LBNE Reconfiguration

Steering Committee Report

August 6, 2012

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Executive Summary

Introduction

The Department of Energy (DOE) Office of Science (SC) is planning investments in the next generation neutrino experiment, the 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 produced an interim report and presented it to Pier Oddone on June 4. Pier Oddone briefed the interim conclusions to Dr. Brinkman on June 6. On June 29, Dr. Brinkman wrote a letter to Pier Oddone, asking the laboratory to proceed with planning a Critical Decision 1 review later this year based on the reconfigured LBNE options that we presented. Dr. Brinkman's letter is given to *Appendix C*.

The Steering Committee had twelve conference call meetings and had two face-to-face meetings on April 26, 2012 and May 22-23, 2012 at Fermilab. The Steering Committee organized and held a workshop on April 25-26, 2012 at Fermilab to inform the high-energy physics community, to discuss the status of the work in progress and to seek input from the community. *Appendix D* 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 the LBNE and other neutrino experiment collaborations to carry out the studies. Each working group provided a report of their analysis and their reports can be found at http://www.fnal.gov/directorate/ lbne_reconfiguration/. 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, including 6 U.S. national laboratories, from 5 countries.

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 including underground detector only options (no accelerator-base neutrino beam) and a range of baselines from the existing 700-800 km available with Fermilab's NuMI beam to as far as 2,600 km, 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:
	  ○ 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.

The LBNE collaboration has conducted initial studies to verify whether the cosmic ray backgrounds are manageable for the operation of LAr-TPCs on the surface. The studies were concentrated on photon induced cascades as the major source of background events, as this is potentially the most serious problem. Two independent techniques have been investigated to reduce these backgrounds using the ability of the LAr detector to reconstruct muon tracks and electron showers and separate electron- from gamma-induced showers. Both techniques have been shown to be viable, even without the assumption of a photon trigger system or fast timing veto. It was found that a combination of simple cuts together with the low (2%) expected probability of e-γ misidentication can reject this background to a level well below the expected ν_e appearance signal. Studies will continue in the next few months. In addition, the shorter drift distance for surface options is chosen to mitigate the effects of space charge build-up due to cosmic rays. Detailed information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

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. For the Homestake case, the LBNE collaboration has examined strategies to maintain the initial scientific performance without a full near detector complex. Although detailed evaluation must await full simulations, the conclusion is that there are viable strategies that will be adequate for the initial period of LBNE running. However, a complete LBNE near detector system will be required in a later stage to achieve the full precision of the experiment. Studies will continue as the design of LBNE is developed. Details information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

Studies have been done to understand the possibilities for optimizing the NuMI beamline for a lower-neutrino-energy spectrum and a higher flux to enhance the physics sensitivity for the two NuMI options. The conclusion is that modest increases in the flux below 2 GeV are possible, but that no options for large gains are known. Detailed information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

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; it would determine the mass hierarchy and explore the CP-violating phase δ_{CP}, and measure other oscillation parameters: θ_{13}, θ_{23}, and $|\Delta m^2_{32}|$. Moreover 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. Subsequent phases will include:

- A highly capable near neutrino detector, which will reduce systematic errors on the oscillation measurements and enable a broad program of short-baseline neutrino physics.
- An increase in far detector mass to 35 kton fiducial mass placed at the 4850 ft level, which will further improve the precision of the primary long-baseline oscillation measurements, enable measurement of more difficult channels to make a fully comprehensive test of the three-neutrino mixing model, and open or enhance the program in non-accelerator-based physics, including searches for baryon-number-violating processes and measurements of supernova neutrinos.
- A staged increase in beam power from 700 kW to 2.3 MW with the development of Project X, which will enhance the sensitivity and statistical precision of all of the long- and short-baseline neutrino measurements.

The actual order and scope of the subsequent stages would depend on where the physics leads and the available resources.

At the present level of cost estimation, it appears that this preferred option may be ~15% more expensive than the other two options, but cost evaluations and value engineering exercises are continuing.

Although the preferred option has the required very long baseline, the 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 in 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. Additional national or international collaborators have the opportunity to increase the scope of the first phase of LBNE or accelerate the implementation of subsequent phases. In particular, partnerships with institutions and agencies could add sufficient additional resources to place the initial 10 kton LAr TPC detector 4850 feet underground and provide a full near detector in the first phase. Studies of proton decay and neutrinos from supernova collapse are complementary to those being performed with existing water Cerenkov detectors. For the study of supernova collapse, LAr TPCs are sensitive to neutrinos whereas water Cerenkov detectors are sensitive to antineutrinos; for the study of proton decay, the LAr TPC is much more sensitive to the decay of protons into kaons as preferred by supersymmetric theories. There are also a large number of other nucleon decay modes for which liquid argon has high detection efficiency. Detection of even a single event in any of these modes would be revolutionary for particle physics.

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 → 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 matter 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	
$\lvert\Delta m^2_{32}\rvert$	$(2.35 \pm 0.12) \times 10^{-3}$ 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.

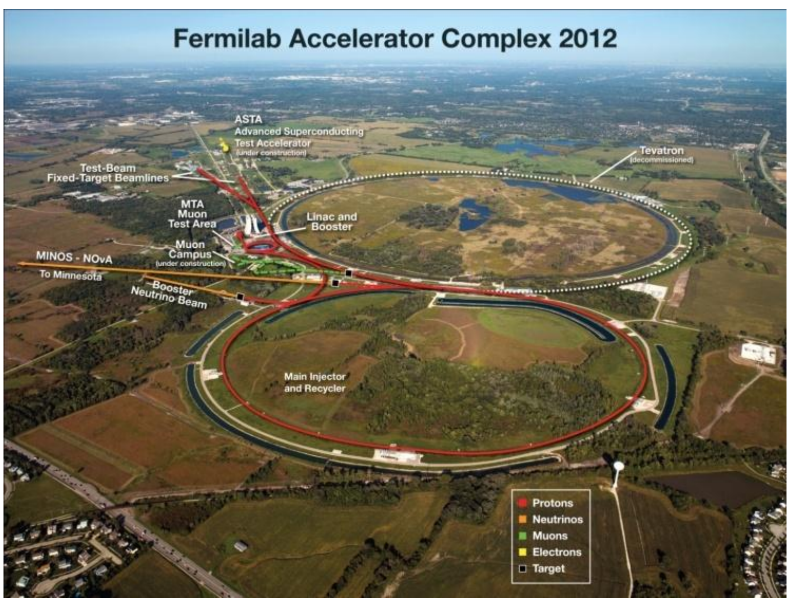

Figure 1. Fermilab's accelerator facility consists of a 400 MeV linear accelerator, 8 GeV Booster accelerator and 120 GeV Main Injector synchrotron. The complex delivers proton beams to a variety of target stations: 8 GeV protons to the Booster Neutrino Beam target and 120 GeV protons to the NuMI target,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

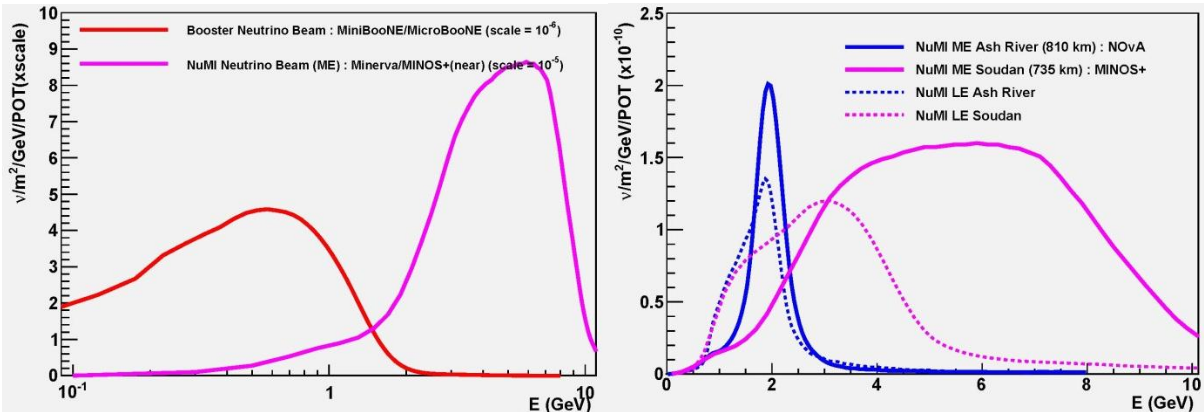

Figure 2. (Left) Energy distributions of neutrinos from the 8 GeV Booster and the 120 GeV Main Injector; (Right) Energy distributions of neutrinos from the 120 GeV Main Injector at Soudan (MINOS) and Ash River (NOvA) for low-energy and medium-energy target options.

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.

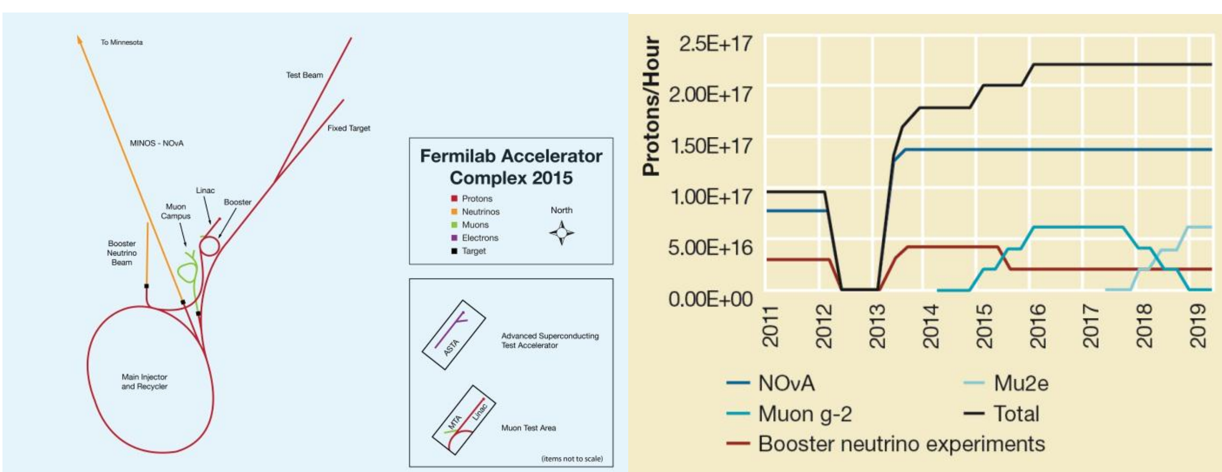

*Figure 3. Layout of the accelerator complex (left) and the total number of protons needed for Fermilab's NOvA neutrino experiments and Muon g-2 and Mu2e experiments through 2020 (right)***.**

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 for other experiments to make the most accurate determination of oscillation parameters.

Physics goal	2011	2013	2015	2017	2019	2021
Constrain mass hierarchy			NOvA			
Sterile neutrino sector						
Appearance	MiniBooNE	MicroBooNE				
Disappearance		MINOS+				
Establish framework						
Precision mass difference	MINOS					
Neutrino interaction rates with nuclei	MINERvA					
Confirm θ_{13} through appearance		NOvA				

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.

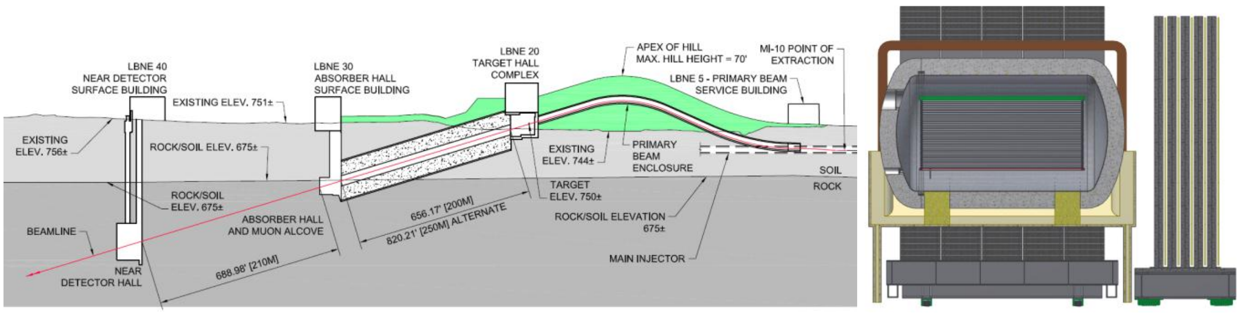

Figure 5. Layout of the LBNE beamline (left) and the near detector (right).

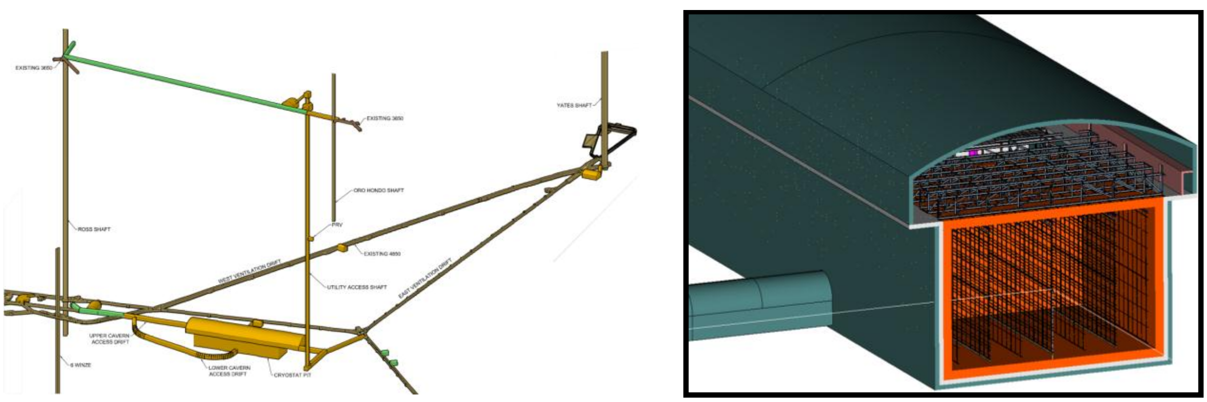

Figure 6. Layout of the underground facility at Homestake (left) and the LAr-TPC far detector (right).

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. A 1,300 km baseline is the ideal distance for resolving the neutrino mass hierarchy and maintaining significant reach for CP violation as illustrated in Figure 7. 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.

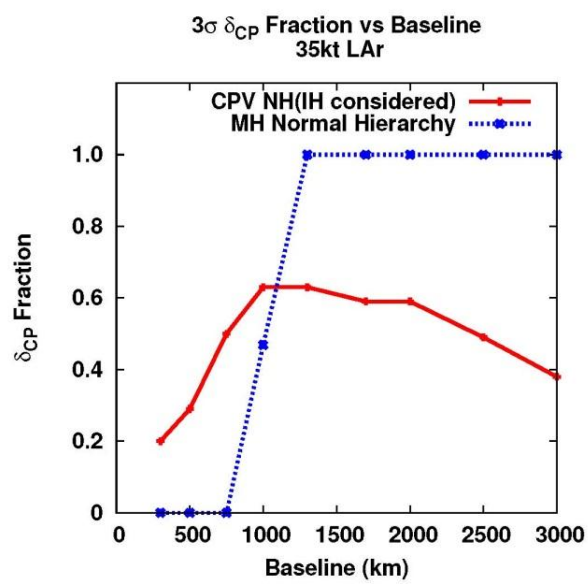

Figure 7. Fraction of δ_{CP} values covered for a 3σ measurement of the mass hierarchy (blue curve) and CP violation (red curve) as a function of baseline for a 35 kton (fiducial mass) LAr detector in 5+5 years of neutrino+antineutrino running in a 700 kW beam for assuming $\sin^2 2\theta_{13}$=0.095.. This shows that the beam from Fermilab to Homestake is optimized for CP measurements and that the experiment can definitively resolve the mass hierarchy. The energy of the first oscillation maximum increases with baseline, so the beam focusing is adjusted to optimize the spectrum in the oscillation probability.

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 8 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).

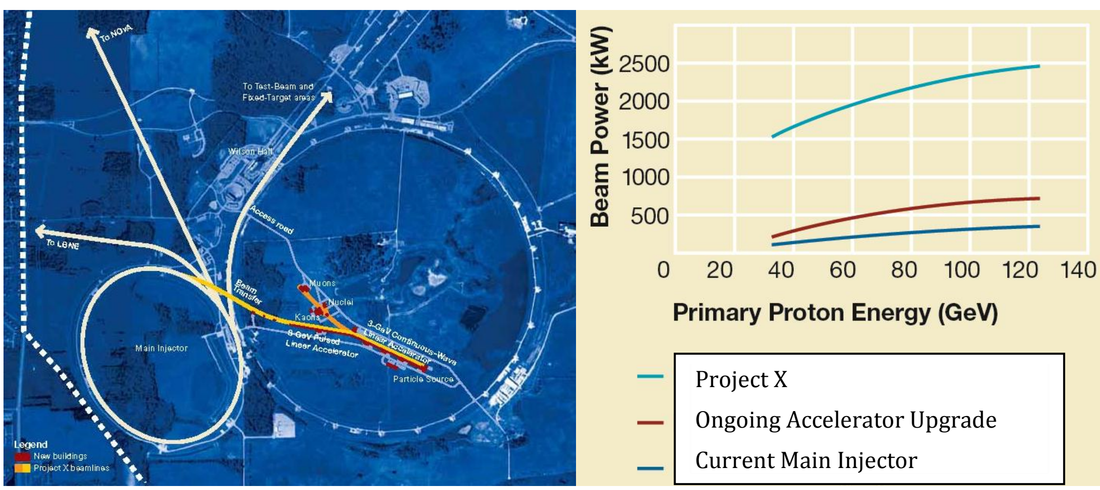

Figure 8. Layout of Project X (left) and beam power from the Main Injector for three neutrino facilities: the existing NuMI beam, the ongoing accelerator upgrade and Project X (right).

Fermilab has developed a phased approach for Project X, leveraging existing accelerator assets at the Fermilab accelerator facility. The first stage 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. Detailed information on the physics program of the first stage of Project X is documented and available at http://www.fnal.gov/

directorate/lbne_reconfiguration/. 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.

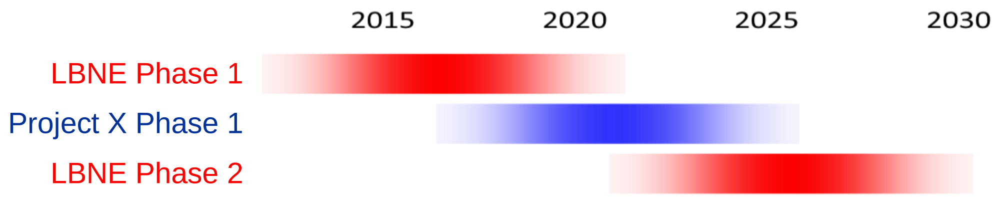

Figure 9. Potential timeline for various phases of LBNE and Project X.

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 10 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 ± 0.006 (or $\theta_{13} = 8.8^o \pm 0.3^o$)[1] 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 11. Physics capabilities are described in more detail in the Physics Working Group Report (http://www.fnal.gov/directorate/lbne_reconfiguration/).

[1] The assumed uncertainty on θ_{13} is the ultimate uncertainty expected from the reactor experiments.

*Table 2. Summary of the oscillation measurements with various configurations given θ_{13} = 8.8°, θ_{23} = 40°, and Δm^2_{31} = +2.27 x $10^{-3}eV^2$. 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_{31}^2) ν ($10^{-3}eV^2$)	σ(Δm_{31}^2) 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					

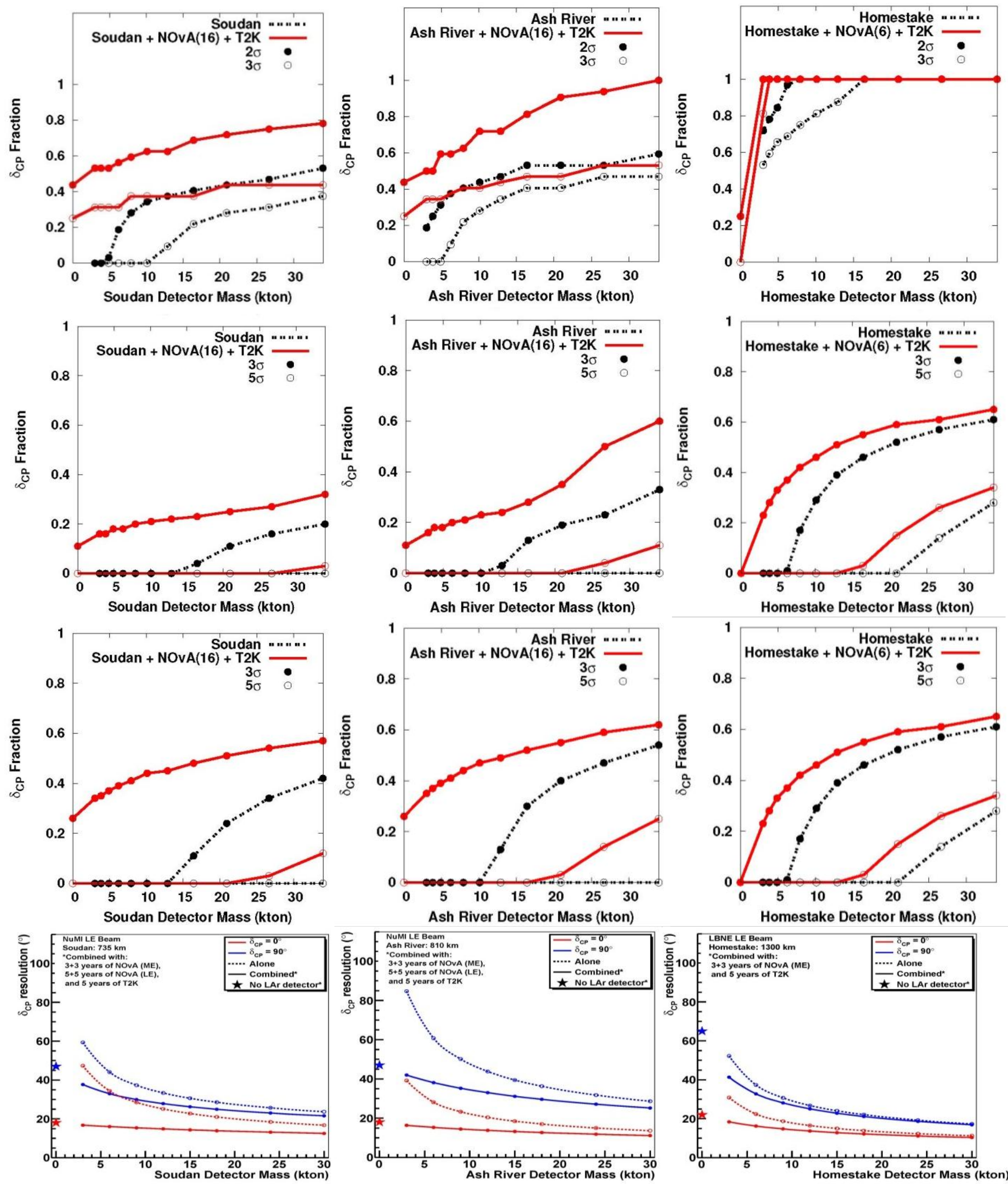

*Figure 10. The plots from top to bottom: the fraction of δ_{CP} values for which **the mass hierarchy** can be resolved at 2/3σ (solid/open points), **CP violation** can be resolved at 3/5σ (solid/open points), and **CP violation** can be resolved at 3/5σ (solid/open points) when the mass ordering is known, and **the 1σ resolution on the measurement of δ_{CP}** for δ_{CP} = 0 (red), $\pi/2$ (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} = $8.8^o \pm 0.3^o$ 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.*

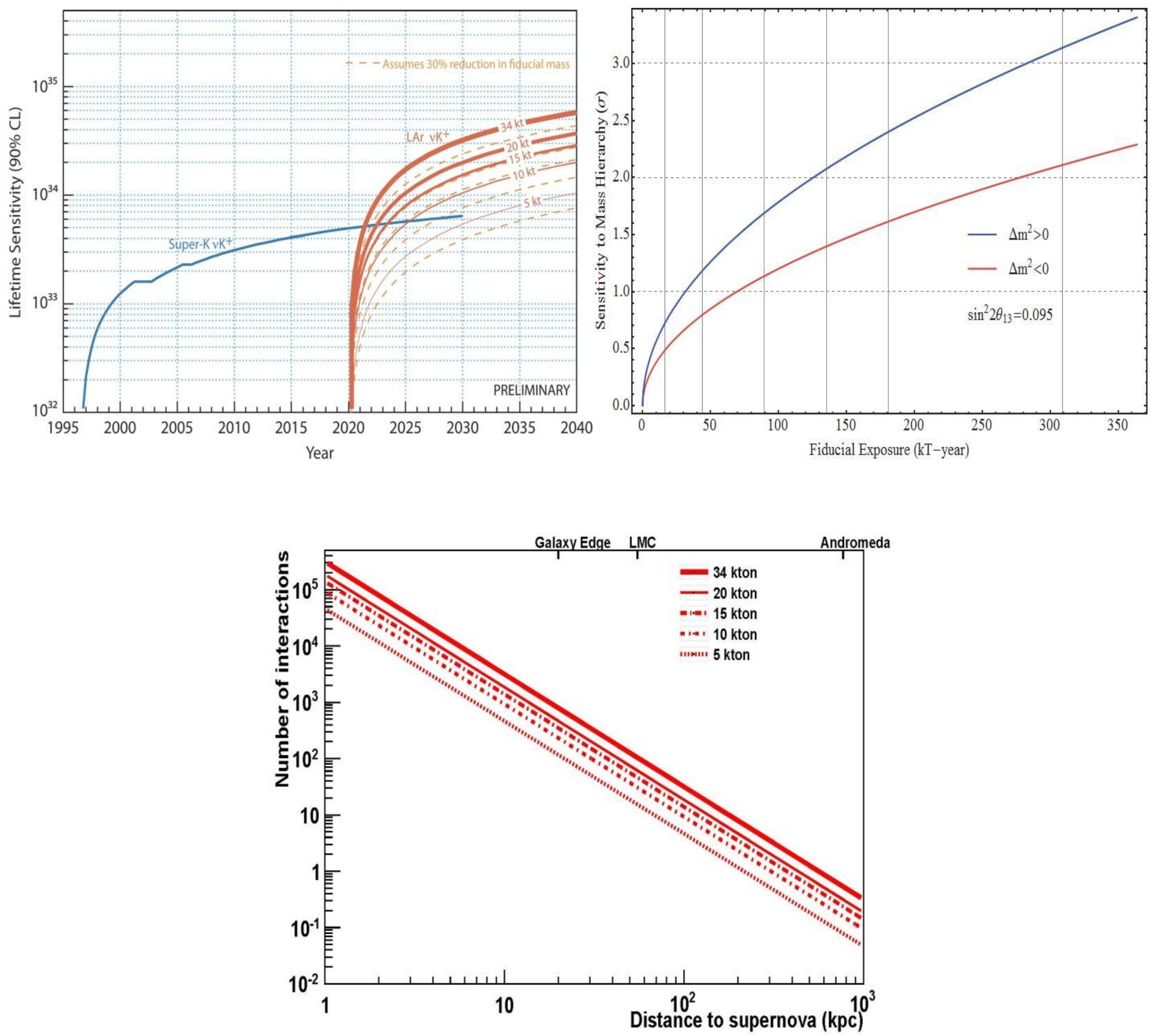

Figure 11. (Top-left) The 90% CL proton lifetime limit in the proton decay mode, p → Kν, in units of years as a function of time for Super-Kamiokande compared to different LAr-TPC masses at the Homestake 4850 ft level starting in 2020. The dashed lines show the limit for the Soudan 2340 ft level option, 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 (~$40M), 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. Photon detectors and a 37% reduction in the drift length relative to the underground design are included in the current cost estimates, but a top veto system is not. Cost estimates are still very preliminary and evaluations and value engineering exercises are in progress.

Figure 12 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 the Engineering/Cost Working Group Report (http://www.fnal.gov/directorate/lbne_reconfiguration/).

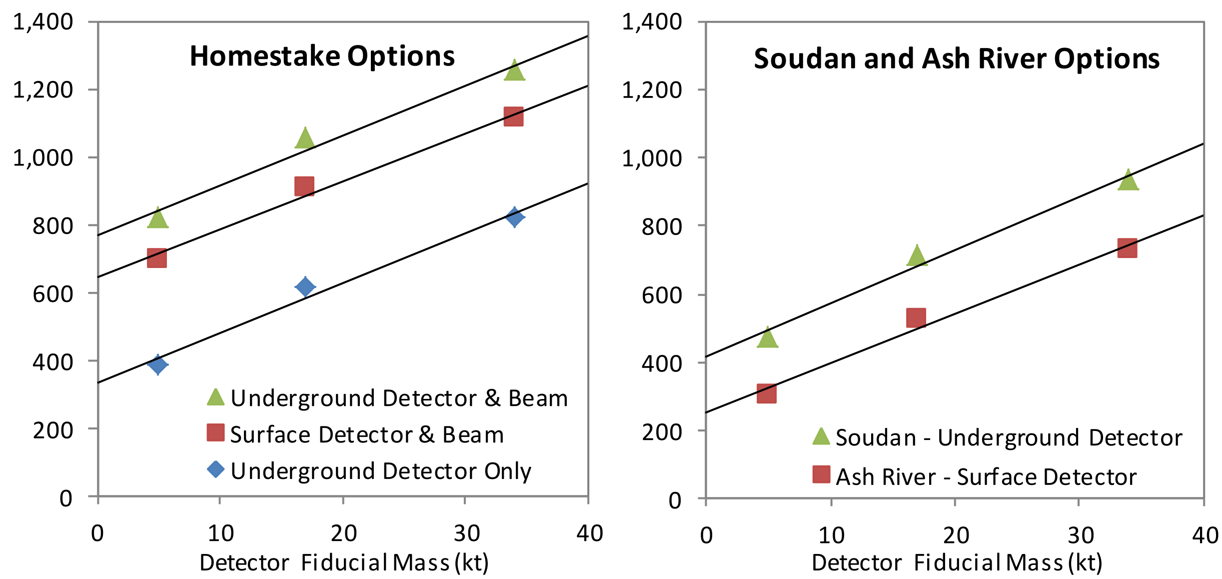

Figure 12. Cost estimates ($M), including contingency and escalation, as a function of LAr-TPC detector mass at Homestake (left) and Soudan and Ash River (right). Straight lines are linear fits.

5. 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 including underground detector only options (no accelerator-base neutrino beam) and a range of baselines from the existing 700-800 km available with Fermilab's NuMI beam to as far as 2,600 km, 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 6×10^{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 $p \rightarrow K\nu$ 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 $\delta=\pi/2$ 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

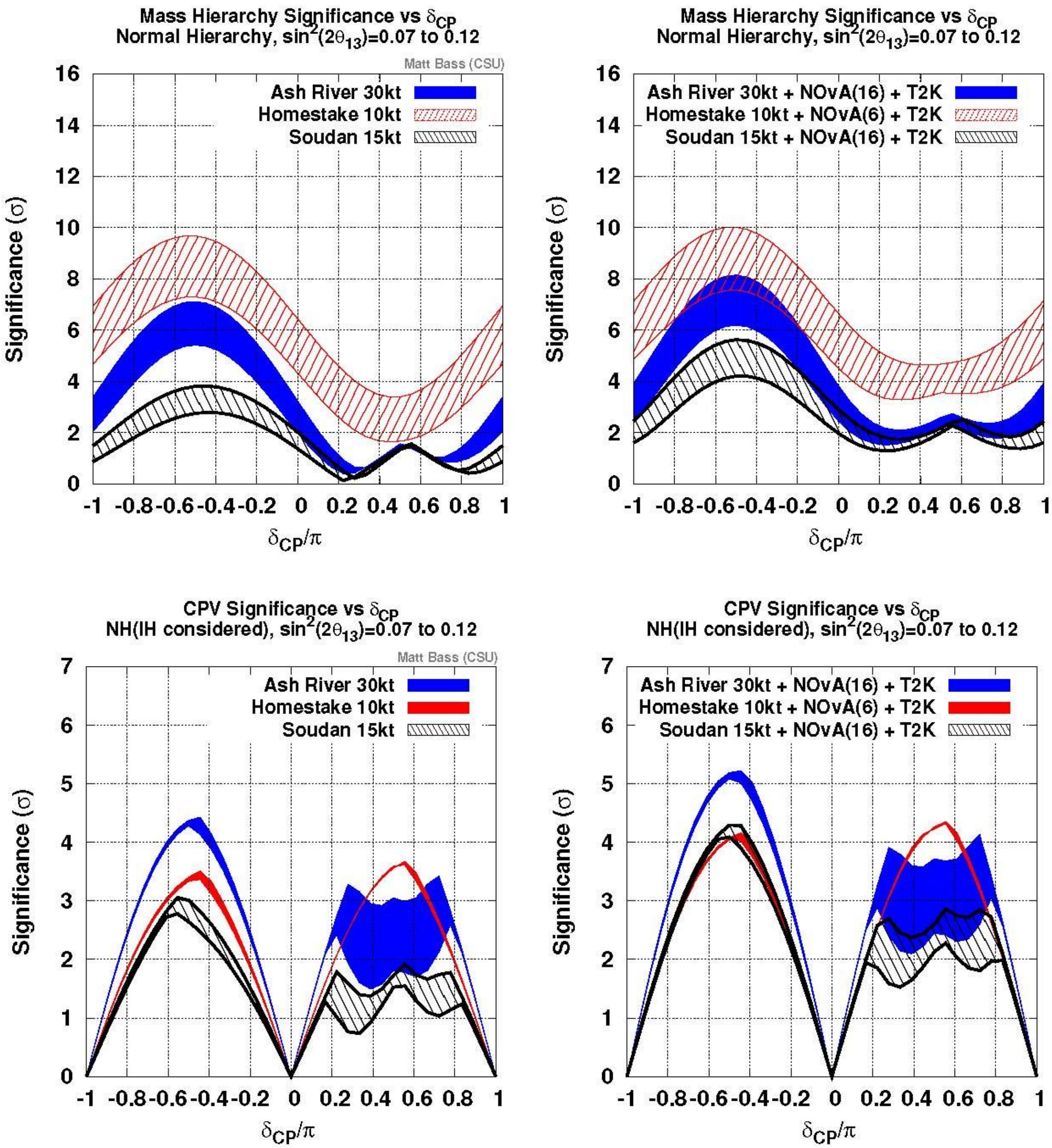

Figure 13. The significance with which the mass ordering (top) and CP violation (bottom) is resolved with a 10 kton surface detector at Homestake (red), a 30 kton surface detector at Ash River (blue), and a 15 kton underground detector at Soudan (black) as a function of the unknown CP violating phase 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: 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.

The LBNE collaboration has conducted initial studies to verify whether the cosmic ray backgrounds are manageable for the operation of LAr-TPCs on the surface. The studies were concentrated on photon induced cascades as the major source of background events, as this is potentially the most serious problem. Two independent techniques have been investigated to reduce these backgrounds using the ability of the LAr detector to reconstruct muon tracks and electron showers and separate electron- from gamma-induced showers. Both techniques have been shown to be viable, even without the assumption of a photon trigger system or fast timing veto. It was found that a combination of simple cuts together with the low (2%) expected probability of e-γ misidentication can reject this background to a level well below the expected ν_e appearance signal. Studies will continue in the next few months. In addition, the shorter drift distance for surface options is chosen to mitigate the effects of space charge build-up due to cosmic rays. Detailed information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

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. For the Homestake case, the LBNE collaboration has examined strategies to maintain the initial scientific performance without a full near detector complex. Although detailed evaluation must await full simulations, the conclusion is that there are viable strategies that will be adequate for the initial period of LBNE running. However, a complete LBNE near detector system will be required in a later stage to achieve the full precision of the experiment. Studies will continue as the design of LBNE is developed. Details information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

Studies have been done to understand the possibilities for optimizing the NuMI beamline for a lower-neutrino-energy spectrum and a higher flux to enhance the physics sensitivity for the two NuMI options. The conclusion is that modest increases in the flux below 2 GeV are possible, but that no options for large gains are known. Detailed information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

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; it would determine the mass hierarchy and explore the CP-violating phase δ_{CP}, and measure other oscillation parameters: θ_{13}, θ_{23}, and $|\Delta m^2_{32}|$. Moreover 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. Subsequent phases will include:

- A highly capable near neutrino detector, which will reduce systematic errors on the oscillation measurements and enable a broad program of short-baseline neutrino physics.
- An increase in far detector mass to 35 kton fiducial mass placed at the 4850 ft level, which will further improve the precision of the primary long-baseline oscillation measurements, enable measurement of more difficult channels to make a fully comprehensive test of the three-neutrino mixing model, and open or enhance the program in non-accelerator-based physics, including searches for baryon-number-violating processes and measurements of supernova neutrinos.
- A staged increase in beam power from 700 kW to 2.3 MW with the development of Project X, which will enhance the sensitivity and statistical precision of all of the long- and short-baseline neutrino measurements.

The actual order and scope of the subsequent stages would depend on where the physics leads and the available resources.

At the present level of cost estimation, it appears that this preferred option may be ~15% more expensive than the other two options, but cost evaluations and value engineering exercises are continuing.

Although the preferred option has the required very long baseline, the 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 in 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. Additional national or international collaborators have the opportunity to increase the scope of the first phase of LBNE or accelerate the implementation of subsequent phases. In particular, partnerships with institutions and agencies could add sufficient additional resources to place the initial 10 kton LAr TPC detector 4850 feet underground and provide a full near detector in the first phase. Studies of proton decay and neutrinos from supernova collapse are complementary to those being performed with existing water Cerenkov detectors. For the study of supernova collapse, LAr TPCs are sensitive to neutrinos whereas water Cerenkov detectors are sensitive to antineutrinos; for the study of proton decay, the LAr TPC is much more sensitive to the decay of protons into kaons as preferred by supersymmetric theories. There are also a large number of other nucleon decay modes for which liquid argon has high detection efficiency. Detection of even a single event in any of these modes would be revolutionary for particle physics.

Appendix A: March 19th 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 U.	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 U.	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
Jeff Appel, FNAL	LBNE Reconf. Steering Committee's Scientific Secretary

Physics Working Group	Engineering / Cost Working Group
Jeff Appel, FNAL Matthew Bass, Colorado State Univ. Mary Bishai, BNL Steve Brice, FNAL Ed Blucher, U. Chicago Daniel Cherdack, Tufts Milind Diwan, BNL Bonnie Fleming, Yale Gil Gilchriese, LBNL Zeynep Isvan, BNL Byron Lundberg, FNAL Bill Marciano, BNL Mark Messier, Indiana U. Stephen Parke, FNAL Mark Reichanadter, SLAC Gina Rameika, FNAL Kate Scholberg, Duke U. Mel Shochet, U. Chicago (Chair) Jenny Thomas, UCL Bob Wilson, U. Colorado Elizabeth Worcester, BNL Charlie Young, SLAC Sam Zeller, FNAL	Jeff Appel, FNAL Bruce Baller, FNAL Jeff Dolph, BNL Mike Headley, SURF Tracy Lundin, FNAL Marvin Marshak, U. Minnesota Christopher Mauger, LANL Elaine McCluskey, FNAL Bob O'Sullivan, FNAL Vaia Papadimitriou, FNAL Mark Reichanadter, SLAC (Chair) Joel Sefcovic, FNAL Jeff Sims, ANL Jim Stewart, BNL Jim Strait, FNAL (Deputy Chair)

Appendix C: June 29th Brinkman Letter to Oddone in response to the Interim Report

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

June 29, 2012

Dear Pier,

I would like to thank you and your management team for your recent presentation on the revised plans for the Long Baseline Neutrino Experiment (LBNE). The steering group and project team have done an excellent job responding to our request to reconfigure the project in ways that lead to an affordable and phased approach that will enable important science results at each phase. The report of the LBNE steering group outlining the options and alternatives considered provides clear and thoughtful input to our strategic plan for the Intensity Frontier program.

We would like you to proceed with planning a Critical Decision 1 review later this year based on the reconfigured LBNE options you presented. Please work with Jim Siegrist and Dan Lehman on the timing of this review.

I am hopeful that we can put the LBNE project on a sustainable path and thereby secure a leadership position for Fermilab in the Intensity Frontier. We look forward to working with you to achieve this goal.

Sincerely yours,

W.F. Brinkman

Printed with soy ink on recycled paper

Appendix D: 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