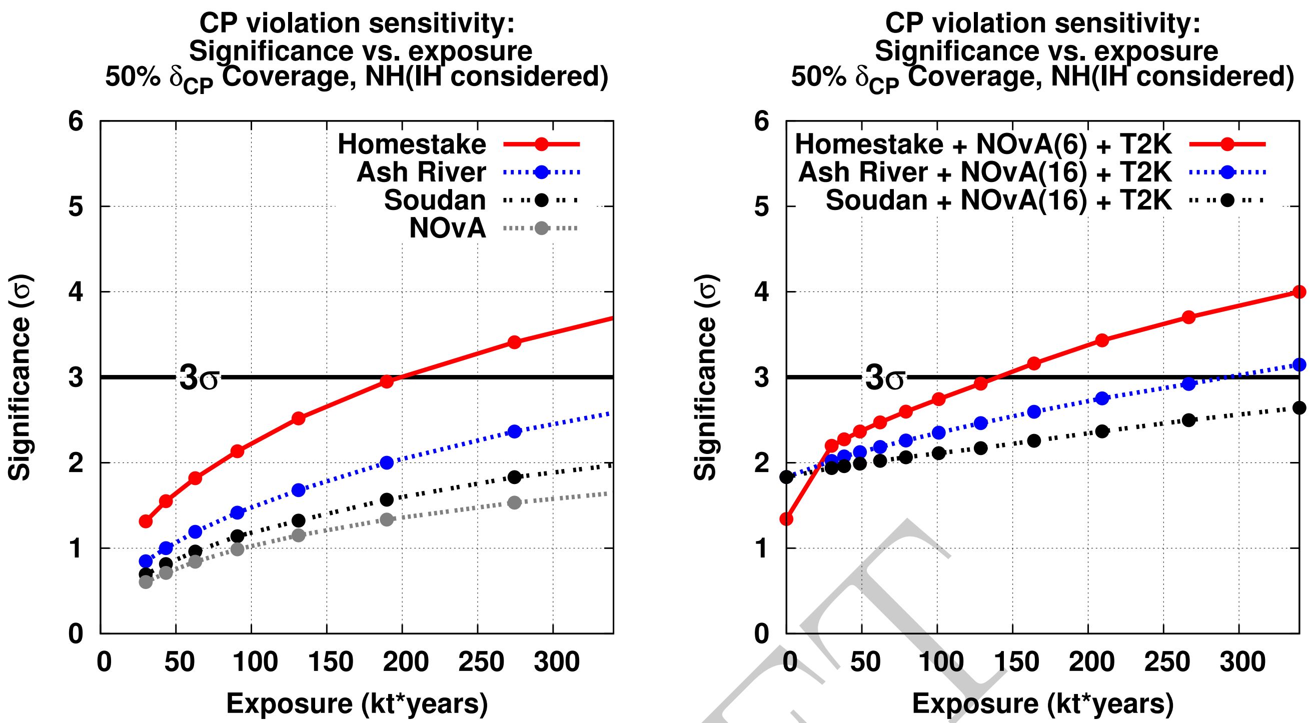

FIG. 10. The significance with which CP violation is resolved for 50% of δ_{cp} values as a function of exposure in kt.yrs with a LAr-TPC at Homestake (red), Ash River (blue-dashed), Soudan (black-dashed). The sensitivity of the NOνA experiment with a totally active liquid scintillator detector (TASD) at Ash River is shown in gray. The results are for neutrino and anti-neutrino running in the ratio 1:1 with a 700kW beam assuming 6.0×10^{20} protons-on-target per year. The NuMI LE beam is used at Soudan and Ash River. The measurements include a constraint on $\theta_{13} = 0.154 \pm 0.005$ and take into account all correlations with the other mixing parameters which are constrained using the current best estimate of the uncertainties as summarized in [4]. Both mass hierarchies are considered when estimating the sensitivities to CP violation. The figure on the left is the sensitivity achieved by each individual experiment. The figure on the right shows the sensitivities achieved combining the LAr-TPC with NOνA and T2K (5×10^{21} integrated protons-on-target). For the Homestake option, it is assumed NOνA will run for 6 yrs at 700kW; for the Minnesota sites it is assumed NOνA will run for 16 yrs.

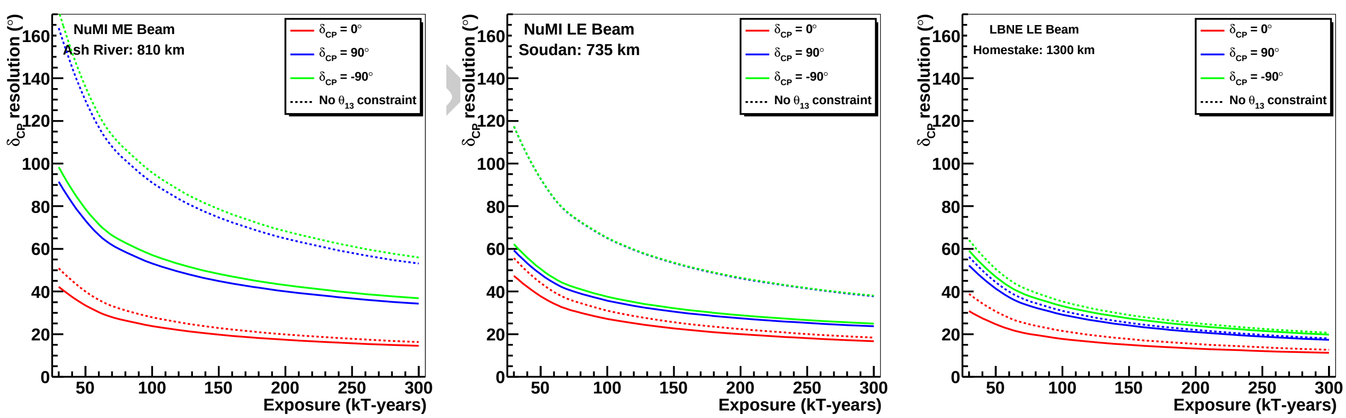

FIG. 11. The 1σ resolution on the measurement of δ_{cp} as a function of exposure in kt.yrs for $\delta_{cp} = 0$ (red), $\pi/2$ (blue), $-\pi/2$ (green). The exposure in yrs is assumed to be $1/2$ ν and $1/2$ $\bar{\nu}$ running at 700kW. The solid lines include the tight external constraint on $\theta_{13} = 0.154 \pm 0.005$. The dashed lines are without any external constraints on θ_{13}. The plots from left to right are for Ash River, Soudan, and Homestake. The measurements assume $\sin^2 2\theta_{13} = 0.092$ and normal hierarchy. **The mass hierarchy is assumed to be known.**

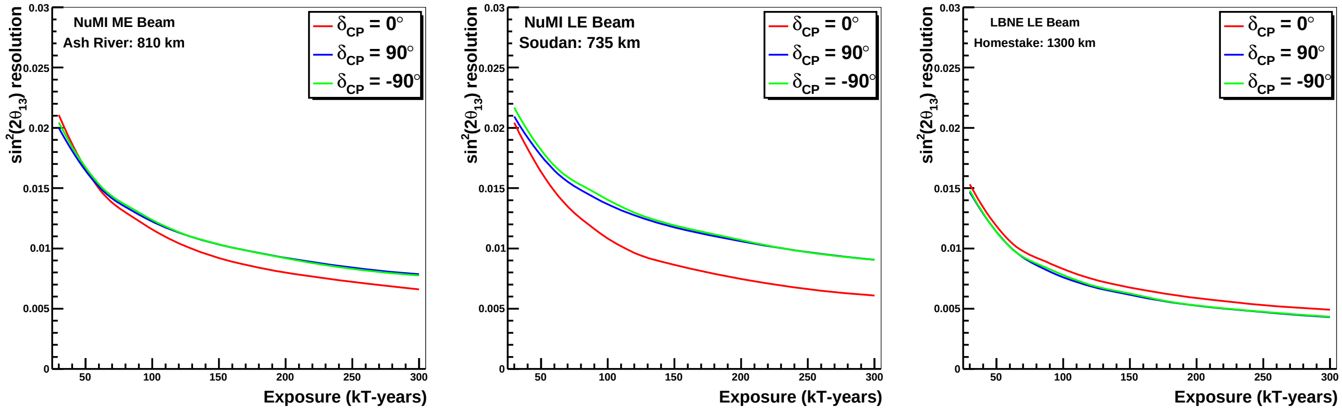

FIG. 12. The 1σ resolution on the measurement of $\sin^2 2\theta_{13} = 0.092$ as a function of exposure in kt.yrs for $\delta_{cp} = 0$ (red), $\pi/2$ (blue), $-\pi/2$ (green). The plots from left to right are for Ash River, Soudan, and Homestake. **The mass hierarchy is assumed to be known.**

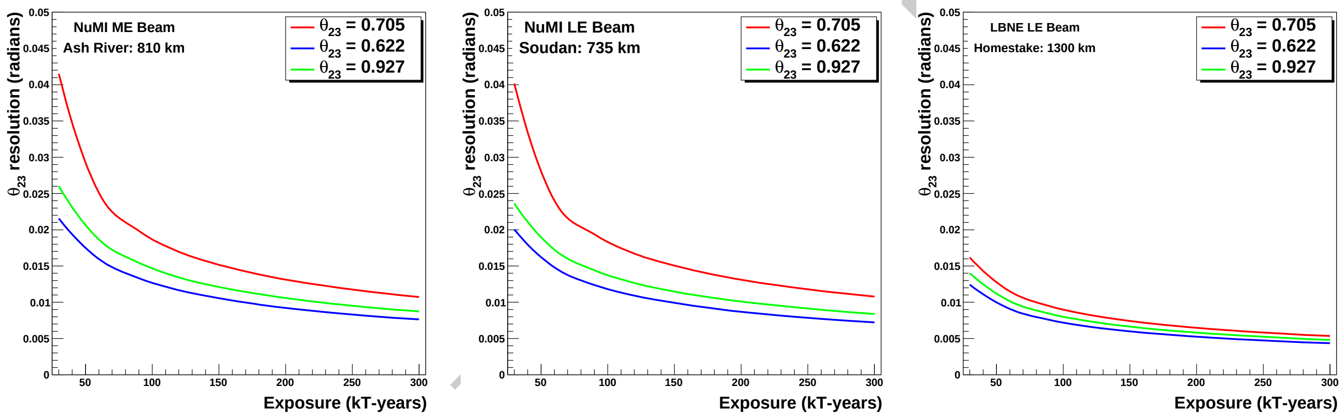

FIG. 13. The 1σ resolution on the measurement of $\sin^2 2\theta_{23}$ from $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ oscillations as a function of exposure in kt.yrs for different values of $\sin^2 2\theta_{23}$. Neutrino and anti-neutrino running are combined in the ratio of 1:1. The plots from left to right are for Ash River, Soudan, and Homestake. **The mass hierarchy is assumed to be known.**

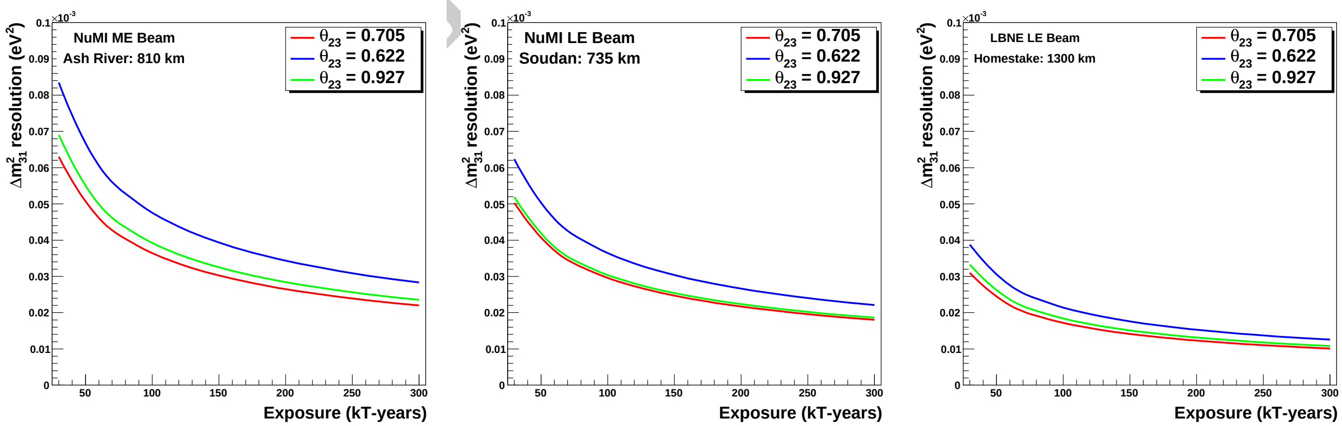

FIG. 14. The 1σ resolution on the measurement of $|\Delta m^2_{31}| = 2.35 \times 10^{-3}$ eV^2 from $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ oscillations as a function of exposure in kt.yrs for different values of $\sin^2 2\theta_{23}$. Neutrino and anti-neutrino running are combined in the ratio 1:1. The plots from left to right are for Ash River, Soudan, and Homestake. **The mass hierarchy is assumed to be known.**

E. Searches for New Physics

In addition to precision measurements of the standard three-flavor neutrino oscillation parameters, LBNE is also well-suited for new physics searches in the neutrino sector. For example, the experiment is sensitive to non-standard neutrino interactions and active-sterile neutrino mixing, provided that these effects are not too weak.

1. Non-standard Interactions

NC non-standard interactions (NSI) can be understood as non-standard matter effects that are visible only in a far detector at a sufficiently long baseline. This is where LBNE has a unique advantage compared to other long-baseline experiments (except atmospheric neutrino experiments, which are, however, limited by systematic effects). NC NSI can be parameterized as new contributions to the MSW matrix in the neutrino-propagation Hamiltonian:

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}\,, \tag{5}$$

with

$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix} \tag{6}$$

Here, U is the leptonic mixing matrix, and the ϵ-parameters give the magnitude of the NSI relative to standard weak interactions. For new physics scales of few $\times$ 100 GeV, we expect $|\epsilon| \lesssim 0.01$.

To assess the sensitivity of LBNE to NC NSI, the NSI discovery reach is defined in the following way: After simulating the expected event spectra, assuming given "true" values for the NSI parameters, one attempts a fit assuming no NSI. If the fit is incompatible with the simulated data at a given confidence level, one would say that the chosen "true" values of the NSI parameters are within the experimental discovery reach. As an example of the reach for new physics, figure 15 shows the NSI discovery reach of a Phase-2 LBNE at Homestake for the case where only one of the $\epsilon^m_{\alpha\beta}$ parameters is non-negligible at a time [25]. It can be concluded from the figure that such an experiment would be able to improve model-independent bounds on NSI in the e–μ sector by a factor of two, and in the e–τ sectors by an order of magnitude.

2. Long-Range Interactions

The small scale of neutrino-mass differences implies that minute differences in the interactions of neutrinos and antineutrinos with background sources can be detected through perturbations to the time evolution of the flavor eigenstates. The longer the experimental baseline, the higher the sensitivity to a new long-distance potential acting on neutrinos. For example, some of the models for such long-range interactions (LRI) as described in [29] could contain discrete symmetries that stabilize the proton and a dark matter particle and thus provide new connections between neutrino, proton decay and dark matter experiments. The longer baseline of LBNE coupled with the expected precision of better than 1% on the ν_μ and $\bar{\nu}_\mu$ oscillation parameters improves the sensitivity to LRI beyond that possible by the current generation of long-baseline neutrino experiments.

3. Search for Active-Sterile Neutrino Mixing

Searches for evidence of active sterile neutrino mixing at LBNE can be conducted by examining the NC event rate at the Far Detector and comparing it to a precision measurement of the expected rate from the near detector. Observed deficits in the NC rate could be evidence for active sterile neutrino mixing. The latest such search in a long baseline experiment was conducted by the MINOS experiment [30]. The expected rate of NC interactions with visible energy > 0.5 GeV in LBNE is approximately 5K events over five years (see Table IV). The NC identification efficiency is high with a low rate of ν_μ CC background misidentification as shown in Table V. LBNE will provide a unique opportunity to revisit this search with higher precision over a large range of neutrino energies.

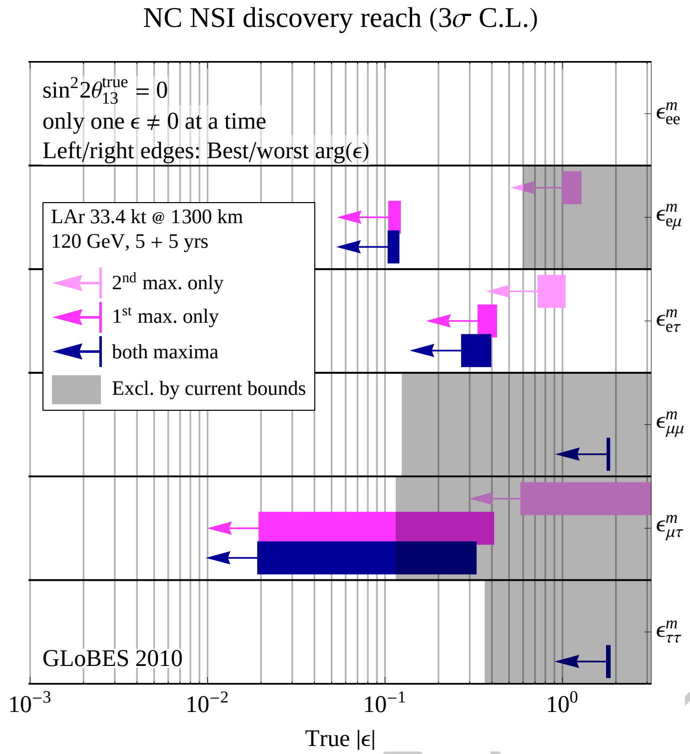

FIG. 15. Non-standard interaction discovery reach in a 34kT LAr-TPC at Homestake. The left and right edges of the error bars correspond to the most favorable and the most unfavorable values for the complex phase of the respective NSI parameters. The gray shaded regions indicate the current model-independent limits on the different parameters at 3 σ [26–28].

F. Summary

The fraction of the possible CP-violating phase angles for which the mass hierarchy can be resolved at 2 or 3 σ is shown in Figure 16 as a function of detector mass. Results are plotted for each detector alone and for a global analysis using the LAr, NOvA, and T2K results. For the Minnesota sites, it is assumed that NOvA would continue to run concurrently with the LAr detector for a total NOvA run of 16 years (NOvA(16)). For the South Dakota site, NOvA would stop data taking when the new beamline turned on, for a total NOvA run of 6 years (NOvA(6)). The fraction of the possible CP-violating phase angles for which CP violation can be resolved at 3 or 5 σ is shown in Figure 17 as a function of detector mass. The opposite mass hierarchy hypothesis is included in the estimation of the significance with which CP violation can be measured. Here again, results are provided for the LAr detector alone and for a LAr-NOvA-T2K global analysis. Figure 18 shows the δ_{cp} resolution achievable at each location with the mass hierarchy assumed to be known.

Table VII summarizes the oscillation measurements achievable with different configurations.

The LBNE Reconfiguration Steering Group has identified three experimental choices for Phase I of the next generation long baseline neutrino experiment: 1) 10kT LAr detector on the surface at Homestake, 2) a 15kT LAr detector underground at Soudan, and 3) a 30 kT LAr detector on the surface at Ash River. Figure 19 summarizes the physics reach for determining the mass hierarchy and CP violation for the three choices alone and in combination with T2K neutrino running for 5×10^{21} protons-on-target. The effect of a change in $\sin^2 2\theta_{13}$ by up to $\pm 2\sigma$ from the current value is shown as colored bands.

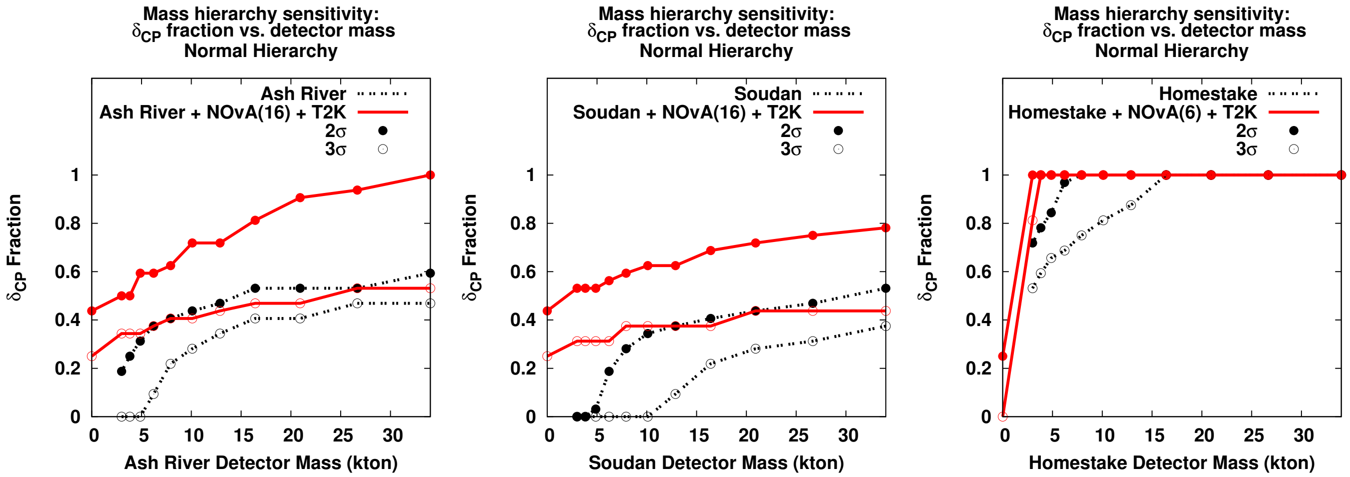

FIG. 16. The fraction of δ_{cp} values for which the mass hierarchy can be resolved at $2/3\ \sigma$ (solid/open points) as a function of LAr-TPC detector mass. The dashed black line indicates the sensitivty from the experiment alone. The solid red line is the resolution obtained from the combination with T2K (neutrinos only) and NOνA. The plots from left to right are for Ash River, Soudan, and Homestake. The measurements assume $\sin^2 2\theta_{13} = 0.092$, normal hierarchy and a combination of 5yrs of running in neutrino mode with 5 yrs of running in anti-neutrino mode with 700kW. The NuMI LE beam is used with the LAr-TPC at both Soudan and Ash River.

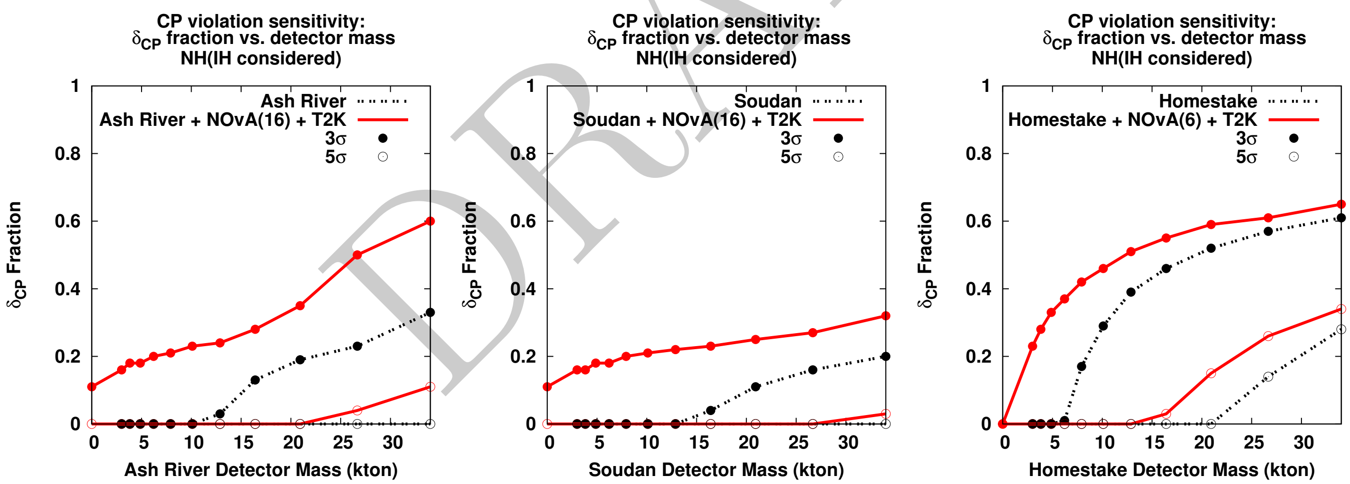

FIG. 17. The fraction of δ_{cp} values for which CP violation can be resolved at $3/5\ \sigma$ (solid/open points) as a function of LAr-TPC detector mass. The dashed black line indicates the sensitivity from the experiment alone. The solid red line is the resolution obtained from the combination with T2K (neutrinos only) and NOνA. The plots from left to right are for Ash River, Soudan, and Homestake. The measurements assume $\sin^2 2\theta_{13} = 0.092$, normal hierarchy and a combination of 5yrs of running in neutrino mode and 5 yrs of running in anti-neutrino mode with 700kW. The NuMI LE beam is used with the LAr-TPC at both Soudan and Ash River.

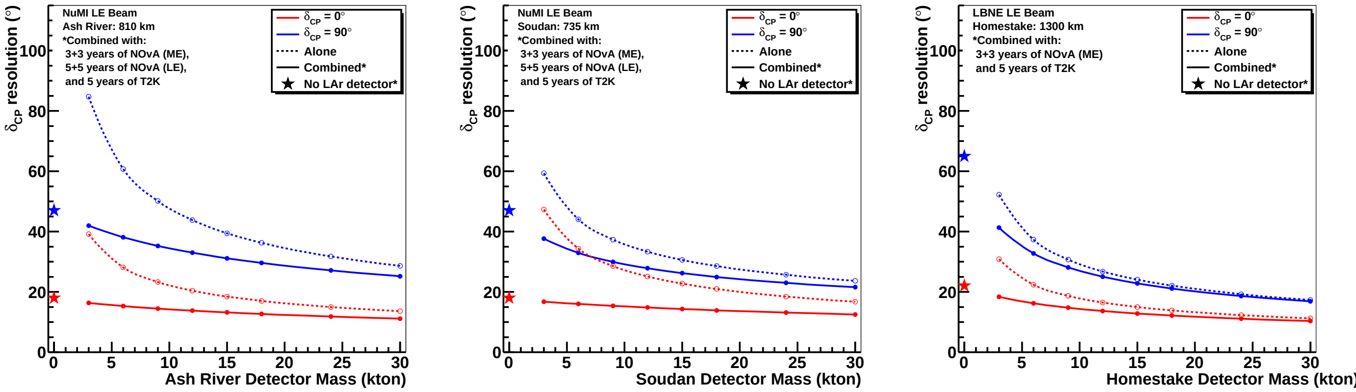

FIG. 18. The 1σ resolution on the measurement of δ_{cp} as a function of LAr-TPC detector mass for $\delta_{cp} = 0$ (red), $\pi/2$ (blue). A tight external constraint on $\theta_{13} = 0.154 \pm 0.005$ is included. The solid lines are the resolution obtained from each experiment alone. The dashed lines include the combination with T2K (neutrino only) and NOνA. The plots from left to right are for Ash River, Soudan, and Homestake. The measurements assume $\sin^2 2\theta_{13} = 0.092$, normal hierarchy and a combination of 5yrs of running in neutrino mode and 5 yrs of running in anti-neutrino mode with 700kW. The NuMI LE beam is used with the LAr-TPC at both Soudan and Ash River. **The mass hierarchy is assumed to be known.** The stars represent the resolutions obtained from the NOνA+T2K combination alone.

TABLE VII. Summary of the oscillation measurements with different configurations given $\theta_{13} = 8.8^\circ, \theta_{23} = 40^\circ, \Delta m^2_{31} = +2.27 \times 10^{-3}\text{eV}^2$. The fraction of δ_{cp} values for which the mass hierarchy (MH) or CP violation (CPV) are determined with 3σ sensitivity are given in the first 2 columns. For the first 2 columns, all correlations and uncertainties on the known mixing parameters, as well as consideration of the opposite mass hierarchy hypothesis, are included. For the estimates of the resolutions on the different oscillation parameters, the mass hierarchy is assumed to be known. The measurements assume 5 years of neutrino running and 5 years of anti-neutrino running at a beam power of 708kW with 6×10^{20} protons-on-target accumulated per year with a LAr-TPC. We assume NOνA will run for a minimum of 3+3 years with the NuMI ME energy beam (NOνA I). An additional 5+5 years of running with NOνA in the NuMI LE beam (NOνA II) is assumed when combining with Soudan and Ash River options. We assume 5×10^{21} protons-on-target total accumulated by T2K ($\sim$ 6 yrs) in neutrino only mode. * These measurements are for the combination of neutrino and anti-neutrino running.

Configuration	MH* fraction of δ (3σ)	CPV* fraction of δ (3σ)	$\sigma(\delta_{cp})^*$ $0, 90^\circ$	$\sigma(\theta_{13})^*$ $\delta = 90^\circ$	$\sigma(\theta_{23})$ ν	$\sigma(\theta_{23})$ $\bar{\nu}$	$\sigma(\Delta m^2_{31})$ ν (10^{-3} eV^2)	$\sigma(\Delta m^2_{31})$ $\bar{\nu}$ (10^{-3} eV^2)
Soudan 10kt	0.00	0.00	27,36°	0.70°	1.3°	1.6°	0.045	0.065
Soudan 15kt	0.17	0.05	23,30°	0.60°	1.1°	1.3°	0.036	0.055
Soudan 30kt	0.34	0.18	16,24°	0.45°	0.80°	0.97°	0.028	0.040
Ash River 10kt	0.28	0.00	23,48°	0.60°	1.3°	1.8°	0.058	0.080
Ash River 15kt	0.37	0.10	19,40°	0.50°	1.0°	1.5°	0.048	0.069
Ash River 30kt	0.47	0.27	18,29°	0.40°	0.74°	1.1°	0.035	0.050
Homestake 5kt	0.66	0.00	25,41°	0.60°	0.92°	1.4°	0.035	0.055
Homestake 10kt	0.81	0.27	17,30°	0.40°	0.69°	0.97°	0.025	0.040
Homestake 15kt	0.95	0.43	15,25°	0.30°	0.52°	0.80°	0.020	0.030
Homestake 20kt	1.0	0.50	13,21°	0.25°	0.46°	0.63°	0.018	0.026
NOνA I (6yrs) +T2K (6yrs)	0.0	0.0	22,65°	0.62°				
NOνA I+II (16yrs)+T2K (6yrs)	0.25	0.11	18,47°	0.53°				
Soudan 10kt +NOνA (I+II)+T2K	0.38	0.21	16,30°					
Soudan 15kt +NOνA (I+II)+T2K	0.38	0.23	14,26°					
Soudan 30kt +NOνA (I+II)+T2K	0.45	0.29	12,21°					
Ash River 10kt +NOνA (I+II)+T2K	0.40	0.23	14,34°					
Ash River 15kt +NOνA (I+II)+T2K	0.45	0.25	13,30°					
Ash River 30kt +NOνA (I+II)+T2K	0.50	0.55	13,25°					
Homestake 5kt +NOνA I+T2K	1.00	0.33	15,31°					
Homestake 10kt +NOνA I+T2K	1.00	0.45	12,25°					
Homestake 15kt +NOνA I+T2K	1.00	0.53	12,24°					

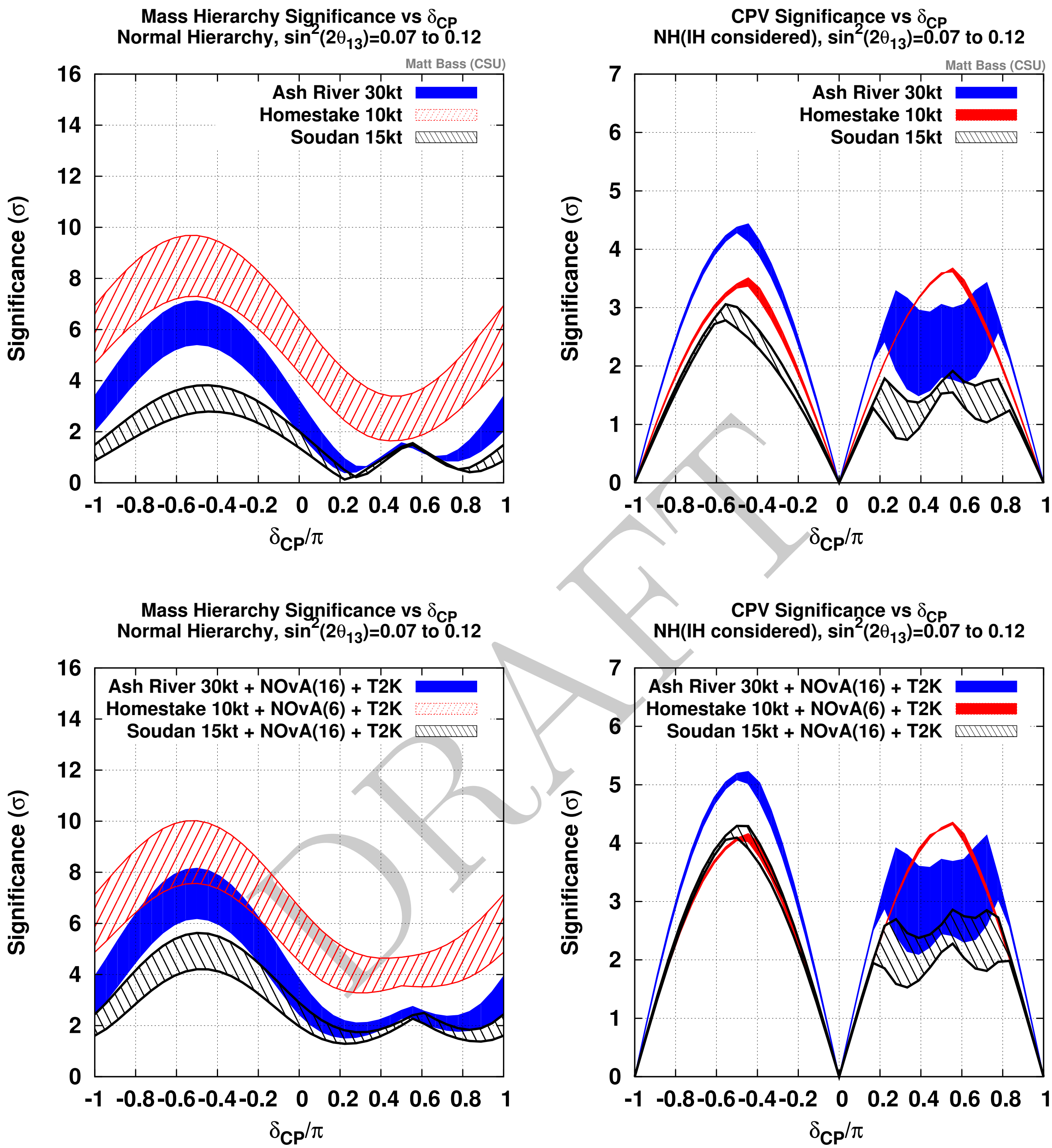

FIG. 19. Comparison between the 3 selected configurations. Significance with which the mass hierarchy is resolved is on the left. The significance with which δ_{cp} is determined to be $\neq 0, \pi$ is on the right. The top set of plots is for the 3 choices alone : 10kT at Homestake, 15kT at Soudan and 30kT at Ash River. The bottom set of plots is for the 3 choices combined with NOνA and T2K running. NOνA is assumed to run for 6 years in combination with LBNE-Homestake and for 16 years in combination with the Minnesota sites. T2K is assumed to run for an integrated 5×10^{21} protons-on-target. The colored bands indicate the change in significance when the central value of $sin^2 2\theta_{13}$ assumed is changed from 0.07 to 0.12.

IV. NON-ACCELERATOR PHYSICS REACH

A large liquid argon TPC, when sited underground, has significant capabilities for addressing diverse physics topics, including proton decay, and atmospheric and supernova neutrinos. These capabilities are described in detail in reference [23]. For non-beam physics, no external trigger will be available, and therefore the key issue is selection of signal from background, assuming suitable triggering can be implemented. Photon collection will likely be required. Since backgrounds are dominated by cosmic rays, physics reach for a given detector size depends primarily on depth. Table VIII summarizes expected signal rates. Proton decay and atmospheric neutrino events are, like beam events, $\sim$GeV scale, and should in principle be quite cleanly identifiable in a LArTPC: see Figs. 20 and 21. Proton decay events, although distinctive, would be extremely rare, and hence highly intolerant of background; in contrast, atmospheric neutrinos (which are background for proton decay) have a higher rate and could tolerate some background. The signatures of individual supernova burst neutrino interaction events are much less clean. With only a few tens of MeV of energy, these neutrinos will create small tracks involving only a few adjacent wires: see Fig. 22. For diffuse "relic" supernova events which arrive singly, the very low expected signal rate makes their selection overwhelmingly difficult, and we will not consider them further here. A nearby core collapse is more promising: it will provide a pulse of low energy events all arriving within $\sim$30 seconds, so that we can hope to make a meaningful measurement of signal over a (well-known) background.

TABLE VIII.

Physics	Energy range	Expected signal rate (events kton^{-1}s^{-1})
Proton decay	$\sim$ GeV	$< 2 \times 10^{-9}$
Atmospheric neutrinos	$0.1 - 10$ GeV	$\sim 10^{-5}$
Supernova burst neutrinos	few-50 MeV	$\sim$ 3 in 30 s at 10 kpc
Diffuse supernova neutrinos	20-50 MeV	$< 2 \times 10^{-9}$

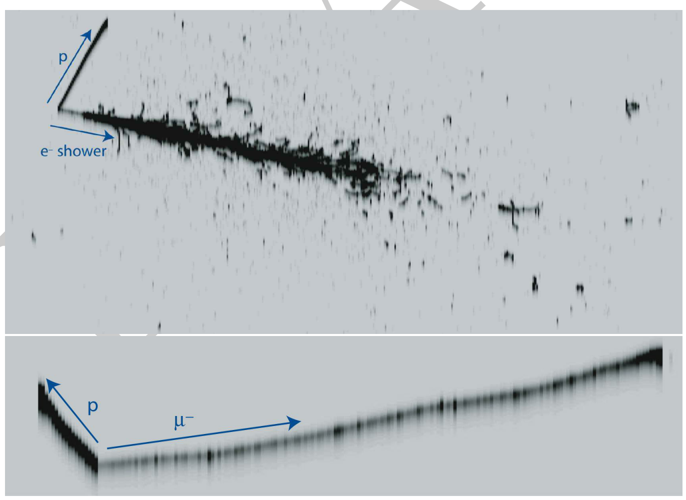

FIG. 20. Example ν_e and ν_μ CC atmospheric neutrino events in liquid argon from reference [32].

We will consider the physics reach as a function of detector mass and depth for proton decay, supernova bursts and atmospheric neutrinos. (Solar neutrinos will not be considered; with mostly <10 MeV energies, they require stringent control of background. Other than providing a ν_e calibration in argon for supernova neutrinos, they are not likely to tell us anything not already known in the detectors under consideration.)

A. Searches for baryon number non-conservation

Searches for baryon-number-violating processes are highly motivated by grand unified theories. Even a single event could be evidence of physics beyond the Standard Model. Current limits are dominated by Super-K [31]; however for

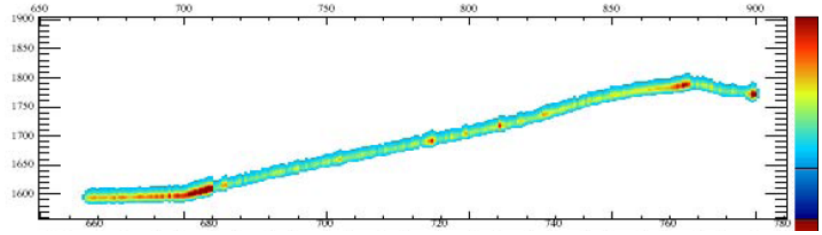

FIG. 21. LArSoft simulation of $p \to K^+\bar{\nu}$ decay with $K^+ \to \mu^+ \to e^+$ in the MicroBooNE geometry. The drift time is along the vertical axis. The wire number is along the horizontal axis (3-mm wire spacing).

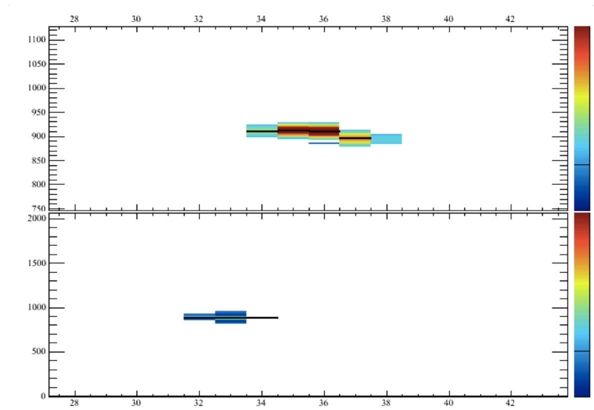

FIG. 22. LArSoft simulation of a 10 MeV electron (which would resemble a supernova neutrino event) in the MicroBooNE geometry (3-mm wire spacing). There are four reconstructed hits (black bands) on five adjacent wires. This event would create signals on about four wires with 5-mm spacing. The drift time is on the vertical axis, and the wire number is on the horizontal axis.

some predicted modes, most prominently $p \to K^+\bar{\nu}$, efficiency for water Cherenkov detectors is low, and detectors which can cleanly reconstruct kaon decay products have a substantial efficiency advantage. Other modes for which LArTPCs have an edge include $n \to e^-K^+$ and $p \to e^+\gamma$. Figure 23 shows the expected limit as a function of time for $p \to K^+\bar{\nu}$. According to this plot, approximately 10 kton of LAr is required to improve the limits significantly beyond continued Super-K running.

In LAr, the most pernicious background for proton decay with kaon final states comes from cosmic rays that produce entering kaons in photonuclear interactions in the rock near the detector. Backgrounds as a function of depth have been studied for LAr in references [32, 33]. These studies show that proton decay searches can be successful at moderate depth via reduction of fiducial mass or in conjunction with a high-quality veto, but cannot be done at the surface. Among the sites under consideration, Homestake would be excellent. Soudan would likely be acceptable, although it would require some reduction in fiducial mass. Proton decay searches are not feasible for any of the surface options.

B. Atmospheric Neutrinos

Atmospheric neutrinos are unique among sources used to study oscillations: the oscillated flux contains neutrinos and antineutrinos of all flavors, and matter effects play a significant role. The expected interaction rate is about 285 events per kton-year. The excellent CC/NC separation and the ability to fully reconstruct the hadronic final state in CC interactions in an LArTPC would enable the atmospheric neutrino 4-momentum to be fully reconstructed. This would enable a higher-resolution measurement of L/E to be extracted from atmospheric-neutrino events in an LArTPC compared to the measurements obtained from Super-K, and would provide good sensitivity to mass hierarchy and to the octant of θ_{23}. Since the oscillation phenomenology plays out over several decades in energy and path length,

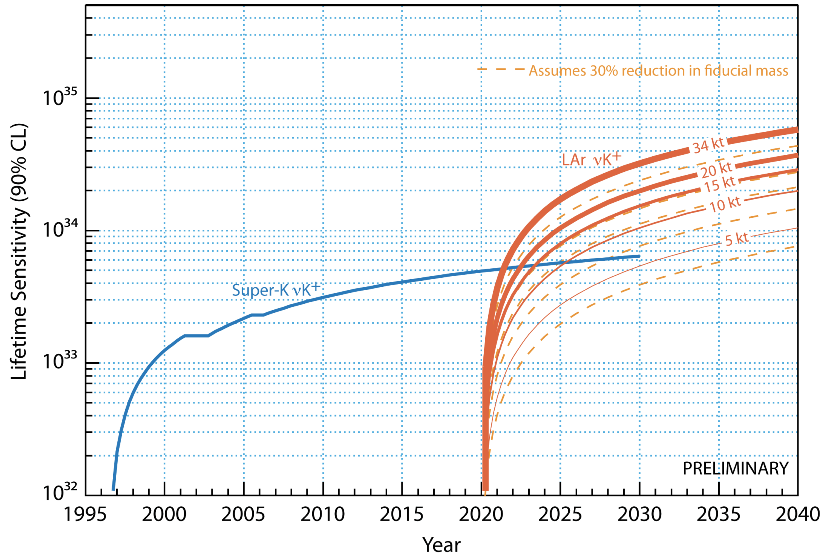

FIG. 23. Proton decay lifetime limit for $p \to K^+\bar{\nu}$ as a function of time for Super-Kamiokande compared to different LAr masses at the 4850 level starting in 2020. The dashed lines show the effect of a 30% reduction of fiducial mass, conservatively assumed for a Soudan-depth detector. The limits are at 90% C.L., calculated for a Poisson process including background assuming that the detected events equal the expected background. (Figure from J. Raaf.)

atmospheric neutrinos are very sensitive to alternative explanations or subdominant new physics effects that predict something other than the characteristic L/E dependence predicted by oscillations in the presence of matter.

Because atmospheric neutrinos are somewhat more tolerant of background than proton decay, a depth which is sufficient for a proton decay search should also be suitable for atmospheric neutrinos. For 4850 ft depth, a veto should not be necessary, and one can assume full fiducial mass; at Soudan depth, a 1 meter fiducial cut should be adequate. Figure 24 shows expected sensitivity to mass hierarchy: for ten years of running, a Soudan-depth 20 kton detector could rival beam sensitivity, and even a 10 kton detector would add to world knowledge.

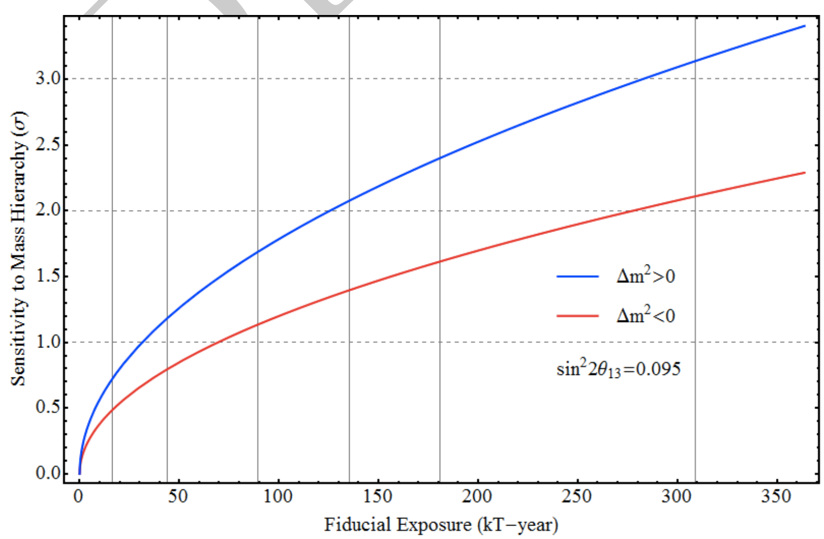

FIG. 24. Sensitivity to mass hierarchy using atmospheric neutrinos as a function of fiducial exposure in a LAr detector. (Figure from H. Gallagher, J. Coelho, A. Blake.)

C. Core Collapse Supernova Neutrinos

A nearby core-collapse supernova will provide a wealth of information via its neutrino signal (see [34, 35] for reviews). The neutrinos are emitted in a burst of a few tens of seconds duration. Energies are in the few tens of MeV range, and luminosity is divided roughly equally between flavors. Ability to measure and tag the different flavor components of the spectrum is essential for extraction of physics and astrophysics from the signal. Currently, world-wide sensitivity is primarily to electron anti-neutrinos, via inverse beta decay on free protons, which dominates the interaction rate in water and liquid scintillator detectors. Liquid argon has a unique sensitivity to the *electron neutrino* component of the flux, via the absorption interaction on ^{40}Ar, $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$. In principle, this interaction can be tagged via the de-excitation gamma cascade. About 3000 events would be expected in 34 kton of liquid argon for a supernova at 10 kpc; the number of signal events scales with mass and the inverse square of distance as shown in Fig. 25. For a collapse in the Andromeda galaxy, a 34-kton detector would expect about one event. This sensitivity would be lost for a smaller detector. However even a 5 kton detector would gather a unique ν_e signal from within the Milky Way.

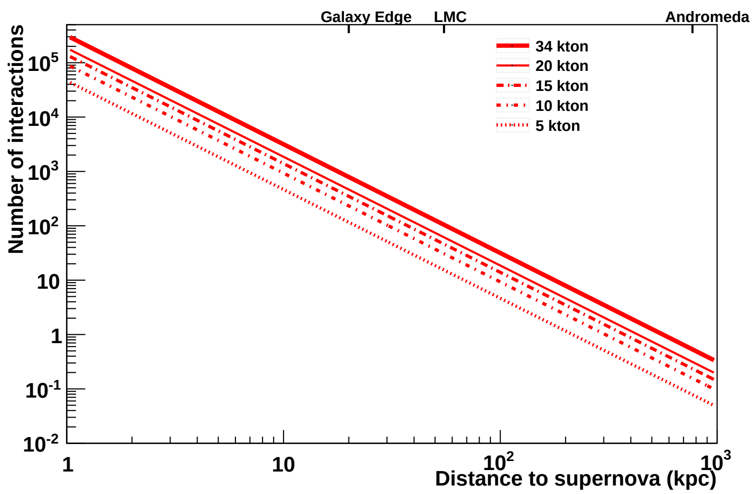

FIG. 25. Number of supernova neutrino interactions in a LAr detector as a function of distance to the supernova, for different detector masses. Core collapses are expected to occur a few times per century, at a most-likely distance of about 10-15 kpc.

As noted above, due to their low energy, supernova events are subject to background, although the short-timescale burst nature of the signal means that the background can be well known and subtracted. Muons and their associated Michel electrons can in principle be removed. Radioactive decays, including cosmogenic spallation products, tend to make $<$10 MeV signals. They lie below the main supernova signal range, but inhabit a potential region of interest for physics signatures. Preliminary studies from reference [36], extended for cosmic ray rates on the surface, suggest that while Soudan depth is likely acceptable, the surface cosmic-ray associated signal rates are daunting. It will require at least a few orders of magnitude of background rejection to pull the signal from background. While more work needs to be done to determine the extent to which the background can be mitigated, a surface option is highly unfavorable for supernova neutrino physics.

D. Summary

Although more work needs to be done to understand backgrounds at shallow depth, the following findings are fairly robust:

- Proton decay capabilities as a function of depth are the best documented, and a search at the surface seems impossible. A modest fiducial mass reduction would be required at Soudan. A detector mass of at least 10 kton would be needed for competitiveness.
- For atmospheric neutrinos, less is known about signal selection on the surface; however it is probably extremely difficult. Soudan depth is acceptable. Underground, a 20 kton detector would be needed for competitiveness, although a smaller detector could still provide useful information.

- For supernova burst neutrinos, selection of signal events over background at the surface will be a daunting task, and information will be highly degraded even in the best case. Soudan depth would be acceptable. More mass is better, but even a 5-kton detector would provide a unique ν_e-flavor supernova signal.

The overall conclusions are: a reasonably-sized detector sited at 4850 ft depth would provide excellent opportunities for a diverse range of physics topics. Soudan depth requires only modest compromise in physics reach. At the surface, capabilities for non-beam physics are extremely poor.

V. SUMMARY

The results presented here show that the CP-violating phase δ and the neutrino hierarchy can be determined with a number of the options being considered. The accessible range of δ and the confidence in the hierarchy determination increases with detector mass. For shorter baselines, results from the T2K experiment in Japan are required to establish the hierarchy.

The options with a longer baseline and wide-band beam can observe multiple oscillation peaks and the valleys between them. This provides broader sensitivity to neutrino oscillation physics beyond that described by the 3×3 PMNS matrix.

The search for proton decay and the study of atmospheric neutrinos and neutrinos from nearby supernova explosions can be successfully carried out by a liquid argon detector underground, but not one on the surface.

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Appendix E

LBNE Reconfiguration

Engineering/Cost Working Group

Interim Report

DRAFT

5 June 2012

[LBNE-doc-5968-v18]

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Project Manager James Strait

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Contents

Acronyms, Abbreviations, and Definitions

APA	Anode Plane Assembly
CF	Conventional Facilities
CFFS	Conventional Facilities at the Far Site
CPA	Cathode Plane Assembly
Homestake	Former Homestake gold mine, now the Sanford Laboratory in Lead, South Dakota
OHEP	DOE Office of High Energy Physics
LAr	Liquid argon
NDC	Near Detector Complex
SURF	Sanford Underground Research Facility
TPC	Time Project Chamber or Total Project Cost, depending on context
UGI	Underground Infrastructure
27L	The 27^{th} level in the Soudan Mine, at a depth of 2340 feet (~2100 meters water equivalent)
4850L	A level in the Homestake mine at a depth of 4850 feet (~4300 meters water equivalent)

1 Introduction

1.1 Executive Summary

The Long-Baseline Neutrino Experiment (LBNE) is in the Conceptual Design stage, approaching CD-1 readiness. A complete Conceptual Design and corresponding plan has been developed and thoroughly reviewed in preparation for a planned DOE CD-1 review. However, it was judged that the cost of LBNE as planned was not sustainable, and on March 19, William Brinkman, Director of the DOE Office of Science asked Fermilab to lead the development of an affordable and phased approach to LBNE, including alternate configurations, that will enable important science results at each phase. He noted that this decision is not a negative judgment about the importance of the science, but rather it is a recognition that the peak cost of the project cannot be accommodated in the current budget climate or that projected for the next decade. To develop the response to this charge, Pier Oddone, Director of Fermilab, formed a Steering Committee, a Physics Working Group, and an Engineering/Cost Working Group. This is the interim report from the Engineering/Cost Working Group. The final report will be prepared by the end of June 2012.

The primary goals of LBNE are to determine if there is CP-violation in the lepton sector, determine the ordering of the neutrino mass states, make other precision neutrino oscillation measurements, search for proton decay, and measure supernova neutrinos. LBNE would employ a 700 kW beam from Fermilab and a large liquid argon time-projection chamber (LAr TPC) at the Sanford Underground Research Facility (SURF) in the Homestake mine in South Dakota, 1,300 km away. With the 1,300 km baseline, a broad-band neutrino beam designed specifically for this purpose, and the highly capable detector, LBNE would measure many of the oscillation parameters to high precision and, in a single experiment, test the internal consistency of the three-neutrino oscillation model. The neutrino beam can utilize the full beam power of Project X, which would further extend its reach. Placing the detector underground enables the proton decay and astrophysical neutrino measurements.

The Steering Committee considered reduced scope versions of LBNE with the 1,300 km baseline as candidates for the first phase of LBNE. These have the advantage of providing a clear path through subsequent phase(s) to achieve all the goals of LBNE. However, they require significant investment in the new beamline, limiting the mass of the far detector within the budget guideline for the first phase. The Steering Committee also considered alternatives utilizing the existing NuMI beamline, with detectors placed either at the Soudan Lab or the Ash River site in Minnesota, with baselines of 735 km or 810 km respectively. These have the advantage of not requiring construction of a new beamline, permitting larger detectors to be built in the first phase. But at the shorter baseline, there are fundamental ambiguities between matter effect and CP-violating asymmetries that could be very difficult to resolve, limiting their capabilities for the main oscillation physics.

The Engineering/Cost Working Group investigated the engineering feasibility and estimated the costs of a large number of options for the far detector, the neutrino beam, and the near detector. These included LAr TPC detectors of 5, 17 and 34 kt fiducial mass, located deep underground at Homestake or at Soudan or on the surface at Homestake, Soudan or Ash River. For the beamline, many value engineering proposals were considered which would either lower the cost of the LBNE beamline design with minimal if any impact on functionality, or would result in some compromises in the first phase, e.g. limiting the beam power handling capability to 700 kW or accepting a less than optimal beam spectrum below the first oscillation maximum, which could be restored in a subsequent phase of the project. In addition, an evaluation was done of the limitations and risks related to operation of the NuMI beamline for an extended period of 10 or more years beyond the currently planned NOvA running. Near detector options studied included possible first-phase near detectors in the LBNE beamline which could be fit in a much smaller space than the originally planned near detector hall, and adaptations of the LBNE near detector deigns to fit into the near detector halls in the NuMI beamline.

Based on the cost information developed by the Engineering/Cost Working Group and the evaluation of scientific capabilities of the different configurations done by the Physics Working Group, the Steering Committee identified three phase one options that would provide significant scientific results and are consistent with the budget guideline that the first phase cost should be limited to $700-800M, including contingency and escalation. These three options and their estimated costs are:

Option	Estimated Total Project Cost
30 kton surface detector at Ash River (NuMI low energy beam, 810 km baseline)	$684M
15 kton underground (2340 ft) detector at Soudan (NuMI low energy beam, 735 km baseline)	$675M
10 kton surface detector at Homestake (new beamline, 1,300 km baseline)	$789M

The pros and cons of each are summarized in the Steering Committee Report. While each of these first-phase options has some advantages over the others, the Steering Committee in its discussions strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface. The physics reach of this first phase is very strong and balanced for neutrino physics. This option is seen by the Steering Committee as a start of 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. Ultimately this option would exploit the full power provided by Project X. For an additional investment of ~$135M, the detector could be placed underground, rather than on the surface.

1.2 Plan of the Report

The report begins with a discussion in Chapter 2 of the status of the LBNE design and project plan prior to the decision that a phased or alternative program needed to be developed, the reasons for developing a phased plan, and the constraints and assumptions under which the cost estimates for the phased program options were developed. Chapter 3 presents the different technical options considered, organized according to LBNE subproject: Far Detector, Conventional Facilities at the Far Site, Neutrino Beamline and its Conventional Facilities, and the Near Detector and its Conventional Facilities. The main phase 1 scenarios are presented in Chapter 4, together with sketches of possible phase 2 options for each. The cost estimates for different far detector locations and sizes are presented in Chapter 5, including discussion of subproject-specific cost estimating methodology, and contingency, escalation and cost range estimations. Chapter 6 presents the conclusions.

1.3 Work to be Completed for the Final Report

Additional work is required to prepare the Final Report of the LBNE Reconfiguration Engineering/Cost Working Group. This includes:

- Do further checks on the accuracy and consistency of the cost estimates.
- Add discussion on the relative risks of each of the scenarios.
- Add a chapter comparing the scope and cost estimates presented here with those of the LBNE reference design.

2 Context

The Long-Baseline Neutrino Experiment (LBNE) Project worked in conjunction with the LBNE Collaboration for more than two years to produce a Conceptual Design for a world-class facility that would enable the scientific community to carry out a compelling research program in neutrino physics. The ultimate goal in the operation of the facility and experimental program is to measure fundamental physical parameters, explore physics beyond the Standard Model, and better elucidate the nature of matter and antimatter. During this pre-conceptual stage, major alternates were studied and choices were made regarding a far detector technology and siting, as well an innovative beamline design to reduce risk. Thorough cost estimates and schedules were developed, including assessments for risk, and when those costs were documented for a CD-1 Director's Review, it became apparent that the Project could not be supported as originally conceived in the current budget climate in the U.S. The DOE Office of Science directed development of an affordable and phased approach to LBNE that produces important science at each step, in time to inform the next round of budget planning [1].

2.1 Reference LBNE Conceptual Design, Cost, and Schedule

The six-volume LBNE Conceptual Design Report [2] documents a reference design configuration of the LBNE Beam, Near Detector, Far Detector, and Near and Far Site Conventional Facilities for which total project cost and schedule were compiled. The reference LBNE Conceptual Design consists of a primary proton beam extracted from Fermilab's Main Injector. The proton beam strikes a target to generate neutrinos through a 200m decay pipe. Also, within the Fermilab site, an on-axis Near Detector Complex provides beam monitoring and characterization of the neutrino spectrum transmitted to the LBNE Far Detector. The LBNE beam is aimed at a 33 kt Liquid Argon (LAr) Far Detector located deep underground at the 4850 foot level (4850L) in the Sanford Underground Research Facility (SURF) in the former Homestake mine in Lead, SD. Many details of the technical systems and conventional facilities of the Near Site at Fermilab, and the Far Site at Homestake, can be found in the LBNE Conceptual Design Report.

The CD-1 project cost and schedule were developed for the Director's Independent Conceptual Design and CD-1 Readiness Review of LBNE conducted on March 26-30, 2012, and were found to be in an advanced stage at that review. The review website [3] provides links to documents describing cost range development [4], estimate uncertainty [5], cost book and basis of estimate navigation aids [6], and other documents that assist in study of the LBNE cost and schedule.

The LBNE Cost Summary Report [7] documents the Total Project Cost (TPC) and provides details of costs for all of LBNE project management and subprojects. Various methodologies, tailored to the type of estimate, were used. Expert scientists and engineers developed technical systems costs using past similar projects. In some cases experienced private companies were tasked with generating full estimates from engineering design through installation as was done in the case of the LAr Far Detector cryostat and cryogenics systems. The Conventional Facilities subproject also used experienced private companies to estimate design and construction costs for both Near and Far Site. LBNE technical systems' scientists and engineers provided detailed requirements where private companies developed the costs.

The LBNE schedule [8] was developed using Primavera P6 software and COBRA analysis tools. The schedule as of the March 26-30, 2012 Director's Independent Review reflects an effort to conform to a funding profile discussed with the Department of Energy. Resource level-loading was not entirely accomplished prior to the review; therefore, details of the schedule presented at the Review retained artificial peaks. The schedule of installation of the Far Detector was influenced by external conditions, including the need to rehabilitate the existing shafts at Sanford Laboratory. The schedule for construction of Near Site Conventional Facilities, Beamline and Near Detector Complex was influenced by the need to delay as long as possible to avoid interference with NOvA experiment running.

The LBNE cost and schedule referred to in this report reflects the status of development of the conceptual reference design at the time of the LBNE Director's Independent Conceptual Design and CD-1 Readiness Review.

2.2 Need to Phase the Program or Find Alternatives

Just prior to the LBNE Director's Review in March 2012, Office of Science Director Bill Brinkman sent a letter to Fermilab Director Pier Oddone indicating the ~ $1.5B unescalated cost of LBNE was unaffordable as a single project [1]. Dr. Brinkman charged Fermilab with finding a path forward to reach the scientific goals of the Long-Baseline Neutrino Experiment in a phased approach. A Steering Group was formed by Fermilab to study phased approaches and alternative experimental configurations. Two working groups were formed to support the work of the committee – Physics and Engineering/ Cost. Under consideration are phased programs based on the original LBNE design, with a new beamline and a far detector at Homestake; and alternatives utilizing the existing NuMI beamline at Fermilab and a far detector either at the Soudan Underground Laboratory in Minnesota, the site of the MINOS experiment, or at Ash River, the site where the NOvA experiment is under construction.

2.3 Constraints and Assumptions at each Phase

There are several constraints and assumptions that control the design and the estimating for options under consideration. These include (in no particular order):

- Estimate basis: To the extent possible, estimates are based on the LBNE reference design as presented at the LBNE CD-1 Director's Review in March 2012.
- Maximum cost for each phase: Based on guidance from DOE OHEP, the cost of each phase of LBNE should be no more than $700-800M. This amount is not absolute, but is a strong guideline.
- Cost range: DOE OHEP has strongly suggested that the Phase 1 CD-1 cost range should stay within the LBNE CD-0 cost range of $660M-$940M. The upper end of the cost range for the reference design is about 15% above the point estimate; this implies that the point estimates should stay below about $800M.

- Annual available funding: DOE OHEP and Fermilab Management have provided guidance that annual expenditures for LBNE should not exceed about $120M/year.

- Science capabilities: Per Dr. Brinkman's letter, each phase must produce important science on its own.

- Accelerator-based oscillation physics has higher priority and should be addressed in Phase 1.

- The Sanford Underground Research Facility will be operated independently of LBNE for the Early Science Program and potentially for other subsequent experiments. The Soudan Underground Laboratory and the Ash River sites will be operated independently of LBNE for the existing neutrino experiments and potentially other subsequent experiments. The operating costs of these facilities will not be the responsibility of the LBNE Project during its construction.

3 System Options Considered

This section describes the technical systems and the conventional facilities options that can be combined into various configurations. The starting basis for all work is the LBNE reference design and this section will describe the evolution of or relationship to the systems from that design. Along with the description of the scope of each system option, evaluation of the quality and maturity of the engineering designs for the various options is included. The options considered for this exercise and for which costs were developed (see Chapter 5) include:

- Liquid Argon Far Detectors of 5 kt, 17 kt and 34 kt fiducial mass. Note that for this exercise, the largest mass detector (34 kt) is slightly more massive than the one in the reference design (33 kt). The cost of other detector masses are estimated by interpolation.

- Conventional facilities (CF) to support the Far Detector construction and operation for all three detector sizes at the Sanford Underground Research Facility at Homestake at the 4850L or on the surface; at the Soudan Underground Laboratory at the 27L (2340 foot depth) or on the surface; and at the Ash River facility on the surface. The cost of CF for other detector sizes are estimated by interpolation.

- The LBNE neutrino beamline, modified from the original design according to a set of value engineering proposals that have been evaluated since the Director's Review.

- Required investments in the existing NuMI beamline to allow it to operate in the low-energy configuration at 700 kW for at least 10 years beyond the end of the NOvA run.

- Near Detector configurations for use in either the LBNE or NuMI beamlines, based on the reference design of a magnetized liquid argon TPC or the alternative magnetized straw-tube tracker design, as well as several simplified designs that could be part of a phase 1 implementation. The option of constructing no near neutrino detector in phase 1 for the Homestake options was also considered. In this case the beam would be monitored by muon detectors downstream of the absorber until a neutrino detector cold be constructed in phase 2. For the NuMI options, the possibility of utilizing the existing MINERvA, MINOS and NOvA near detectors in phase 1 was also considered.

3.1 Far Detector

The far detector is a Liquid Argon Time Projection Chamber (TPC). The construction of the basic TPC components, anode plane assemblies (APA) and cathode plane assemblies (CPA), are the same for all options. The modular detector is constructed in a rectangular array of double-sided drift cells, each consisting of a central APA and two CPAs. The options differ in the number of components and their relative spacing. The APA/CPA spacing is the maximum drift distance over which ionization electrons must travel and has been set in the range of 3.6 – 3.9 meters for underground options and in the range of 2.3 – 2.4 meters for surface options. The selection of drift distance for the underground options reflects the need to limit the cavern span to a reasonable size (~30 m) while minimizing the number of TPC components. [9] The shorter drift distance for surface options was chosen to mitigate the effects of space charge build-up due to cosmic rays [10] [11]. The detector would ideally be constructed as a cube to minimize the surface area, and therefore the cost, of the cryostat and to maximize self-shielding from external background sources. The chosen options reflect this general principle.

The options shown in Table 1 are characterized by five parameters: 1) the number of detector modules, 2) the number of drift cells high, 3) the number of drift cells wide, 4) the number of longitudinal drift cells along the beam direction and 5) the drift distance. The applicability of each of the options to a specific depth and location are shown. All options include a cryogenic refrigeration plant sized for each cryostat and a standby refrigeration plant.

Table 1: Far Detector Options

Option	Fid Mass (kt)	Level	Drift (m)	Cryo Plants	Location
1x2Hx3Wx10L	5	0	2.3	2 x 45 kW	Homestake, Ash River, Soudan
1x2Hx2Wx9L	5	27L	3.65	2 x 60 kW	Soudan
1x2Hx2Wx9L	5	4850L	3.65	2 x 60 kW	Homestake
2x2Hx4Wx12L	17	0	2.38	3 x 50 kW	Homestake, Ash River, Soudan
2x2Hx3Wx10L	17	27L	3.63	3 x 70 kW	Soudan
2x2Hx3Wx10L	17	4850L	3.63	3 x 70 kW	Homestake
2x2Hx4Wx23L	34	0	2.42	3 x 75 kW	Homestake, Ash River, Soudan
2x2Hx3Wx18L	34	27L	3.89	3 x 100 kW	Soudan
2x2Hx3Wx18L	34	4850L	3.89	3 x 100 kW	Homestake

The quality of the TPC design for these options is the same as for the reference design. The options differ primarily in the number of components constructed and installed. The options for the 17 kt and 34 kt options include a 1 kt engineering prototype. These large-detector options are constructed in two cryostats, allowing both cryostats and both detector modules to be qualified before final filling of the second cryostat.

A 5 kt detector is considered too small to devote such a significant level of prototyping resources as well as being too small to break into two cryostats. This loss of flexibility has been compensated for to some extent by including a liquid argon surface storage tank. Additional prototyping activities, e.g., installing a TPC in the 35 ton membrane cryostat prototype, could reduce risk for the smaller detector.

3.2 Conventional Facilities at the Far Site (CFFS)

The conceptual design of the LBNE project has evolved over the last several years culminating in the reference design for a 33 kt far detector that was the subject of a Director's Independent Conceptual Design and CD-1 Readiness Review of LBNE in March 2012. As part of the project reconfiguration exercise the reference design has undergone a re-scoping process that included consideration of constructing far site detector facilities at either the former Homestake mine in Lead, South Dakota (the reference design location), the former Soudan Mine in Soudan, Minnesota, or the Ash River site in northern Minnesota. Scope and cost models of 5, 17, and 34 kt detector sizes were developed for deep underground locations at Homestake (4850 foot depth) and Soudan (2340 foot depth) and for surface configurations for all three sites.

For all options considered, the following modifications to the scope of the reference design have been incorporated into the Conventional Facility (CF) scope and cost models.

- Cryogens will be delivered to the underground detector enclosure as a gas instead of a liquid. This eliminates the need for pressure reducing stations previously required every ~800 feet down the shaft, and reduces the amount of power delivered to the detector enclosure and also reduces the heat load rejected to air.
- The "muffin top" has been omitted from all detector enclosure options.
- Redundant UGI systems for cyber infrastructure and power delivery systems have been omitted.
- Surface detector options include the LAr pit excavated into the earth with the top of the pit placed near existing grade. The septum area and the highbay portion of the cavern that houses equipment are located in a surface structure for the surface detector option.
- Surface detector options have omitted emergency and standby electrical power distribution systems. The small amount of equipment that requires electrical power will be connected to uninterruptible power supplies.
- Layouts of all options were discussed with the LBNE ES&H manager to validate that emergency egress and ventilation system requirements were met.

3.2.1 CFFS at Homestake

Detector options evaluated at the Homestake site include detectors sited below grade at the 4850L and at the surface. Details of the scope of the 4850L and surface detector options at Homestake are described below.

3.2.1.1 Siting at the 4850L

Designs are based on the reference design with the scope scaled to reduced detector requirements. The 5-kt and 17 kt excavation scope applied to Homestake are not as mature as the 34 kt design. For the 5, 17, and 34 kt detector sizes located at the 4850L, the following additional assumptions are included in the scope and cost models.

- UGI systems outside the cavern required for fire/life safety or for early science at Homestake have been omitted from the LBNE scope and have become a SURF responsibility, as they are necessary to support the on-going early science program.

- Ross and Yates shaft rehabilitation scope and costs are separated from LBNE costs since they may be funded by others.

- Construction management will be self-performed by SURF.

The description of the facility layout, including graphics and cost models for the following detectors located at the 4850L are documented for each detector size: 5 kt [12], 17 kt [13], and 34 kt [14].

3.2.1.2 Siting at the Surface

The pre-conceptual design of the pit excavation and the surface structure is based on a NOvA-like facility roughly scaled to LAr detector size requirements. The UGI is based on work done by SURF engineers to scale the reference design utilities to a surface installation and detector requirements. The description of the facility layout, including graphics and cost models for the following detectors located at the surface have been documented for each detector size: 5 kt [15], 17 kt [16], and 34 kt [17].

3.2.2 CFFS at Soudan

Detector options evaluated at the Soudan site include detectors sited underground at the 27L and at the surface. In addition to the modifications made to the reference design as described above, all Soudan scopes incorporate the following:

- Tailoring of the reference design to the Soudan site and its existing infrastructure.

- Use of existing temporary warehouse space at no cost to the project.

- Construction administration performed by the University of Minnesota (U of MN) and construction management performed by an independent firm.

Details of the 27L and surface detector options at Soudan are described below.

3.2.2.1 Siting at the 27L

Two new shafts are required to provide primary personnel and equipment access and ventilation. The existing shaft would provide secondary egress. The sizes of the two shafts were established by LBNE based on the function that they would serve. They are the same for all detector sizes. Standardized 5 and 17 kt dimensions of all caverns, drifts, and shafts at the 27L were used by CNA consulting engineers to determine site specific shaft locations which determined the drift lengths required to connect caverns and shafts to each other and to existing underground enclosures. LBNE used this information to create the layout of 34 kt facilities. Soudan layouts were discussed with the LBNE ES&H manager to validate that emergency egress and ventilation system requirements were met. The 34 kt cavern and drift excavation design is based on the reference design and is at the pre-CD-1 level. The 5 kt and 17 kt excavation scopes are not as mature as the 34 kt design.

The UGI and surface infrastructure components are adapted and scaled from the reference design to apply to Soudan and specific detector size requirements and are less mature than the Homestake models.

The description of the facility layout, including graphics and cost models for the following detectors located at the 27L are documented for each of the detector sizes: 5 kt [18], 17 kt [19], and 34 kt [20].

3.2.2.2 Siting at the Surface

The pre-conceptual design of the pit excavation and the surface structure is based on a NOvA-like facility roughly scaled to LAr detector size requirements. UGI is the same as that for a Homestake surface option. The description of the facility layout, including graphics and cost models for the following detectors located at the surface are documented for each of the detector sizes: 5 kt [15], 17 kt [16], and 34 kt [17].

3.2.3 CFFS at Ash River

Detector options evaluated at the Ash River site are limited to siting the detectors at the surface. The pre-conceptual design of the pit excavation and the surface structure is based on a NOvA-like facility roughly scaled to LAr detector size requirements. UGI is the same as that for a Homestake surface option. The description of the facility layout, including graphics and cost models for the following detectors located at the surface are documented for each of the detector sizes: 5 kt [15], 17 kt [16], and 34 kt [17].

3.3 Beamline and its Conventional Facilities

In the context of the LBNE reconfiguration effort the following three options have been considered:

I. Beam to Homestake - NOvA continues running and NuMI components are not available for LBNE use. In this option NOvA can keep running until right before LBNE is ready to run.

II. Beam to Homestake - NOvA has finished data-taking and components from NuMI are available for LBNE use.

III. Use NuMI Beamline to aim to Soudan for continued 700 kW operation after the end of NOvA data-taking.

For option III, additional considerations are that i) NuMI cannot run at proton energies significantly below 120 GeV; ii) NuMI cannot be upgraded to run at beam power of 2.3 MW.

The assumptions for options I. and II. are that:

a. Although the LBNE to Homestake will be able to be upgraded to 2.3 MW of beam power, in the initial phase the shielding at the target hall roof is appropriate for 700 kW only; more concrete will be required (~1.5 ft) on the roof of the target hall.

b. New primary beam optics will be implemented, reducing the length of the primary beam and therefore sacrificing some, but still allowing for sufficient beam tuneability.

c. The Near Detector Hall will stay where it is now (independent of b), since locating it upstream provides insufficient rock cover above it. This implies that the muon range out distance will increase the when the primary beamline length is shortened.

d. NuMI-design horns with horn 1 upgraded for 700 kW will be used and run at 200 kA. This results in the same neutrino flux at the first oscillation maximum (2.4 GeV) as in the reference design, but a ~25% loss in flux at the second maximum (0.8 GeV).

3.3.1 Option I – Beam to Homestake, no NuMI components

In trying to reduce the Beamline Facility costs (Technical Components and Conventional Facilities) for the first phase of LBNE, additional value engineering proposals were considered [21], on top of the ones considered for the reference design. All the proposed changes have been reviewed by members of the Fermilab ES&H staff to ensure that they are compatible with radiological, environmental and personnel safety requirements.

Primary Beam: The main cost savings in the primary beam are related to the implementation of new primary beam optics reducing the length of the primary beam by 148' and therefore sacrificing some, but still allowing for sufficient, beam tuneability [22]. This allows for reduction of the apex of the beamline center and the corresponding soil embankment, for fewer drilled piers to rock and for moving the target hall, decay pipe and absorber hall further upstream, and therefore reducing conventional facilities costs [23], [24]. It also allows for reduction of the costs of technical components in this shorter beamline [21].

At the same time the embankment side slopes are increased to 30 degrees (the reference design has 21.8 degree slopes) and on the basis of updated MARS calculation, the soil shielding on top of the primary beamline is reduced from the 25 ft used in the reference design (same as for the Main Injector) to 23 ft. This provides the necessary shielding for 2.3 MW operation.

In addition, the optical transition radiation 2D exit window profile monitor is eliminated from the beam instrumentation and the labor cost for beam loss calculations has been re-optimized.

Neutrino Beam: There are several sources of the cost savings in the Neutrino Beam area. These include using a NuMI style design for the target, horns, and target hall instrumentation in order to reduce the design time and the prototyping cycle. They also include using NuMI approach to support the baffle and the target and to make target repairs, implying a reduction in the scope of remote handling and its impact on conventional facilities [21]. By so doing, Phase 1 of a phased LBNE program produces a less optimized neutrino spectrum, more frequent target change-outs, and longer accesses for maintenance.

Due to improved MARS modeling, and by adding a water resisting liner around the target chase bath tub, the steel walls and floor of the target shield pile are reduced by 24 inches on each side. Eliminating the flexibility to install magnets from the target hall side reduces the footprint of the target hall complex further. The combination of all of the improvements in the neutrino beam allow a reconfiguration of the target hall complex to a three story facility with fewer drilled piers to rock, resulting in substantial savings for the conventional facilities [23], [24].

Additional cost savings come from reusing some onsite steel for the target shield pile shielding and postponing the installation and cooling of the target chase water-cooling panels until 2.3 MW operation. The panels were serving also as shielding, but carbon steel filler plates will be used instead [21].

Tritium interceptors were removed from the walls of the 200 m long decay pipe but retained at its floor [23], [24].

3.3.2 Option 2 – Beamline to Homestake, NOvA has finished data-taking

This option uses all the value engineering proposals applied in Scenario I. In addition some components are re-used from NuMI, which include:

- A few quadrupole magnets, a few quadrupole, kicker and lambertson magnet power supplies, a kicker magnet tank, and some beam instrumentation components for the Primary Beam
- Some target and Target Hall Instrumentation components, the horn power supply, part of the horn strip line, the steel door and lift table for the Target Hall Work Cell for the Neutrino Beam
- A few controls components for System Integration.

These components are worth about $10 M in TPC FY2010. Some of them, like the power supplies for the horns and the magnets, can be moved and repurposed quickly (in less than a month) and some of them will take several months. For all of them though, the moving and repurposing will take less than one year.

Many value engineering proposals were review intensively by the LBNE beamline team with oversight by the Project Office, and a subset were accepted as forming the basis of a first phase LBNE beamline. A summary of all of the accepted value engineering proposals for reducing the cost of the LBNE neutrino beamline in phase 1 is presented in Table 2. The total identified cost reduction is $86M (FY2010) including contingency.

3.3.3 Option 3 – NuMI Beamline

This option assumes that the Beamline has been already running at 700 kW and will continue with the same beam power. However, some investment will be required to permit operation at 700 kW in the low-energy configuration. (NOvA will run in the medium–energy configuration.) The main items are development of a target that works at 700 kW while inserted fully in the first horn, and returning Horn 2 to its previous “nest” to have the two horns 10 m apart. A document discussing ES&H concerns for long term running of the NuMI line can be found in [25]. Risks involved in long term running of the NuMI Beamline and possible mitigations are discussed in [26].

Table 2: Summary of LBNE beamline cost savings in FY2010 M$, including contingency.

Simplify Technical Systems Design	Cost Savings
Shorten primary beam 148'	0.8
Eliminate OTR profile monitor	0.2
Re-optimize beam loss calculation labor	0.5
Reduced target shield pile	4.4
Recycle old shielding steel	1.3
No target chase water-cooling panels in phase 1	3.7
NuMI design target and horns (200 kA)	13.0
Reduced target R&D in phase 1	3.0
NuMI design target hall instrumentation	2.3
Combined target-baffle module	0.7
No in-chase target handler	7.7
Reduce and combine vision systems	0.7
Total - technical systems	**38.2**

Re-use NuMI beamline components	Cost Savings
NuMI horn PS + stripline	3.6
Beamline Magnets	1.3
Magnet power supplies	0.5
Primary beam instrumentation	1.0
Target	0.8
Target hall instrumentation	1.9
Total - reusing NuMI components	**9.5**

Simplify Conventional Facilities Design	Cost Savings
Target Hall Complex Reconfiguration	30.2
Shorten primary beam 148'	6.6
Reduced tritium interceptor	1.4
Total - Conventional Facilities	**38.2**

Grand Total	**85.9**

3.4 Near Detector and its Conventional Facilities

The near detector complex (NDC) envisioned for LBNE included post-absorber measurements of the tertiary muon spectra, neutrino measurements in an underground hall a few hundred meters after the absorber, and a global DAQ (GDAQ) system including a GPS to provide timestamps to the data and communicate with the rest of the experiment [27]. From the standpoint of the near detector, the LBNE reconfiguration options considered can be classified into two categories, those that represent full or phased LBNE reference design, and those that employ the existing NuMI beam and near-site underground facilities. For the former, the same tertiary muon systems and same GDAQ (with the cost scaled by the number of neutrino detector channels) are employed for all options. For the latter, the same is true except for the assumption of re-use of the existing GPS system in the NuMI hall. The following describes the neutrino detectors anticipated for each option. In all cases, the starting point for the estimates was the LBNE NDC reference design.

3.4.1 Far Detector at Homestake - Near Detector and CF Options

There are several options associated with a phased LBNE program for a far detector at Homestake. Two options include building the NDC as contemplated, or not building it at all. These require little effort to determine the capability and the cost. The designs can be found in the LBNE CDR [27]. The remainder of the LBNE phasing options for the near detector involves the construction of one of the two shafts required for the LBNE near detector hall, and the deployment of a neutrino detector with modest capabilities into the shaft for remote operation.

The shaft [28] would be 22 feet in diameter as is required for the standard LBNE reference design, constructed to the elevation (575 ft) required for LBNE to allow the underground hall to be built in a later phase. A minimal surface building would be constructed. Site utilities would include electricity and water, but no sewer. In the shaft, no permanent crane, stairs or elevator would be constructed. The shaft would be lined with concrete and have a dehumidifier, sump pit and sump pump. No ventilation would be provided. During infrequent pit occupancy, ventilation would be provided by temporary installation of an elephant trunk.

There are three options for detectors [29] labeled Very Basic, Basic and Enhanced Basic, any of which would be placed in the shaft described above. The Very Basic option includes a neutrino detector that is a steel and scintillator sandwich similar to MINOS, but with no magnetic field. The detector has three sections – upstream, mid and downstream. The upstream and downstream sections are the same except the downstream is twice as long. The mid-section includes thinner steel (0.5cm instead of one inch) and makes crude measurements of the aggregate of electron neutrinos and anti-neutrinos vs. the aggregate of muon neutrinos and anti-neutrinos as a function of reconstructed (anti)neutrino energy. The Basic option employs the same up and downstream sections as the Very Basic option, but the mid-section is composed of alternating planes of high-pressure gas argon targets in a stainless steel manifold and scintillator. Through the whole detector is a magnet coil to generate a toroidal magnetic field (similar to MINOS). This detector measures CC interactions on the same target nucleus as the far site (argon) and can separate CC muon neutrino and anti-neutrino interactions. It also measures the NC interaction spectrum. The Enhanced Basic option includes a cylindrical liquid argon TPC enclosed in a solenoidal magnetic field and surrounded by detectors to separate muons from pions. It has enough instrumented mass to carry out a large fraction of the measurements contemplated for standard LBNE.

The major components of the Very Basic and Basic designs are based on some of the components of the LBNE reference designs, therefore, the costs are well understood. Since the challenges of remote operation have only been considered for one month, some additional contingency was applied to the costs for these options. For the Enhanced Basic design, there are significant design differences when compared with the standard LBNE designs. More contingency has been applied to this design to accommodate the larger project risk.

3.4.2 Far Detector at Soudan - Near Detector and CF Options

For on-axis options that employ a far detector at Soudan, the simplest phase one option is just to use the existing MINERvA and MINOS detectors. However, to achieve the best results from the far detector, a fully capable LBNE-type near detector would be required in a second phase, if not in phase 1. Two options that involve building detectors in the current MINOS near detector hall were initially considered [30]: a liquid argon detector and a fine-grained straw-tube tracking detector (FGD), each with the same fiducial mass as the LBNE reference design. Since the hall is narrower than that contemplated for LBNE, it is clear each design must be narrower and longer. For the FGD, the straw-tube length goes from 2.5 meters to 2 meters. For the liquid argon TPC, the transverse size is reduced to such a level as to threaten the viability of the detector. A redesign of the magnet would likely solve this problem. There is no difficulty designing to this option if necessary. However, given the limited time, only the FGD option has been considered for this exercise. Based on the relative costs of the LAr and FGD reference designs, it is believed that this approach would provide adequate budget for either type. In order to install and operate either design, significant infrastructure work is required – especially related to the ODH hazard associated with a large mass of liquid cryogen, this design has been developed quickly and must be considered to be relatively immature.

3.4.3 Far Detector at Ash River – Near Detector and CF Options

For off-axis options that employ a far detector at Ash River, as for the Soudan option, the simplest phase one option is just to use the existing NOvA, MINERvA and MINOS detectors, but eventually a fully capable LBNE-type near detector would be needed. It is not possible to fit either of the LBNE designs into the near-site off-axis hall that will be constructed to house the NOvA near detector. This leaves two options. The first is to build an on-axis FGD in the MINOS Near Detector Hall and a small non-magnetized off-axis liquid argon detector in the NOvA near hall [31]. The small liquid argon detector is surrounded by an array of steel/scintillator sandwiches that distinguish muons from pions. The second is to remove the NOvA detector and enlarge the off-axis cavern to accommodate an LBNE-type detector. Given the short time available for this study, only the first option has been developed so far. The same design maturity issues associated with the Soudan options are true here.

4 Phasing Options

Based on studies done by the Physics Working Group and preliminary cost estimates presented by the Engineering/Cost Working Group (discussed in detail in Section 5), the Steering Committee identified three viable configurations for a Phase 1 long-baseline neutrino experiment that have the potential to accomplish important science [32]. These have been chosen because they fit within the budget guidelines. Each has possible Phase 2 configurations that would extend the science reach of LBNE. A fourth option is identified by the LBNE Collaboration as potentially viable, and is also included. This section describes these four phasing options, for which costs are summarized in Chapter 5.

4.1 Phase 1 - 30 kt Detector at Ash River on the Surface

Phase 1 of this scenario utilizes the existing NuMI beamline at 700kw, reconfigured for a low energy beam, as described in 3.3.3. A 30 kt LAr TPC detector on the surface would be constructed at the Ash River site adjacent to the existing NOvA detector at a baseline of 810 km and an off-axis angle of 14 mrad. The detector would be very similar to the 34 kt surface detector described in Section 3.1. The conventional facilities for the 30 kt detector would be very similar to those described for a 30 kt detector option at Ash River in Section 3.2.3.

In phase 1, a combination of the existing MINERvA detector, MINOS near detector, and the by-then existing NOvA near detector would serve as the near detector for this experiment. Given the large mass and therefore relatively high statistics in the far detector, a more sophisticated near detector is likely to be required as an early phase 2 project in order to limit the systematic errors. In phase 2, a pair of near detectors would be constructed in the existing NOvA and MINOS near detector halls at Fermilab as described in Section 3.4.3.

Possible phase 2 options for this configuration include:

- Construction of a full-performance LBNE-type near detector.
- Upgrading the NuMI beamline to accept beam power of 1.1 MW in conjunction with the construction of the first phase of Project X.
- Constructing an additional 15-20 kt detector underground at Soudan.
- Construction of a new neutrino beamline optimized for lower beam energy and capable of taking the full Project X beam power of >2 MW. This beam could be aimed directly at Ash River to provide a broad-band on-axis beam if appropriate.

4.2 Phase 1 - 15 kt Detector at Soudan 2340 foot depth

Phase 1 of this scenario utilizes the existing NuMI beamline at 700kw, reconfigured for a low energy beam, as described in Section 3.3.3. A 15 kt LAr TPC detector would be constructed at the existing 27L, 2340 feet underground at the Soudan Laboratory, at a baseline of 735 km and on the NuMI beam axis. The detector would be very similar to the 17 kt detector described in Section 3.1. The conventional facilities for the 15 kt detector would be very similar to the 17 kt detector option described in Section 3.2.2.1.

In phase 1, a combination of the existing MINERvA detector and MINOS near detector would serve as the near detector for this experiment. After several years of operation, a more sophisticated near detector is likely to be required in a phase 2 project in order to limit the systematic errors.

Possible phase 2 options for this configuration include:

- Construction of a full-performance LBNE-type near detector.
- Upgrading the NuMI beamline to accept beam power of 1.1 MW in conjunction with the construction of the first phase of Project X.
- Construction of a 30 kt detector on the surface at Ash River.
- Constructing an additional 25-30 kt detector underground at Soudan.
- Construction of a new neutrino beamline optimized for lower beam energy and capable of taking the full Project X beam power of >2 MW.

4.3 Phase 1 - 10 kt Detector at Homestake on the Surface

Phase 1 of this scenario includes construction of a new beamline at Fermilab aimed at the Sanford Underground Research Facility in the Homestake Mine in Lead, South Dakota, and a 10 kt LAr TPC detector located on the surface, at a baseline of 1300 km and on the beam axis. The beamline is designed for 700kW, but is upgradable to 2.3MW, an uses components reused from the NuMI beamline, as described in Section 3.3.2. The 10 kt detector would be similar to the 17 kt detector described in Section 3.1. The detector is subdivided into two 5 kt modules, and the first of these would serve as the prototype for the second. Therefore, there is no 1 kt prototype in this scenario. The conventional facilities would be similar to that described in Section 3.2.1.2 for the 5 kt and 17 kt options. The only component of the NDC included in this phase 1 option is the muon monitor system located in the absorber hall. The experiment is expected to be limited by the statistics in the far detector for at least the first several years, but a full-function near detector is likely to be required in phase 2, to limit the systematic errors on the oscillation measurements before the end of the initial 10-year run.

Possible phase 2 options for this configuration include:

- Construction of a full-performance near detector.

- Upgrading the beamline to accept higher beam power in conjunction with the construction of the first phase of Project X.

- Construction of a 20-25 kt detector at the 4850 foot depth at Homestake, yielding a configuration with nearly the full capability of LBNE as originally planned.

4.4 Phase 1 - 10 kt Detector at Homestake at 4850L

Phase 1 of this scenario includes construction of a new beamline at Fermilab aimed at the Sanford Underground Research Facility in the Homestake Mine in Lead, South Dakota, and a 10 kt LAr TPC detector located underground at the 4850L, at a baseline of 1300 km and on the beam axis. The beamline designed for 700kW, but upgradable to 2.3MW, and uses components reused from the NuMI beamline, as described in Section 3.3.2. The 10 kt detector would be similar to the 17 kt detector described in Section 3.1. . The detector is subdivided into two 5 kt modules, and the first of these would serve as the prototype for the second. Therefore, there is no 1 kt prototype in this scenario. The conventional facilities are similar to that described in Section 3.2.1.1 for the 5 kt and 17 kt options. The only component of the NDC included in this phase 1 option is the muon monitor system located in the absorber hall. The experiment is expected to be limited by the statistics in the far detector for at least the first several years, but a full-function near detector is likely to be required in phase 2, to limit the systematic errors on the oscillation measurements before the end of the initial 10-year run.

Possible phase 2 options for this configuration include:

- Construction of a full-performance near detector.

- Upgrading the beamline to accept higher beam power in conjunction with the construction of the first phase of Project X.

- Construction of an additional 25-30 kt detector at the 4850L at Homestake, yielding a configuration with the more than the full capability of LBNE as originally planned.

5 Cost Estimates

This chapter describes the cost estimates for both the technical system and CF options. In Section 5.1, the cost estimate methodology is presented for each level 2 subproject, then the methodology for estimating contingency and escalation is presented, and finally the estimation of a CD-1 type cost range is discussed. Section 5.2 presents a summary of the major options considered, including the viable options for Phase 1.

5.1 Cost Estimating Methodology

Each technical system and its CF have developed cost estimates using its own methodology. Sections 5.1.1 through 5.1.5 describe that methodology as well as the maturity of the cost information. Each of these sections includes information about subproject-specific considerations of contingency. Section 5.1.6 describes the overall contingency methodology, including estimate uncertainty, risk and top-down contingency. Section 5.1.7 describes the method used to estimate escalation. The estimation of a CD-1-type cost range is discussed in Section 5.1.8.

To the greatest extent possible, cost estimates have been based on the designs and utilizing the same methodologies used for the LBNE Project reference design described in Section 2.1. The reference design and cost estimates have been thoroughly reviewed both internally by the LBNE Project and in an independent Director's Review, and found to be sound. Therefore, they provide a solid basis for estimating costs of the various phasing options. However, in a number of cases, new information had to be developed for configurations that do not correspond to the reference design, e.g. conventional facilities for detectors located at Soudan or Ash River.

For the far detector and its conventional facilities, costs were developed for specific detector fiducial masses: 5 kt, 17 kt, and 34 kt. Costs for alternate fiducial masses (10 kt, 15 kt and 30 kt) were done through interpolation of scalable costs from the three fiducial masses, added to fixed costs.

Cost estimates presented here do not include the cost of operating the Far Site laboratory facilities during the design and construction period. The Sanford Underground Research Facility will be operated independently of LBNE for the Early Science Program and potentially for other subsequent experiments for at least the next five years. The Soudan Underground Laboratory and the Ash River sites will be operated independently of LBNE for the existing neutrino experiments and potentially other subsequent experiments. The Soudan Underground Laboratory will be operated independently of LBNE for the MINOS+ and possibly other experiments for a similar period, and the Ash River site will be operated for NOvA until at least the end of the decade. The cost to DOE of operating SURF is currently $10-15M per year, and that for the Soudan Lab is about $2M/year. Operations at Ash River have not yet begun. None of these operating costs are included in the LBNE cost estimates.

5.1.1 Estimates for the Liquid Argon Far Detector

The cost estimates for all options are derived by parametric scaling from the cost estimate presented at the March Director's CD-1 Readiness Review as the cost basis [33]. The estimate includes direct costs, indirect costs and contingency. Escalation is not included. The cost estimate and the detector parameters presented at the review [34] were merged into a single spreadsheet [35] that generates a cost estimate for a variety of user-defined configurations. Unit costs for constructed TPC components such as APAs are obtained from the estimate for the reference design and then the costs are scaled by the number of components required for each option.

The cost estimates for design and tooling are the same for all options. Project management costs are scaled by the estimated project duration from CD-3 to CD-4. Contingency is re-calculated at the lowest level of the cost estimate and scaled appropriately.

The quality of the TPC cost estimate for all options is the same as for the reference design. The costs of the options differ primarily in the number of components constructed and installed. The cost estimates for the 17 kt and 34 kt options include a 1 kt engineering prototype ($24M). For the 5 kt options, a surface storage tank is included ($7-11M).

5.1.1.1 Cryostat and Cryogenic System

The cost estimate for the reference design cryostat and cryogenics systems was performed by Arup Energy and evolved through three design cycles [36] [37] [38] over a two year period. Cost estimates for cryostats located on the 300L, 4850L and lastly the 800L at Homestake were developed by Arup. The quality of the cryostat cost estimate is also the same as for the reference design as it is based on the same cost estimating methodology used by the membrane cryostat vendor. The Arup cost estimates predate a value engineering proposal to place the cryogenic refrigerator nitrogen compressors on the surface and change the delivery of argon from the surface to underground from liquid to cold gas form. Adjustments to elements of the Arup cost estimate have been made to incorporate this proposal. This change also has significant impact on the conventional facilities by reducing underground space and electrical power requirements, and eliminating the need for pressure reducing stations periodically down the shaft.

The Arup cost estimate for the cryostat and cryogenic system were deconstructed in reference [35]. The Arup cost estimate for each major system included a break-down by equipment M&S cost, transportation cost to the underground cavern and labor costs for installation and testing. The cost estimate report included the relevant material take-off quantity for the system in some cases, e.g. cryostat surface area. For systems with no defined material take-off quantity, a reasonable scaling quantity was chosen, e.g. total liquid argon mass for one cryostat (24.64 kt) for the liquid filtration system.

The scaled cost of each system is split into a fixed and variable fraction. We make the assumption that equipment M&S costs scale almost linearly with the system size, i.e. the fixed cost fraction is small. This assumption is supported by comparing quotes for stainless steel pipe and cryogenic valves of varying sizes. We also make the assumption that labor costs are independent of the system size and are 100% fixed cost. This assumption is considered reasonable for systems that are within a factor of 2x of the Arup reference design.

Two factors were used to scale the cost of transporting materials to the work site. The Arup reference design assumed material would be transported through the Yates shaft and the transportation cost was estimated from the volume of material. For underground options, the transportation cost is scaled by the relevant material take-off quantity, e.g. cryostat surface area. The transportation cost for surface options is assumed to be 20% that of the underground options.

The Arup design included cryogenic piping to transport liquid argon from the surface to the 800L as well as nitrogen and argon vent lines. The estimate has been adjusted for the change from liquid to gas delivery of the argon. The piping includes 53m of horizontal and 500m of vertical run. The cost per meter of each pipe was identified from the piping line list. The unit cost for carbon steel pipe for the high pressure nitrogen lines is based on internet quotes. The resulting unit cost for each pipe size was used to estimate the installed cost for transfer piping for detectors at varying depths.

The Arup design report included a risk based contingency analysis and recommended assigning a 30% contingency to the cryogenic system. The contingency on the cryogenic system and cryostat was increased to 50% for estimating these options.

5.1.2 Estimates for Conventional Facilities at the Far Site

Developing cost models for the far site detector options began with the reference design at the Homestake 4850L cost estimate. The reference design was reconfigured into a "base case" spreadsheet model for each option which ensured that all project components were accounted for. Base case models were then scaled to apply to each detector size, location, and elevation option. All cost models were developed as part of an iterative process that incorporated more refined estimates as they were developed for the different components of the estimate models.

5.1.2.1 Surface CF Cost Models

Surface detector cost models for Ash River, Soudan and Homestake are all based on recent actual construction costs for rock excavation and surface structures from the NOvA project at Ash River with some site specific "site adapt" additions made to each site as appropriate. Using actual construction costs for the surface detector options allows a reduction in the construction cost contingency from 35% to 30%. For the Soudan and Ash River options only, construction management costs for all detector options were estimated to be 14% of the construction cost based on a S. Dixon analysis of NOvA change order costs.

The estimates for pit excavation and surface structure component for the surface detector options are at conceptual design level. The underground infrastructure (UGI) and surface utility cost model, and the construction management plus the University of Minnesota (UMN) construction administration cost models are at a pre-conceptual level of maturity.

5.1.2.2 Homestake Underground 4850L CF Cost Models

The 5, 17, and 34 kt underground excavation cost models were created by SURF engineers by applying the re-scoping assumptions to the reference design and then scaling these costs to develop the 5 kt, 17 kt and 34 kt cost models. The SURF/LBNE construction management team firm of Kiewit reviewed the reconfigured excavation cost models. The 5 kt and 17 kt excavation cost models applied to Homestake are not as mature as the 34 kt design.

UGI costs were initially reviewed and modified by SURF in a scaling exercise. A subsequent iteration involved a more rigorous examination of UGI costs by SURF and LBNE which resulted in UGI systems required for fire/life safety, or for early science at Homestake, being omitted from the LBNE scope and they became a SURF responsibility. One notable item are materials required for the rehabilitation of the Ross and Yates shafts, which were initially included in the LBNE cost estimate since SURF had not identified any other source of funding for them. Recently, they have stated that they believe that they will be able to identified a source, and these costs have been removed from the LBNE cost estimate. If they were restored to the LBNE budget, this would increase the cost of the underground options at Homestake by approximately $30M. Iterations by the SURF electrical engineer resulted in detailed electrical cost estimates based on modified detector specifications and requirements. This process also resulted in SURF's decision that some medium voltage electrical work would be performed by SURF employees. The UGI estimate for the reference design was scaled in response to scope modifications made to the reference design and is near a CD-1 level of maturity. The UGI estimates for 5 and 17 kt at Homestake are less mature than the 34 kt UGI estimate.

Surface infrastructure for the underground detector option, including surface structures, was estimated by SURF engineers. The construction management cost model applied to Homestake was developed by SURF engineers and includes SURF staff performing as the construction manager. The surface infrastructure estimate for 34 kt was scaled in response to scope modifications made to the reference design and is near a CD-1 level of maturity. The surface infrastructure estimates for 5 and 17 kt at Homestake are less mature than the 34 kt surface infrastructure estimate. The SURF construction manager model is at a pre-conceptual level of maturity.

5.1.2.3 Soudan Underground 27L CF Cost Models

Once underground facility locations and sizes were understood, the Homestake underground excavation cost models were applied to Soudan with some scaling of drift lengths. Initial estimates of the cost for the two new shafts and the headframe/hoist system required for Soudan were made. The initial estimate of the shaft cost was made on a cost-per-cubic-yard basis, using information from shaft estimates developed as part of the scope evolution of LBNE. Estimating shaft costs on a cubic-yard basis was known to be a flawed approach at the time; however, it was the only mechanism available at the time. Similarly, the initial estimate for the headframe/hoist used the cost model developed for the SURF alternate utility shaft hoist system developed as part of pre-CD-1 explorations of alternative within the development of the reference design. Attempts were made to scale this cost model to allow it to be applied to Soudan. This application was also known to be poor cost model to apply to Soudan because the requirements of each site were different.

Independent of the cost models described above, the U of MN contracted with the Minneapolis consulting firms of CNA Consulting Engineers and Itasca Consulting Group who were familiar to U of MN. CNA and Itasca developed independent cost estimates of the excavation for the caverns, drifts, and shafts, and for the headframe/hoist systems, which were reconciled with each other then compared to the LBNE cost models during a 2-day process in Minneapolis. The three cost models for the cavern and drift components of the scope were surprisingly comparable. The CNA and Itasca cost models for shafts and headframe/hoist systems were also comparable and, not surprisingly, varied from the initial LBNE estimates for these items. This allowed LBNE to abandon the flawed estimates for these items and adopt the average of the CNA and Itasca shaft and headframe/hoist estimates. The cavern and drift excavation cost models for the 34 kt model at Soudan is less mature than the reference design. The 5 kt and 17 kt cavern and drift excavation cost models applied to Soudan are not as mature as the 34 kt cost model. Shaft and headframe/hoist cost models at Soudan are pre-conceptual.

The UGI and surface components of the 27L detector options were developed by studying the existing infrastructure available at Soudan and site adapting and scaling the Homestake UGI and surface cost model to apply it to the Soudan site. Construction management costs for all detector options at Soudan were estimated to be 14% of the construction cost based on a S. Dixon analysis of NOvA change order costs. The Soudan UGI, surface component of the 27L models, and the construction management cost models are at a pre-conceptual level of maturity.

5.1.3 Estimates for Beamline and its Conventional Facilities

The estimate for the LBNE Beamline and its conventional facilities is largely based on the LBNE reference design. However, a significant number of value engineering proposals have been developed to lower the cost of the first phase relative to the reference design, and following internal review, many have been incorporated into the current cost estimate [21]. Some of these are design changes which lower the cost with at most minimal change in functionality, for example shortening the primary beamline or simplifying the foundation of the target hall service building. Others are staging of certain items, for example not installing water cooling in the target hall that is not needed for 700 kW operation, and future investment would be required in a later phase of LBNE. For the NuMI options, rough estimates have been made as to the level of investment that would be required to allow reliable operation at 700 kW for at least 10 years beyond the currently planned end of the NOvA run.

5.1.3.1 Options 1 and 2– Beamline to Homestake with and without NuMI components

The cost estimating methodology and the quality of the estimate for these options is similar to that of the LBNE reference design, including the assignment of contingency. In several cases the cost was adjusted by scaling the number of components (e.g., shortening of the primary beam), or solutions were adopted similar to NuMI without introducing additional risks.

For Option 1 (without NuMI components), the cost savings from the reference design is a total of $76.4M, evenly split between the Beamline and the Conventional Facilities. For Option 2 (with NuMI components), the savings is $47.7M in Beamline and $38.2M in Conventional Facilities, for a total of $85.9M. Details are shown in Table 2 in Section 3.3.2.

5.1.3.2 Option 3 – NuMI Beamline

Two categories of costs were considered in this scenario: calculable costs for reconfiguration, and costs associated with recovering from certain failures that may happen.

Calculable costs for reconfiguration:

The calculable costs include: costs for project and task management; costs to develop a target that can operate at 700 kW in the low neutrino energy configuration and develop/replace target hall instrumentation; costs to revert Horn 2 to the position required for the low energy configuration; studies needed to develop backup solutions for the decay pipe cooling and the absorber cooling; costs for updating of the controls system and costs related to retrofitting NuMI's LCW and RAW water cooling systems.

The cost estimates are of similar quality as those for the reference design. The calculable costs for the reconfiguration sum up to: $10 M TPC FY2010.

Costs associated with recovering from certain failures that may happen:

NuMI was originally designed for a 10 year life cycle at 400 kW of beam power. It has already run for seven years so far and the plan is that in 2014 in will start operating at 700 kW for at least 6 years. With extended running for the LBNE-alternate at 700 kW this approaches 30 years of operation of this Beamline, most of it at a beam power almost twice the original design.

Some systems that were not designed to be repairable may fail during this time. Although the probability of a failure is very hard to estimate, the following items could each be of the order of one year of downtime to mitigate if they fail and of the order of $10 M each: decay pipe cooling, absorber cooling, decay pipe window failure (developing a hole), tritium mitigation systems. The costs associated with these risks are rough estimates at this point and it would take engineering work of a few months to be able to have better quality estimates.

It is not clear at this moment which of these items would require mitigation prior to an extended run of the NuMI line and would therefore have to be included in the total project cost. For the sake of this exercise, an allowance of $10M has been included for the calculable costs plus $15M to cover a fraction of the cost of preventive mitigation of some of the identified major risk items. A 40% contingency has been added to these, yielding a TPC of $35M (FY2010).

5.1.4 Estimates for Near Detector

5.1.4.1 ND for Homestake FD

The lowest cost option, which is used in Phase 1 for the Homestake options, is to build only the muon monitor system that is placed immediately downstream of the absorber at the end of the decay pipe. In this case, the reference design cost estimate for this system is used, and the NDC project management cost is scaled accordingly.

For the Basic and Very Basic NDC designs, most detector elements are based on designs whose costs were estimated by the LBNE NDC project team for LBNE reference design; however, challenges associated with remote operation have only been considered for a few weeks. For the Enhanced Basic design, there are significant design differences when compared with the standard LBNE designs. More contingency has been applied to this design to accommodate the larger project risk. The cost of the shaft was included with the reference design. The minimal surface building would be 25% of the reference design cost, scaled by area.

5.1.4.2 ND for Soudan FD

The assumption for phase 1 is that the existing MINERvA and MINOS near detectors would serve as the near detector. In phase 2, an LBNE-type detector would be constructed. As noted in Section 3.4.2 a cost estimate has been made only for the FGD option, based on the FGD alternated design prepared for the Director's review. More extensive modifications would have to be made to the LAr design to fit it into the MINOS hall, and due to the short time, and the fact that the FGD cost estimate is believed to cover this case, no cost estimate has been done for the LAr near detector option. While there is significant contingency applied to these costs, they were developed quickly and must be considered to be relatively immature.

5.1.4.3 ND for Ash River FD

The same estimate maturity issues associated with the Soudan options are true here.

5.1.5 Project Management

The LBNE Project Office reference design cost estimate has been scaled in proportion to the square root of the prorated cost of each scenario. This somewhat arbitrary scaling formula was used in recognition that the project office costs are likely to scale more slowly than linearly with the total project cost. That is, a project of half the cost is likely to require somewhat more than half the project management cost.

5.1.6 Contingency

For the LBNE reference design cost estimates, contingency was developed in 3 pieces and added to the base costs to create the TPC (without escalation): estimate uncertainty, risk, and project manager's top-down [39]. For the estimates developed for the reconfiguration options, these pieces similarly applied to base costs. This section will describe this process, and the details of the calculations can be found in the Phased LBNE Cost Summary Excel workbook [40], as compiled by the LBNE Project Manager.

In the reference design cost estimate, estimate uncertainty contingency was applied as a percentage at the WBS level, based on the judgment of the estimator using rules developed by the Project to assess estimate maturity. This covers the uncertainty in the cost of building something, assuming that it is built as planned. This contingency was carried over or adjusted, based on new uncertainties by the L2 Project Managers in the estimates for the reconfiguration system options as discussed in each of the sections above. The base cost, plus estimate uncertainty contingency, was transmitted to the LBNE Project Manager, for inclusion into the overall options and configurations estimates.

For the reference design, risk assessment was performed, mitigations developed, and residual risk quantified for specific risks and WBS elements. The cost of residual risk was added to these specific WBS elements as the next piece of contingency in the cost estimates. For the reconfiguration system options, this same percentage level of risk contingency was included on the corresponding WBS elements, proportioned by cost. The one exception to this is the LAr far detector estimates, where the risk was incorporated by the L2 Project Manager into the estimate uncertainty, and therefore not double counted in the risk contingency application.

During the final development of the reference design cost estimates, an evaluation was done by the LBNE Project Manager of the level of contingency on each major system, and where deemed necessary, additional contingency applied top-down as the third piece of the contingency development. The L2 Subproject-specific top-down PM contingency is applied consistent with the reference design estimate, proportioning by the revised cost of the L2 Subproject. In addition,$50M that was held outside of any L2 Subproject in the reference design cost estimate was added to the TPC. For the reconfiguration system options, the corresponding level of contingency is effectively spread to the individual level 2 elements, such that the overall contingency is roughly the same as for the reference design.

In the summary cost estimate tables in Section 5.2, the sum of all three types of contingency is totaled in the column labeled “Total Contingency.”

5.1.7 Escalation

The LBNE reference design cost estimate was made in constant dollars, using FY2010 as the base year. Since the cost estimates for the various LBNE phasing options are based on those for the reference design, the same base year of FY2010 is used. The reference design costs were escalated based on a set of laboratory-specific labor and M&S escalation rates (one for BNL and Fermilab and another for LANL). These rates were obtained from the respective laboratory Budget Offices. An additional rate table was used for conventional facilities, which was obtained from an A/E consultant. These tables are given in the draft Project Management Plan [41]. A resource weighted average escalation factor (ratio of costs in a given year to those in the base year) is calculated using the escalation rates in [41] applied to the resources given in the reference design resource loaded schedule [39]. These escalation factors by fiscal year are shown in Table 3.

Table 3. Integrated escalation ratios of cost in each fiscal year relative to those in the base year FY2010.

Year	(Cost in FY)/(Cost in FY10)
FY10	1.000
FY11	1.011
FY12	1.024
FY13	1.057
FY14	1.094
FY15	1.151
FY16	1.186
FY17	1.220
FY18	1.261
FY19	1.314
FY20	1.319
FY21	1.348
FY22	1.374

To estimate an overall escalation factor for phase 1 of LBNE, a representative profile was made with a "reasonable" ramp up and ramp down at the beginning and end, with peak annual funding of $100M, and which integrates to $750M as-spent dollars for the period FY2013 – FY2022. The escalation values in Table 3 were applied to determine the de-escalated values each year. The escalated (at-year cost) and unescalated (FY2010 cost) profiles used for this exercise are shown in Fig. 1. The ratio of escalated to unescalated cost is 1.23. Based on this and to be conservative, an overall escalation factor of 1.25 was used to convert the FY2010 base-year cost estimate into an at-year cost estimate. Further details of the calculation can be found in [40]. It is worth noting that the escalation rates we use here are somewhat higher than those posted by the DOE Office of Science, Office of Project Assessment [42]. Using the rates in [42] would result in an approximately 5% ($35M) reduction in our escalated TPC estimates.

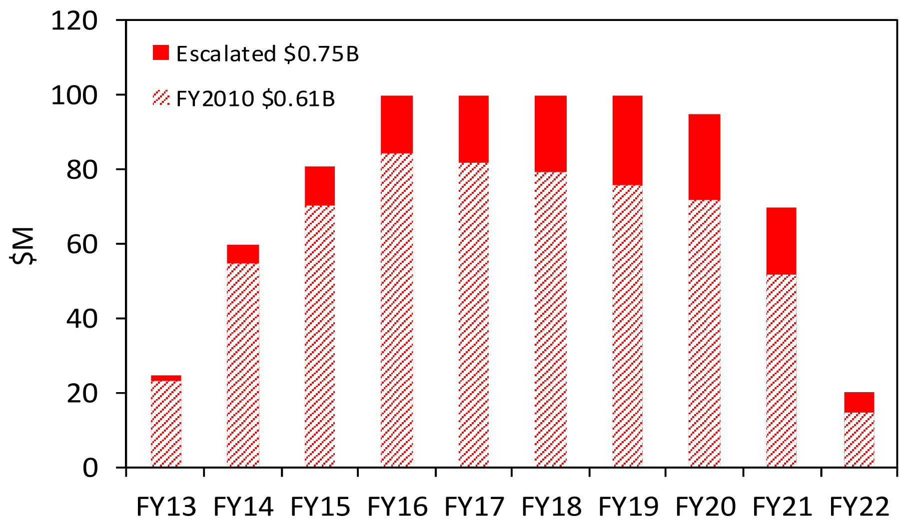

Fig. 1. Cost profile used for estimating overall escalation factor.

5.1.8 Cost Range Development

The cost estimates presented here are based on the LBNE reference design cost estimate, which is approaching CD-1 readiness. As part of preparation for CD-1, the LBNE Project developed a *cost range* for the reference design. This cost range was developed from an analysis of the reference design maturity and followed the procedures in the DOE Cost Estimating Guide DOE G 413.3-21 [43], using, as the DOE Guide recommends, the Association for the Advancement of Cost Engineering (AACE) cost range criteria table. The reference design cost estimate was thoroughly reviewed in a week-long Director's Review held 26-31 March [3] and was found to be sound: "the estimated cost ranges are realistic and consistent with the budgetary and technical objectives and are justified by the supporting documentation." The cost range presented ranged from 13% above to 25% below the point cost estimate, including all contingency factors [44]. Since the cost estimates presented here are based to the greatest extent possible on those developed for the reference design and are based on the same methodology, it is reasonable to estimate the cost range for each option using the same range relative to the point cost estimate, including all contingency factors. The range so obtained is shown, together with the point cost estimate, in the summary tables in Section 5.2.

5.2 Summary of Cost Estimates

Cost estimates for various phase 1 options have been assembled from the individual level 2 cost estimates described above and they are summarized in [40]. The following set of tables, taken from [40], summarize the cost estimates for five different options, each for several different far detector sizes. These options are:

0) Far detector only, located underground (4850L) at Homestake (Table 4).

1) Far detector on the surface at Homestake, LBNE beam, no near detector, muon detectors only (Table 5).

2) Far detector underground (4850L) at Homestake, LBNE beam, no near detector, muon detectors only (Table 6).

3) Far detector underground (2340 ft) at Soudan, NuMI low-energy beam, no new near detectors (Table 7).

4) Far detector on the surface at Ash River, NuMI low-energy beam, no new near detectors (Table 8).

In each table, cost estimates are shown for the Far Site (far detector and supporting conventional facilities), near site (beam, near detector systems and supporting conventional facilities), and the scaled project office cost. The base budget without contingency is show, together with the estimated total contingency, yielding the estimated total project cost in FY2010 dollars (TPC3). The contingency is typically about 40%, as it was for the reference design. The contingency is a bit higher for the underground than for the surface detector configurations, reflecting the greater uncertainty of underground construction, and a little higher for the Soudan or Ash River cases than the Homestake case, reflecting the lower maturity of the designs for the NuMI options. The escalation factor of 1.25, discussed in Section 5.1.7, is applied to give an estimated TPC in at-year (AY) dollars.

A cost range relative to the escalated TPC, as discussed in Section 5.1.8 is presented for each option. The effective contingency at the top end of the cost range is also shown. At the upper end of the cost range, the contingency is typically 55% to 60%, which we believe is adequate or even conservative given the maturity of the designs and the state of the cost estimate basis. That is, we believe that the upper end of the cost range represents a conservative upper bound on the cost of each option. Note also that the cost range goes below the at-year TPC value, reflecting the fact that there remain opportunities for reducing the cost of each of the options before the project is baselined.

In each table, for each option, the cost estimate is shown for detector masses of 5, 17 and 34 kt, for which specific cost estimating was done. Figures 2 and 3 plot the cost estimates versus detector mass for the LBNE (Homestake) and NuMI options respectively. Straight line fits are shown for each, together with the parameters of the fit. In all cases, the cost slope is roughly the same at about $15M/kt; the main difference is in the fixed cost offset, which is larger in the underground than the surface cases, and larger in the Homestake cases with beam than in the others. The cost difference between underground and surface implementation is about $130M at Homestake and about $175M at Soudan. The larger value at

Soudan reflects the need to provide two new shafts and roads and other facilities to access them, partially offset by the shallower depth than at Homestake.

Cost estimates for additional detector mass configurations are also shown in a number of the tables, to indicate detector masses which are consistent with the overall cost guideline that the TPC not exceed $700-800M. These are obtained by interpolating between the cost estimates for the three masses listed above and are highlighted in light blue each of Tables 4-8. Three of these – 10 kt on the surface at Homestake plus a new neutrino beam, 15 kt underground at Soudan, and 30 kt on the surface at Ash River – are the configurations that have been identified by the Steering Committee as viable options for a Phase 1 long-baseline experiment that have the potential to accomplish important science at realizable cost.

Table 4: Cost estimates for construction of a far detector underground at Homestake without a beam or near detector.

	FY2010 M$				AY M$		AY M$		*Top*
	Base				Esc.		Range		*End*
	Budget	Total	Cont.	TPC3	@ *1.25*		*0.75*	*1.13*	*Cont.*
34 kt detector at Homestake (4850) only									
Total	480	203	42%	657	**821**		610	930	*55%*
Project Office	36	13	36%	49	61				
Far Site Cost	444	190	43%	608	760				
25 kt detector at Homestake (4850) only									
Total	*424*	*180*	*42%*	*604*	***755***		*560*	*860*	*62%*
Project Office	*34*	*12*	*36%*	*47*	*58*				
Far Site Cost	*390*	*168*	*43%*	*557*	*697*				
17 kt detector at Homestake (4850) only									
Total	348	148	43%	496	**620**		460	700	*61%*
Project Office	31	11	36%	42	53				
Far Site Cost	317	137	43%	454	567				
5 kt detector at Homestake (4850) only									
Total	216	93	43%	308	**385**		290	440	*63%*
Project Office	24	9	36%	33	41				
Far Site Cost	191	84	44%	276	344				

Table 5: Cost estimates for construction of a beamline and far detector on the surface at Homestake.

	FY2010 M$				AY M$		AY M$		*Top*
	Base				Esc.		Range		*End*
	Budget	Total Cont.		TPC3	@ *1.25*		*0.75*	*1.13*	*Cont.*
34 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	644	247	38%	892	**1,115**		830	1270	*58%*
Project Office	42	15	36%	57	71				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	356	144	40%	499	624				
17 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	528	203	38%	730	**913**		680	1040	*58%*
Project Office	38	13	36%	51	64				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	243	100	41%	343	429				
10 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	*457*	*174*	*38%*	*631*	***789***		*590*	*900*	*58%*
Project Office	*35*	*13*	*36%*	*48*	*60*				
Near Site Cost	*247*	*89*	*36%*	*335*	*419*				
Far Site Cost	*175*	*73*	*42%*	*248*	*310*				
5 kt detector at Hometake (surface) + LBNE beam (phase 1) + no ND									
Total	406	154	38%	560	**700**		520	790	*55%*
Project Office	33	12	36%	45	56				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	127	53	42%	180	225				

Table 6: Cost estimates for construction of a beamline and far detector underground at Homestake.

	FY2010 M$				AY M$		AY M$		*Top*
	Base				Esc.		Range		*End*
	Budget	Total Cont.		TPC3	@ *1.25*		*0.75*	*1.13*	*Cont.*
34 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	735	295	40%	1,004	**1,255**		940	1420	*54%*
Project Office	45	16	36%	61	76				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	444	190	43%	608	760				
17 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	604	241	40%	845	**1,056**		790	1200	*59%*
Project Office	41	15	36%	56	69				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	317	137	43%	454	567				
10 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	*530*	*210*	*40%*	*740*	***926***		*690*	*1050*	*58%*
Project Office	*38*	*14*	*36%*	*52*	*65*				
Near Site Cost	*247*	*89*	*36%*	*335*	*419*				
Far Site Cost	*245*	*108*	*44%*	*353*	*441*				
5 kt detector at Hometake (4850) + LBNE beam (phase 1) + no ND									
Total	474	186	39%	660	**825**		620	940	*59%*
Project Office	36	13	36%	49	61				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	191	84	44%	276	344				

Table 7: Cost estimates for construction of a far detector underground at Soudan, including an allowance for necessary investments in the NuMI beamline to permit reliable long-term operation

	FY2010 M$				AY M$	AY M$		*Top*
	Base				Esc.	Range		*End*
	Budget	Total	Cont.	TPC3	@ *1.25*	*0.75*	*1.13*	*Cont.*
34 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND								
Total	529	220	0.42	749	**936**	700	1060	*60%*
Project Office	38	14	36%	52	65			
Near Detector			-					
NuMI upgrades/maintenance	25	10	40%	35	44			
Far Site Cost	465	196	42%	662	827			
17 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND								
Total	403	169	0.42	572	**715**	530	810	*61%*
Project Office	33	12	36%	45	57			
Near Detector			-					
NuMI upgrades/maintenance	25	10	40%	35	44			
Far Site Cost	345	147	43%	492	615			
15 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND								
Total	*385*	*162*	*42%*	*540*	***675***	*500*	*770*	*60%*
Project Office	*32*	*12*	*36%*	*44*	*55*			
Near Detector			-					
NuMI upgrades/maintenance	*25*	*10*	*40%*	*35*	*44*			
Far Site Cost	*328*	*141*	*43%*	*461*	*577*			
5 kt detector at Soudan (2340) + NuMI LE Beam (700 kW) + no ND								
Total	269	113	0.42	382	**477**	360	540	*61%*
Project Office	27	10	36%	37	46			
Near Detector			-					
NuMI upgrades/maintenance	25	10	40%	35	44			
Far Site Cost	217	93	43%	310	387			

Table 8: Cost estimates for construction of a far detector on the surface at Ash River, including an allowance for necessary investments in the NuMI beamline to permit reliable long-term operation. The cost of detectors on the surface at Soudan would be very similar.

	FY2010 M$				AY M$		AY M$		*Top*
	Base				Esc.		Range		*End*
	Budget	Total	Cont.	TPC3	@ *1.25*		*0.75*	*1.13*	*Cont.*
34 kt detector at Ash River (surface) + NuMI LE beam (700 kW) + no ND									
Total	419	167	40%	586	**732**		550	830	*59%*
Project Office	34	12	36%	46	57				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	360	145	40%	505	631				
30 kt detector at Ash River (surface) + NuMI LE Beam (700 kW) + no ND									
Total	*391*	*156*	*40%*	*547*	***684***		*510*	*780*	*60%*
Project Office	*33*	*12*	*36%*	*44*	*55*				
Near Detector			-						
NuMI upgrades/maintenance	*25*	*10*	*40%*	*35*	*44*				
Far Site Cost	*333*	*135*	*40%*	*468*	*585*				
17 kt detector at Ash River (surface) + NuMI LE beam (700 kW) + no ND									
Total	300	121	41%	421	**527**		390	600	*60%*
Project Office	29	10	36%	39	48				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	246	101	41%	348	435				
5 kt detector at Ash River (surface) + NuMI LE beam (700 kW) + no ND									
Total	174	71	41%	245	**306**		230	350	*61%*
Project Office	21	8	36%	29	36				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	128	53	42%	181	226				

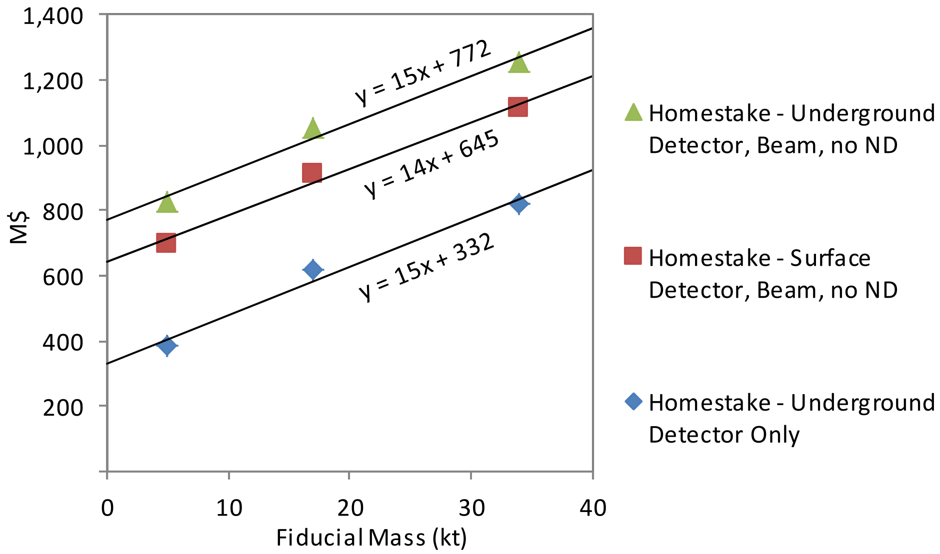

Fig. 2. Total Project Cost versus far detector fiducial mass for Homestake options.

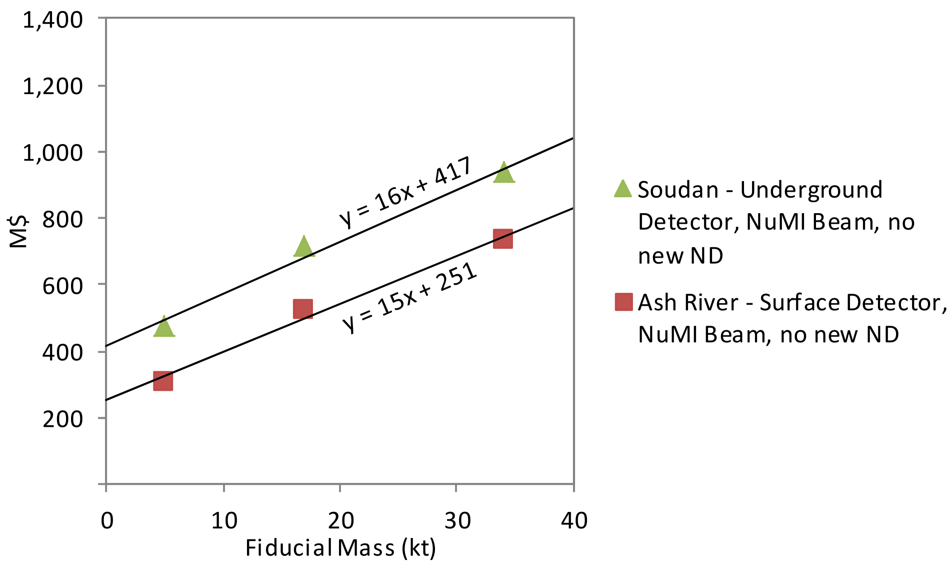

Fig. 3. Total Project Cost versus far detector fiducial mass for NuMI options.

6 Conclusions

Based on the well-developed Conceptual Design and corresponding cost estimates for the LBNE Project, a large number of potential configurations for phasing LBNE alternates to it have been studied for technical feasibility and to estimate their costs, including full contingency and escalation estimates. The cost guideline is that the first phase should have an estimated Total Project Cost no more than $700-800M, and that the CD-1-type cost range should be consistent with the LBNE CD-0 cost range of $660-940M. In parallel with this effort, the Physics Working Group studied the science capabilities of a similar set of options, evaluating their capabilities for accelerator-based neutrino oscillation measurements as well as non-accelerator physics: proton decay searches, sensitivity to supernova neutrinos, and measurements with atmospheric neutrinos. Based on the combination of the physics and cost information, the Steering Committee identified three phase one options that would provide significant scientific results and are consistent with the budget guideline that the first phase cost should be limited to $700-800M, including contingency and escalation. These three are:

- 30 kton surface detector at Ash River (NuMI low energy beam, 810 km baseline)
- 15 kton underground (2340 ft) detector at Soudan (NuMI low energy beam, 735 km baseline)
- 10 kton surface detector at Homestake (new beamline, 1,300 km baseline)

Their estimated costs are summarized and compared in Table 9. All three are consistent with the cost guidelines and with the CD-0 cost range; however, the first two are moderately less expensive than the third.

Each of these first-phase options is more sensitive than the others in some particular physics domain, but none of them is configured with the long baseline and underground detector that is needed to be able to achieve all of the main science goals of LBNE. The Steering Committee strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface. The physics reach of this first phase is very strong; more over this option is seen by the Steering Committee as a start of 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. Ultimately this option would exploit the full power provided by Project X. With an additional investment of an estimated $135M, it would be possible to place the 10 kton detector underground at Homestake, which would provide all of the elements needed to begin to address the full range of research envisioned for LBNE.

Table 9: Comparison of cost estimates for the three options identified by the Steering Committee as viable options for a Phase 1 long-baseline neutrino experiment.

	FY2010 M$				AY M$		AY M$		Top
	Base				Esc.		Range		End
Option	Budget	Total	Cont.	TPC3	@ 1.25		0.75	1.13	Cont.
30 kt detector at Ash River (surface) + NuMI LE Beam (700 kW) + no new ND									
Total	391	156	40%	547	**684**		510	780	60%
Project Office	33	12	36%	44	55				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	333	135	40%	468	585				
15 kt detector at Soudan (2340 ft depth) + NuMI LE Beam (700 kW) + no new ND									
Total	385	162	42%	540	**675**		500	770	60%
Project Office	32	12	36%	44	55				
Near Detector			-						
NuMI upgrades/maintenance	25	10	40%	35	44				
Far Site Cost	328	141	43%	461	577				
10 kt detector at Hometake (surface) + LBNE beam + muon monitors									
Total	457	174	38%	631	**789**		590	900	58%
Project Office	35	13	36%	48	60				
Near Site Cost	247	89	36%	335	419				
Far Site Cost	175	73	42%	248	310				

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Note: References to LBNE documents (lbne-doc-nnnn) refer to the most recent version as of the time of the writing of this report. More recent versions may exist with updated information that is not included in this report.

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