

December 18, 2014

Version 11

Experimental program at the Long- Baseline Neutrino Facility (ELBNF)

Letter of Intent Submitted to the PAC

December 22, 2014

Experimental program at the Long-Baseline Neutrino Facility

1.0 Executive Summary and Introduction

This Letter of Intent (LOI) is a proposal by a global neutrino community to pursue an accelerator-based long-baseline neutrino experiment, as well as neutrino astrophysics and nucleon decay, with an approximately 40-kton (fiducial mass) modular liquid argon TPC (LAr-TPC) detector located deep underground and a high-resolution near detector. Several independent worldwide efforts, developed through many years of detailed studies, have now converged around the opportunity provided by the megawatt neutrino beam facility planned at Fermilab and by the new significant expansion with improved access foreseen at the Sanford Underground Research Facility in South Dakota. The new international team has the necessary expertise, technical knowledge, and critical mass to design and implement this exciting discovery experiment in a relatively short timeframe. The goal is the deployment of the first 10-kton fiducial mass detector on the timescale of 2021, with future expansion to the full detector size as soon as possible after that. The PIP-II accelerator upgrade at Fermilab will provide 1.2 MW of power by 2024 to drive a new neutrino beam line at Fermilab. A plan that could further upgrade the Fermilab accelerator complex to enable it to provide up to 2.3 MW of beam power by 2030 is also in existence. With the availability of space for expansion and improved access at the Sanford laboratory, this international collaboration will develop the necessary framework to design, build and operate a world-class deep-underground neutrino observatory. Fermilab will act as the host laboratory. This plan is aligned with the European Strategy Report and the US HEPAP P5 report.

1.1 Introduction

The study of the properties of the neutrino has already provided many surprises, representing the first evidence in particle physics of physics beyond the Standard Model of particles and interactions. The phenomenon of neutrino oscillations, whereby they change flavor as they propagate through space and time is now well established, as is the modification of this oscillation in their passage through matter. Important conclusions which follow include the fact that neutrinos have mass and that the mass eigenstates are mixtures of the flavor eigenstates.

With the exception of the possible hints for the existence of sterile neutrinos, the current data can be described in terms of the three-neutrino paradigm, in which the quantum-mechanical mixing of three mass eigenstates produces the three

known neutrino-flavor states. The mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, a parameterization that includes a CP-violating phase.

Speculations on the origin of neutrino masses are wide-ranging. An attractive possibility is that neutrino masses are related to a new ultra-high-energy scale that may be associated with the unification of matter and forces. Such theories are able to describe the absence of antimatter in the Universe in terms of the properties of ultra-heavy particles as well as offering a description of cosmological inflation in terms of the phase transitions associated with the breaking of symmetries that pertain at the ultra-high-energy scale. Piecing together the neutrino-mass puzzle will require more precise and detailed experimental information. Long-baseline neutrino oscillation experiments are essential if the requisite neutrino transitions are to be measured with the necessary precision.

One of the primary questions that the experimental program outlined in this LOI seeks to answer is whether the oscillations of neutrinos differ from those of anti-neutrinos, testing whether CP symmetry is violated in the leptonic sector. It is known that the degree of CP violation that occurs in the interactions of quarks is insufficient to explain why our universe is comprised entirely of matter rather than antimatter. In long-baseline neutrino oscillation experiments the rate of oscillations, the way the oscillation rate varies with energy, and the differences between neutrinos and antineutrinos can be exploited to observe for the first time CP violation in the leptonic sector. In the three-neutrino paradigm, CP violation is determined by the value of a complex phase δ_{CP} in the PMNS matrix, whose sign is opposite for neutrinos and antineutrinos; CP violation occurs if the value of δ_{CP} is not zero (or π). Discovery of CP violation in the neutrino sector could have potentially profound implications on our understanding of the matter-antimatter asymmetry in the Universe.

Current neutrino oscillation data tell us about differences in the squared masses of the neutrino mass states, and about the sign of the mass-squared difference between two of the states, but not about the difference of those with respect to the third, which may be heavier (normal ordering) or lighter (inverted ordering) than the other two. Resolving this neutrino mass hierarchy ambiguity, along with precise measurements of neutrino mixing angles, would be a potent discriminator between various classes of models which attempt to take physics beyond the standard model and would have significant theoretical and cosmological implications. It is also an important input into the interpretation of results from other future neutrino experiments. Long-baseline neutrino oscillation experiments can determine the mass ordering by exploiting the matter effect on the oscillation probabilities, which affects the electron-neutrino component of the neutrino beam,

with different effect on neutrinos and antineutrinos, and with opposite sign depending on the mass ordering.

Even without CP violation, electron neutrinos and antineutrinos propagating through the Earth behave differently due to the fact that the material through which the beam passes contains electrons but no positrons. This effect must be distinguished from the differences that arise from true CP violation. To unfold these two effects from each other in a single experiment requires a baseline, the distance from the neutrino source to detector, >1000 km. Discrimination can be further enhanced, remaining ambiguities resolved, and the precision of the measurements improved by measuring the oscillation spectrum as a function of neutrino energy, ideally covering both first and second oscillation maxima.

An important goal of the proposed experimental program is to precisely measure other parameters of the PMNS matrix and to test the three-neutrino paradigm and the validity of the PMNS matrix as the description of neutrino mixing and oscillations. This involves measurements of ν_μ disappearance and both ν_e and ν_τ appearance, with the goal of measuring all of the PMNS matrix elements in this single experiment.

2.0 ELBNF Physics Program

2.1 Long-Baseline Neutrino Oscillation Physics

2.1.1 Phenomenology

The oscillation probability of $\nu_\mu \rightarrow \nu_e$ through matter, to first order, in a constant density approximation is [1]:

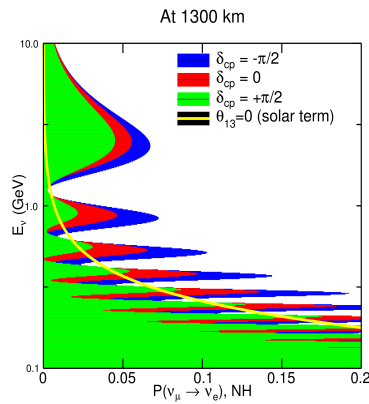
$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta_{CP}) \\
 & + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2,
 \end{aligned}$$

where

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E, \text{ and } a = G_F N_e / \sqrt{2}.$$

In the above, both δ_{CP} and a switch signs in going from the $\nu_\mu \rightarrow \nu_e$ to the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel; i.e., a neutrino-antineutrino asymmetry is introduced both by the CP-violating phase, δ_{CP} , and the matter effect, the origin of which is simply the presence of electrons and absence of positrons in the Earth. The asymmetry from the matter effect increases with baseline as the neutrinos pass through more matter, so an experiment with a longer baseline will be more sensitive to the neutrino mass hierarchy. For baselines longer than ~ 1200 km, the degeneracy between the asymmetries from matter and CP-violation effects can be resolved, so ELBNF, with a baseline of 1300 km, will be able to unambiguously determine the neutrino mass hierarchy and measure the value of δ_{CP} in the same experiment.

The electron neutrino appearance probability, $P(\nu_\mu \rightarrow \nu_e)$, is shown in Figure 1 at a baseline of 1300 km as a function of neutrino energy for several values of δ_{CP} . As this figure illustrates, the value of δ_{CP} affects both the amplitude and frequency of the oscillation. The difference in probability amplitude for differing values of δ_{CP} is larger at higher oscillation nodes, which correspond to energies less than 1.5 GeV. Therefore, a broadband experiment, capable of measuring not only the rate of ν_e appearance but of mapping out the spectrum of observed oscillations down to energies of at least 500 MeV, is desirable. Since there are terms proportional to $\sin \delta_{CP}$ in Eq. 1, changes to the value of δ_{CP} induce opposite changes to ν_e and $\bar{\nu}_e$ appearance probabilities, so a beam that is capable of operating in neutrino (forward horn current) and antineutrino (reverse horn current) is also a critical component of the experiment.



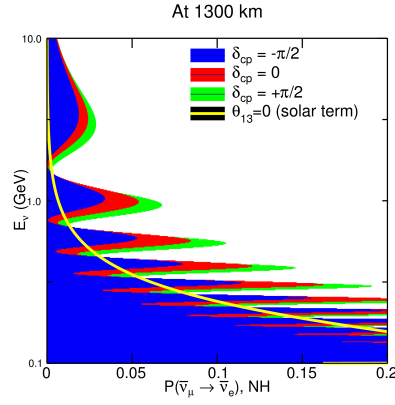


Figure 1: $P(\nu_\mu \rightarrow \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy, for $\delta_{CP} = -\pi/2$ (blue), 0 (red), and $\pi/2$ (green), for neutrinos (left) and antineutrinos (right), for normal hierarchy. The yellow line indicates the oscillation probability if θ_{13} were equal to zero.

Figure 2 shows the expected event rate, including expected flux, cross-section, and oscillation probabilities as a function of neutrino energy for a 40-kt fiducial mass LAr TPC at a baseline of 1300 km, assuming a perfect focus, 60-GeV beam from Fermilab. The perfect focus beam is described in Section **Error! Reference source not found.**; it is important to note that the background from neutral current and ν_τ interactions is larger in the perfect focus than in a realistic beam because the perfect focus beam includes a large high-energy tail. As illustrated in Fig. 2, collection of a large sample of ν_e appearance and ν_μ disappearance events covering a broad range of energies with significant statistics at the energy of the second oscillation maximum is possible. The maximum power available from the Fermilab complex is dependent upon the beam energy and the actual flux will depend upon details of the hadron production and focusing design; optimization of the beam design to maximize experimental sensitivity is a critical aspect of the experiment design and will be discussed further in Section **Error! Reference source not found.**

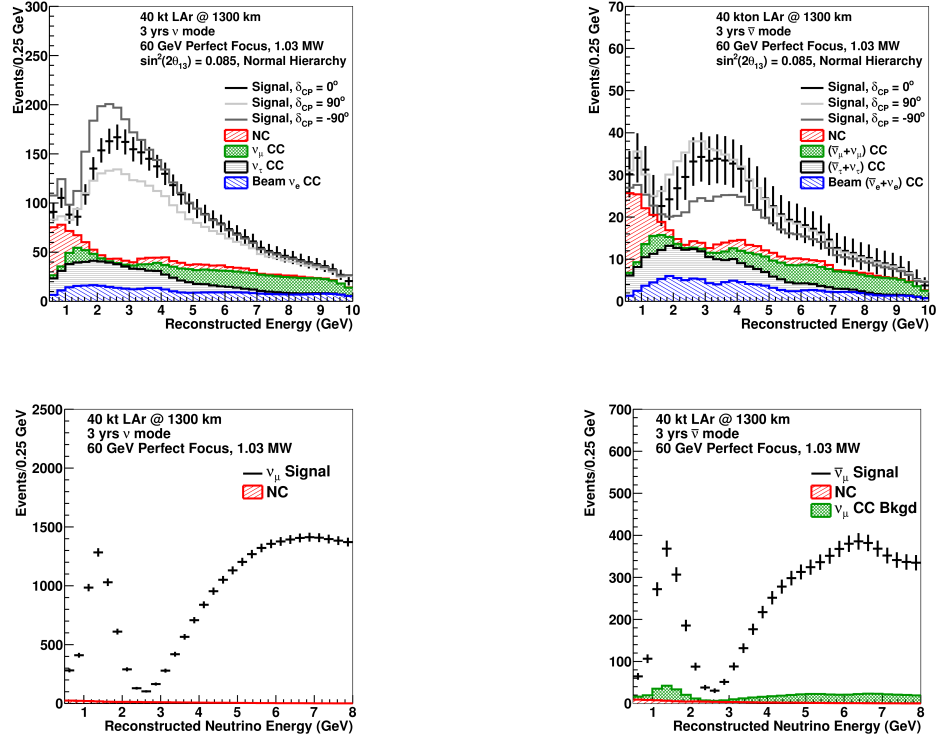


Figure 2: The expected reconstructed neutrino energy spectrum of ν_e appearance (top) and ν_μ disappearance (bottom) events in a 40-kt fiducial mass LArTPC for three years of neutrino (left) and three years of antineutrino (right) running with a 1.03-MW, 60-GeV perfect focus beam. The number of expected signal plus background events is shown for $\delta_{CP} = -\pi/2, 0$, and $\pi/2$. Spectra are for normal hierarchy.

2.1.2 Mass Hierarchy and CP Violation Sensitivities

The experimental sensitivities presented here are estimated using GLoBES[2, 3]. GLoBES takes flux simulation, cross-sections, and detector-response parameterization as inputs. In this document we consider experimental performance for four beams that are labeled according to the proton energy of the primary beam: 120-GeV horn focused, 120-GeV perfect focus, 80-GeV horn focused, and 60-GeV perfect focus. These beams are chosen to demonstrate the possible range of sensitivity, with the perfect focus beams illustrating a more ideal case, though it is important to note that because of their high-energy tails, perfect focus beams are not perfectly optimized beams. The beam power available from the FNAL beam complex varies with proton beam energy, so different power is used in association with each beam energy. The four example beams are described in some detail in Section **Error! Reference source not found.** The cross-section inputs to GLoBES have been generated using GENIE.

The LAr TPC performance parameters that go into the GLoBES calculation have been described in detail in [4]. The detector response assumed in these calculations is summarized in Table 1. The smearing and misidentification rates for the ν_τ background vary with energy; these parameters are taken from GENIE simulations. The neutrino oscillation parameters and the uncertainty on those parameters are taken from the Nu-Fit[5] global fit to neutrino data; the values are given in Table 2.

Table 1: LArTPC detector performance parameters assumed in GLoBES sensitivity calculations. Signal efficiencies, background levels, and resolutions are obtained from ICARUS results and LArSoft simulations.

Parameter	Value Used for ELBNF Sensitivities
	For ν_e CC appearance studies:
ν_e CC efficiency	80%
ν_μ NC mis-identification rate	1%
ν_μ CC mis-identification rate	1%
	For ν_μ CC disappearance studies:
ν_μ CC efficiency	85%
ν_μ NC mis-identification rate	1%
Other background	0%
	Neutrino energy resolutions:
ν_e CC energy resolution	$15\%/\sqrt{E(GeV)}$
ν_μ CC energy resolution	$15\%/\sqrt{E(GeV)}$

Table 2: Central value and relative uncertainty of neutrino oscillation parameters from a global fit to neutrino oscillation data, for normal hierarchy. The relative uncertainty is computed using 1/6 of the 3σ allowed range from the fit.

Parameter	Central Value	Relative Uncertainty
θ_{12}	0.5843	2.3%
θ_{23}	0.738	5.9%
θ_{13}	0.148	2.5%

Δm_{21}^2	$7.5 \times 10^{-5} \text{ eV}^2$	2.4%
Δm_{31}^2	$2.457 \times 10^{-3} \text{ eV}^2$	2.0%

Sensitivity to determination of the neutrino mass hierarchy and discovery of CP violation are obtained by simultaneously fitting the $\nu_\mu \rightarrow \nu_{\mu'}$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\mu'}$, $\nu_\mu \rightarrow \nu_e$, and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillated spectra. An example of the ν_e appearance and ν_μ disappearance spectra is shown in Fig. 2. The background to ν_e appearance is composed of: i) intrinsic ν_e and $\bar{\nu}_e$ from the beam; ii) mis-identified ν_μ and $\bar{\nu}_\mu$ CC events; iii) neutral current (NC) backgrounds; iv) ν_τ and $\bar{\nu}_\tau$ CC events in which the τ 's decay leptonically into electrons/positrons. NC and ν_τ backgrounds are due to interactions of higher energy neutrinos but they contribute to backgrounds mainly at low energy, which is important for the sensitivity to CP violation. Compared to the number of events shown in Figure 2, an optimization of the beam, reducing the high energy tail of the flux, will help in significantly reducing this background. As shown in [6], ν_τ interactions have a different energy-missing momentum distribution compared to the signal events and with appropriate cuts, which have not yet been included in this analysis, this background can be significantly reduced.

The neutrino oscillation parameters are all allowed to vary, constrained by a Gaussian prior with 1σ width given by the relative uncertainties shown in Table 2. The effect of systematic uncertainty is approximated using signal and background normalization uncertainties, which are treated as 100% uncorrelated among the four samples. Unless otherwise stated, the goal uncertainties of 1% on signal normalization and 5% on background normalization for the ν_e and $\bar{\nu}_e$ appearance measurements, in conjunction with uncorrelated 5% signal and 10% background normalization uncertainties in the ν_μ and $\bar{\nu}_\mu$ disappearance measurements, are used to calculate the sensitivities. Further discussion of systematic uncertainty, including a preliminary justification of these values and the effect of considering larger signal and background normalization uncertainties, is in Section 2.1.4.

In these fits, experimental sensitivity is quantified using a test statistic, $\Delta\chi^2$, which is calculated by comparing the predicted spectra for alternate hypotheses. These quantities are defined, differently for neutrino mass hierarchy and CP violation sensitivity, to be:

$$\Delta\chi_{MH}^2 = \chi_{IH}^2 - \chi_{NH}^2 (\text{true normal hierarchy}),$$

$$\Delta\chi_{MH}^2 = \chi_{NH}^2 - \chi_{IH}^2 (\text{true inverted hierarchy}), \quad (2)$$

$$\Delta\chi_{CPV}^2 = \text{Min}[\Delta\chi_{CP}^2(\delta_{CP}^{\text{test}}=0), \Delta\chi_{CP}^2(\delta_{CP}^{\text{test}}=\pi)], \text{where} \quad (3)$$

$$\Delta\chi_{CP}^2 = \chi_{\delta_{CP}^{\text{test}}}^2 - \chi_{\delta_{CP}^{\text{true}}}^2. \quad (4)$$

Since the true value of δ_{CP} is unknown, a scan is performed over all possible values of $\delta_{CP}^{\text{true}}$. We define a “typical experiment” as one with the most probable data given a set of input parameters, i.e. in which no statistical fluctuations have been applied. In this case, the predicted spectra and the true spectra are identical; for the example of CP violation, $\chi_{\delta_{CP}^{\text{true}}}^2$ is identically zero and the $\Delta\chi_{CP}^2$ value for a typical experiment is given by $\chi_{\delta_{CP}^{\text{test}}}^2$.

The expected sensitivity of ELBNF to determination of the neutrino mass hierarchy and discovery of CP violation are shown in Fig. 3. These calculations are for a 40-kt fiducal mass detector operating for three years in neutrino mode and three years in antineutrino mode, with an 80-GeV beam from FNAL using NuMI-style focusing. The results are shown as a function of the true value of δ_{CP} for the range of true values of θ_{23} allowed by the current global fit. The number of events expected in each mode are shown in Table 3.

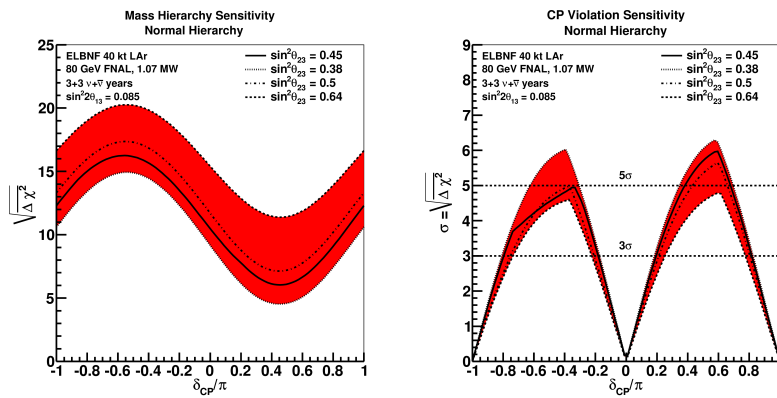


Figure 3: Expected sensitivity of ELBNF to determination of the neutrino mass hierarchy (left) and discovery of CP violation, i.e. $\delta_{CP} \neq 0$ or π , (right) for a 40-kt fiducal mass LAr TPC and an 80-GeV, 1.07-MW beam from FNAL to SURF with

three years of running in neutrino and three years in antineutrino mode. The Nu-Fit central value for Θ_{23} (solid line) is shown in comparison with other values of Θ_{23} . The width of the band corresponds to the 3σ range allowed by Nu-Fit. Note that the sensitivity to MH increases for increasing values of Θ_{23} while the corresponding sensitivity to CP violation decreases. Sensitivities are for true normal hierarchy; neutrino mass hierarchy is assumed to be unknown in the CPV fits.

Table 3: Expected number of ν_e appearance signal and background events in the energy range 0.5-10.0 GeV at the far detector after detector smearing and event selection. The signal events are shown for $\delta_{CP} = -\pi/2, 0$, and $\pi/2$, for a 40-kt fiducial mass LAr TPC and an 80-GeV, 1.07-MW beam from FNAL to SURF with three years of running in neutrino and three years in antineutrino mode. Neutrino and antineutrino events are combined for both signal and background. Normal hierarchy is assumed.

Run Mode	Signal Events			Background Events			
	δ_{CP} $-\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	1068	86	649	72	83	182	55
		4					
Antineutrino	166	21	231	41	42	107	33
		3					

The value of the test statistic for a typical experiment, $\overline{\Delta\chi^2}$, is representative of the mean or the most likely value of $\Delta\chi^2$ that would be obtained in an ensemble of experiments. With the exception of Figure 4, the sensitivity plots in this document have been generated using this method. However, to address the expected sensitivity of a future experiment requires consideration of the effect of statistical fluctuations and variations in systematics. If the experiment is repeated many times, a distribution of $\Delta\chi^2$ values will appear. Studies in [7, 8] show that, in the case of the mass hierarchy determination, the $\Delta\chi^2$ metric *does not* follow the commonly expected chi-squared function for one degree of freedom, which has a mean of $\overline{\Delta\chi^2}$ and can be interpreted using a Gaussian distribution with a

standard deviation of $\sqrt{|\Delta\chi^2|}$. Rather, these studies show that when the observed counts in the experiment are large enough, the distribution of $\Delta\chi^2$ used here approximately follows a Gaussian distribution with a mean and standard deviation of $\overline{\Delta\chi^2}$ and $2\sqrt{|\Delta\chi^2|}$, respectively. Figure 4 shows the range of sensitivity to the neutrino mass hierarchy, for the nominal exposure of 257 kt-MW-years, when statistical fluctuations are included and the statistical power as a function of exposure for 3σ and 5σ sensitivity.

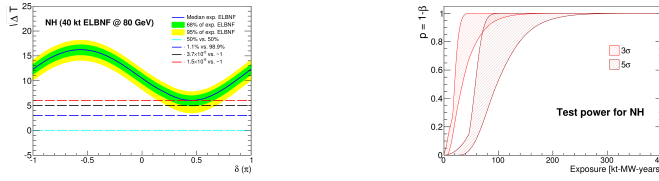


Figure 4: Sensitivity to neutrino mass hierarchy including statistical fluctuations. Expected sensitivity of ELBNF to determination of the neutrino mass hierarchy for a 40-kt fiducial mass LAr TPC and an 80-GeV, 1.07-MW beam from FNAL to SURF with three years of running in neutrino and three years in antineutrino mode. **Left:** The sensitivity, given by $\sqrt{\Delta T} = \sqrt{\Delta\chi^2}$, for a typical experiment (solid blue line) is compared to the bands within which 68% (green) and 95% (yellow) of experiments are expected to fall. The dashed lines represent the value of the ΔT metric above which the minimum probability of determining the correct neutrino mass hierarchy is 50% (cyan), 98.9% (blue), or $1-3.7 \times 10^{-6}$ (black). The red line shows the minimum sensitivity for a typical experiment. **Right:** The test power ($p=1-\beta$), which represents the probability of accepting the correct (NH) hypothesis, while excluding the incorrect (IH) hypothesis at the 3σ and 5σ level, shown as a function of exposure in kt-MW-years. The width of the bands represent the range of δ_{CP} values. Sensitivities are for true normal hierarchy.

2.1.3 Beam Optimization

A planned upgrade to the FNAL accelerator complex (PIP-II) will provide 1.2 MW of 120-GeV protons. Proton beam energies lower than 120 GeV may be desirable for ELBNF because they produce more neutrino flux at lower energies and produce less background from higher-energy neutrino interactions, facilitating spectral analysis covering a wider range of energy. The beam power expected for energies in the 60-120 GeV range is shown in Table 4; these values for beam power are

included in the sensitivity calculations in this document.

Table 4: Beam power expected from the FNAL accelerator complex after the PIP-II upgrade for several values of proton energy.

Beam Energy (GeV)	Power (MW)
60	1.03
80	1.07
120	1.2

A comparison of unoscillated flux from the four example beams considered in this document is shown in the left panel of Fig. 5. The “perfect focus” beams assume perfect hadron focusing and a decay pipe that is 4 m in diameter and 380 m long. Note that this is for illustration only; constraints from the FNAL site limit the actual length of the decay pipe to 250 m. The flux for the two “FNAL-NuMI” beams is from GEANT-based simulations of a NuMI-like beam line. The 120-GeV beam is described in the LBNE CDR[9]: a ~ 1 -m graphite target, a focusing system consisting of two parabolic horns operating at 200 kA, and an air-filled decay pipe that is 4 m in diameter and 200 m long. The beam energy is tunable by adjusting the distance from the target to the upstream face of the first focusing horn; in the nominal design this distance is 35 cm. The 80-GeV beam is also based on the NuMI design but includes a number of upgrades relative to the 120-GeV beam to increase the neutrino flux in the desired energy range. These changes are an upgrade to the target composition, increased horn current to 230 kA, and a helium-filled decay pipe that is 6 m in diameter and 250 m long. The flux increase from each of these changes is given in Table 5 for energy ranges roughly corresponding to the first and second oscillation maxima. Figure 6 shows the sensitivity to mass hierarchy and CP violation for these four example beams.

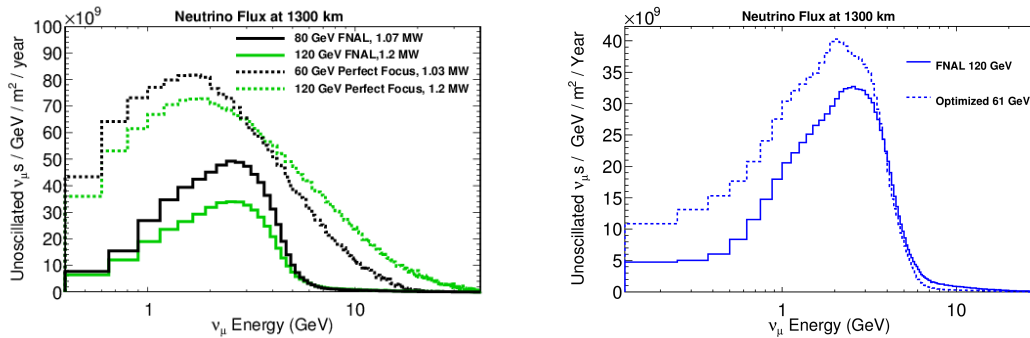
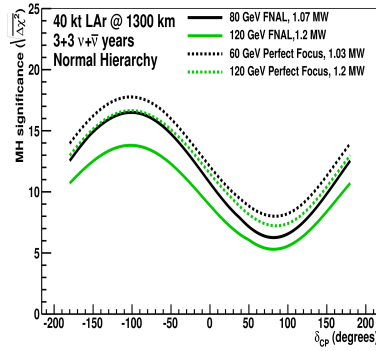


Figure 5: Unoscillated ν_μ flux at 1300 km in units of neutrinos per GeV per square

meter per year. The left panel shows the flux for the four beams described in the text: 120-GeV FNAL (solid green), 80-GeV FNAL (solid black), 120-GeV perfect focus (dashed green), and 60-GeV perfect focus (dashed black). The right panel shows the flux resulting from a preliminary attempt at beam optimization (dashed) compared to the 120-GeV FNAL beam (solid). In all cases, the variation in beam power with proton beam energy is considered in the normalization.

Table 5: Increase in neutrino flux relative to the 120-GeV FNAL beam in the energy ranges 0.5-2 GeV and 2-5 GeV for each upgraded design feature in the 80-GeV FNAL beam.

Design Change	Flux Increase 0.5-2 GeV	Flux Increase 2-5 GeV
Target: NuMI graphite \rightarrow Be cylinder	1.10	1.0
Horn current: 200 kA \rightarrow 230 kA	1.0	1.12
Decay pipe: Air \rightarrow He	1.07	1.11
Decay pipe diameter: 4 m \rightarrow 6 m	1.06	1.02
Decay pipe length: 200 m \rightarrow 250 m	1.04	1.12



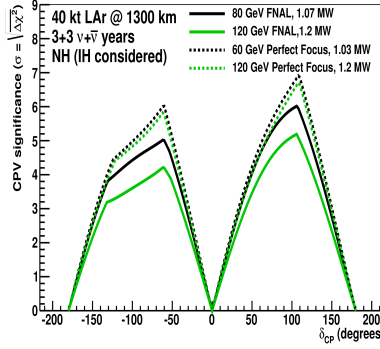


Figure 6: Expected sensitivity of ELBNF to determination of the neutrino mass hierarchy (left) and discovery of CP violation, i.e. $\delta_{CP} \neq 0$ or π , (right). Sensitivities are shown for a 40-kt fiducial mass LAr TPC, with three years of running in neutrino and three years in antineutrino mode, for four example neutrino beams, 120-GeV and 80-GeV beams with NuMI-style focusing (solid lines) and 120-GeV and 60-GeV perfect focus beams (dashed lines), details of which are described in the text. Sensitivities are for true normal hierarchy; neutrino mass hierarchy is assumed to be unknown in the CPV fits.

The right panel of Fig. 5 shows a comparison between the 120-GeV FNAL beam and a preliminary attempt at optimization, which has been done using a genetic algorithm that maximizes estimated sensitivity to δ_{CP} . Within this optimization, parameters such as primary proton momentum, target dimensions, and horn shape are varied. The best configuration found by the algorithm produces a muon neutrino flux that is 20% greater than the nominal configuration at the first oscillation maximum, 50% greater at the second oscillation maximum, and reduces the antineutrino contamination of the beam. It is expected that the optimized beam will lead to improvements in sensitivity to both mass hierarchy and CP violation. Refinement of the optimization procedure, quantification of the sensitivity improvement, and evaluation of the feasibility of the optimized designs are in progress.

The sensitivities for the perfect focus beams set the scale of improvement that is possible from optimization of the focusing system for the neutrino beam. As seen in Fig. 6, the most dramatic improvements are for mass hierarchy sensitivity in the region near $\delta_{CP} = \pi/2$, where additional events from the second oscillation maximum help to break the near-degeneracy between the CP and matter asymmetries. Sensitivity to CP violation also has significant room for improvement.

As illustrated in Fig. 7, which shows the sensitivity as a function of exposure for the 120-GeV FNAL beam and the 60-GeV perfect focus beam, which are expected to span the range of potential beam performance, optimization of the beam design will allow discovery-level sensitivity to be reached with significantly lower exposure, making this optimization a crucial feature of the experiment design.

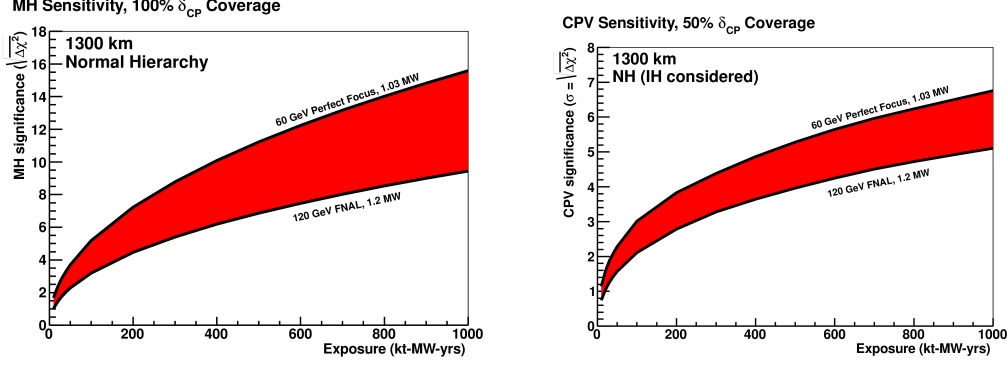


Figure 7: Expected sensitivity of ELBNF to determination of the neutrino mass hierarchy (left) and discovery of CP violation, i.e. $\delta_{CP} \neq 0$ or π , (right) as a function of exposure in kt-MW-years, assuming equal running in neutrino and antineutrino mode, for neutrino beams ranging from the 120-GeV beam with NuMI-style focusing to the 60-GeV perfect focus beam, details of which are described in the text. The sensitivities quoted are the minimum sensitivity for 100% of δ_{CP} values in the case of mass hierarchy and 50% of δ_{CP} values in the case of CP violation. Sensitivities are for true normal hierarchy; neutrino mass hierarchy is assumed to be unknown in the CPV fits.

2.1.4 Systematic Uncertainties

As described in Section 2, the effect of systematic uncertainty on experimental sensitivity is approximated using signal and background normalization uncertainties. In the sensitivities presented here, the normalization uncertainties on the ν_μ and $\bar{\nu}_\mu$ samples are 5% on signal and 10% on background. In this section, we consider the effect of varying the size of the residual normalization uncertainties on the ν_e and $\bar{\nu}_e$ samples, which are 100% uncorrelated from each other and from the ν_μ and $\bar{\nu}_\mu$ uncertainties. Figure 8 shows the LBNE sensitivity to neutrino mass hierarchy and discovery of CP violation as a function of exposure for several levels of this uncertainty.

As seen in Fig. 8, for early phases of ELBNF with exposures less than 100 kt-MW-years, the experiment will be statistically limited. In the full experiment, signal and background normalization uncertainties remain relatively unimportant for the

mass hierarchy measurement, when considering minimum sensitivity for 100% of δ_{CP} values, because the minimum sensitivity occurs in the near-degenerate region where δ_{CP} is near $\pi/2$. In this region, much of the sensitivity to mass hierarchy comes from spectral analysis of the oscillations and is therefore less sensitive to normalization uncertainty. It is important to note that the sensitivity calculations presented here do not consider the effect of energy scale uncertainty, which may have a more significant impact on mass hierarchy sensitivity. Studies of the impact of energy scale uncertainty are in progress and will be included in future analyses of experimental sensitivity. The impact of systematic uncertainty on the CP violation sensitivity is obvious in Fig. 8; the normalization of the ν_e sample, relative to the $\bar{\nu}_e$, ν_μ , and $\bar{\nu}_\mu$ samples after all constraints from external, near detector, and far detector data have been applied, must be determined at the 1-2% level in order to reach 5σ sensitivity for exposures less than 900 kt-MW-years.

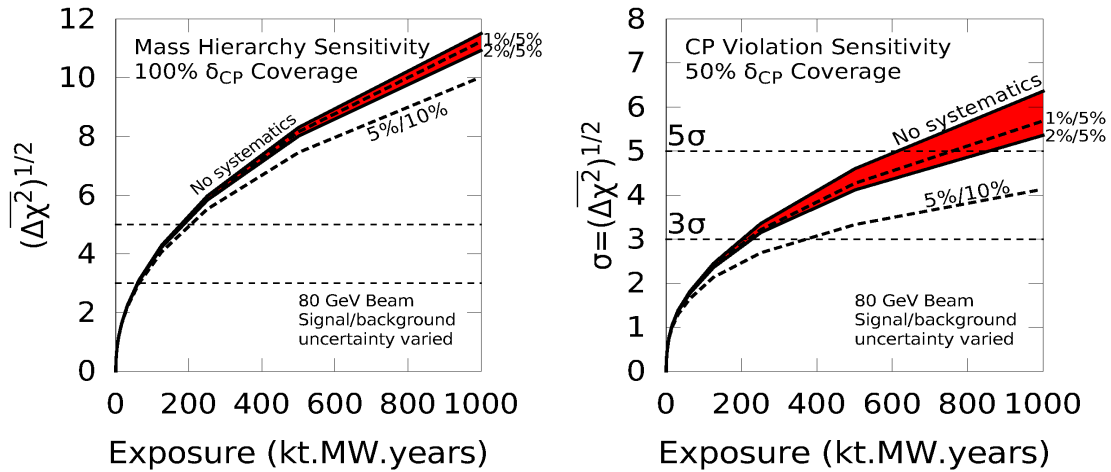


Figure 8: Expected sensitivity of ELBNF to determination of the neutrino mass hierarchy (left) and discovery of CP violation, i.e. $\delta_{CP} \neq 0$ or π , (right) as a function of exposure in kt-MW-years, assuming equal running in neutrino and antineutrino mode, for a range of values for the residual ν_e and $\bar{\nu}_e$ signal and background normalization uncertainties. The sensitivities quoted are the minimum sensitivity for 100% of δ_{CP} values in the case of mass hierarchy and 50% of δ_{CP} values in the case of CP violation. Sensitivities are for true normal hierarchy; neutrino mass hierarchy is assumed to be unknown in the CPV fits.

Uncertainties in ELBNF will be constrained by external data, near detector data, and the combined fit to the four (ν_e , $\bar{\nu}_e$, ν_μ , $\bar{\nu}_\mu$) far detector samples. Experience from previous and currently-running neutrino oscillation experiments

suggests that 1-2% uncertainty in uncorrelated ν_e signal normalization and 5% uncorrelated uncertainty in background normalization for the ν_e -appearance measurement is reasonably achievable in LBNE given a capable near detector. Table 6 shows the uncertainties in a ν_e appearance analysis achieved by MINOS [10] and T2K [11] and compares the expected uncertainty in ELBNF. The projected uncertainties in ELBNF are chosen by determining which of the existing experiments is more representative of ELBNF for each source of systematic uncertainty and then setting the reasonable goal that a next generation experiment, with the high resolution of a LArTPC and precise measurements from a highly capable near detector, should be able to improve on a similar earlier experiment. Based on this exercise, the *total* uncertainty on the ν_e sample in ELBNF is expected to be less than 4%; significant cancellation of uncertainty is expected in the four-sample fit, so the residual uncorrelated uncertainty is expected to be reduced to the 1-2% level.

Table 6: The dominant systematic uncertainties on the ν_e -appearance signal prediction in MINOS and T2K and a conservative projection of the expected uncertainties in ELBNF. In each case, the quoted uncertainty is the effect on the ν_e -appearance signal only. These uncertainties are the *total* expected uncertainties on the ν_e -appearance signal which include both correlated and uncorrelated uncertainties in the three-flavor fit.

Source of Uncertainty	MINOS ν_e	T2K ν_e	ELBNF ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	2.9%	2%	MINOS is normalization only. ELBNF normalization and shape highly correlated between ν_μ/ν_e .
Neutrino interaction modeling				
Simulation includes: hadronization cross sections	2.7%	7.5%	~2%	Hadronization models are better constrained in the ELBNF LArTPC. N/F cancellation larger in MINOS/ELBNF. X-section uncertainties larger at T2K energies.

nuclear models				Spectral analysis in ELBNF provides extra constraint.
Detector effects				
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in ELBNF ν_μ sample uncertainty only in 3-flavor fit. MINOS dominated by hadronic scale.
Energy scale (ν_e)	2.7%	includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	8.8%	3.6 %	Uncorrelated ν_e uncertainty in full ELBNF 3-flavor fit = 1-2%.

Detailed determination of expected systematic uncertainty using ELBNF-specific simulations and tools is a high priority of the collaboration and is in progress. Detailed description of this effort is beyond the scope of this document; only a brief summary of preliminary results will be presented here.

As described in Section 2 initial studies using a Fast Monte Carlo with a parameterized detector response predict 2-3% statistical uncertainties on the absolute flux using fully leptonic neutrino interactions for which high-precision cross-section predictions exist. Specifically, the statistical uncertainty is expected to be 2% for neutrino-electron scattering ($E_\nu < 5$ GeV) and 3% for inverse muon decay ($E_\nu > 11$ GeV). Relative normalization using the low- ν_0 method is expected to constrain the flux shape and the near/far flux ratio to 1-2%. Studies using a multi-sample fit to constrain the flux with simulated near detector event samples show significant constraints on all flux uncertainties. The post-fit uncertainty in most flux bins for a preliminary fit is less than 5%, which is the uncorrelated ν_μ signal normalization uncertainty assumed by the sensitivity calculations.

Results from a fit to Fast MC simulation of all four far detector samples ($\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$) significantly constrains cross-section systematic uncertainty even in the case where many cross-section parameters are allowed to vary simultaneously within their GENIE uncertainties. As seen in the example shown in Figure 9, a fit in which both $M_A^{QE,CC}$ and $M_A^{RES,CC}$ are allowed to vary within their GENIE

uncertainties ($\pm 20\%$), which could significantly alter the energy distribution of the the selected events, results in a dramatic reduction in sensitivity if one considers only the ν_e appearance signal without constraint from the $\bar{\nu}_e$ and $\nu_\mu/\bar{\nu}_\mu$ samples. In contrast, for a four sample fit, this same parameter variation results in only a small reduction in sensitivity to CP violation. This result includes a 10% uncertainty in the $\nu/\bar{\nu}$ cross-section ratio and a 2.5% uncertainty in the ν_e/ν_μ cross-section ratio. Preliminary studies also demonstrate significant constraint on cross-section systematics from the near detector. The validity of the GENIE model parameter uncertainties are being studied via comparisons with available data (e.g. MINERvA), and alternate models (e.g. the Intranuke intranuclear recattering model will be compared with GiBUU). These comparisons are a high priority of the whole neutrino community as well as the ELBNF collaboration.

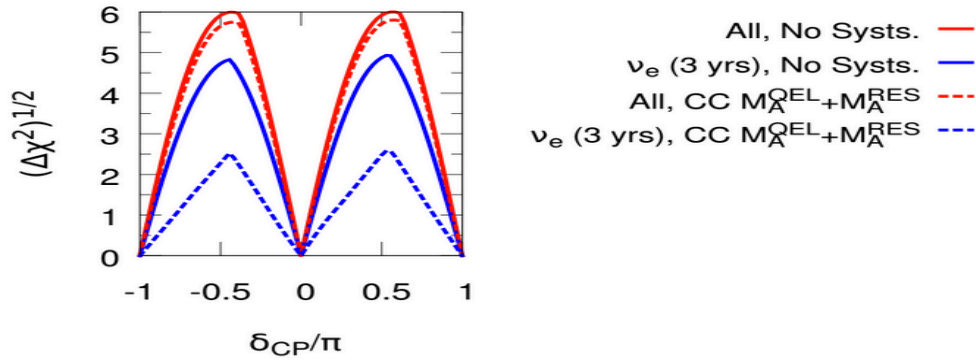


Figure 9: An example CP violation sensitivity calculated using inputs from the FastMC in a fit to all four ($\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$) samples (red) and a fit to the ν_e appearance sample only (blue), for the case of no systematic uncertainty (solid) and the case in which both $M_A^{QE,CC}$ and $M_A^{RES,CC}$ are allowed to vary with a 1σ uncertainty of 20% (dashed). This example was taken from an earlier LBNE study, so the absolute sensitivity can not be compared with the ELBNF sensitivities presented in this document.

Uncertainty from nuclear interactions, in which particles exiting the primary interaction vertex interact with the nuclear medium prior to depositing energy in the detector, and detector effects, such as resolutions and energy scale uncertainty, are somewhat more difficult to address with early simulation efforts. However, in analogy to the treatment of cross-section uncertainty described above, the effect of varying nuclear interaction parameters within their GENIE uncertainties and comparisons of GENIE predictions to those of other event generators are in

progress. Efforts to improve modeling of nuclear interactions and to develop reconstruction and analysis tools for a full Monte Carlo simulation are also underway. At the same time, a number of test-beam and prototype experiments, including the LBNE 35-t prototype, LARIAT, CAPTAIN, and the CERN neutrino platform experiments, are being designed and built to reduce these uncertainties with experimental data.

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2.2 Physics with a Precision Near Detector

To achieve the precision required to make a significant advance in the measurement of neutrino oscillation parameters over current experiments and to reach the desired 5σ sensitivity to CP violation, a highly-capable, high-precision near detector is required to measure the unoscillated flux spectrum to a few percent for all neutrino species in the beam (n_μ , \bar{n}_μ , n_e , \bar{n}_e) and to precisely measure neutrino cross sections necessary to interpret the far detector signal and backgrounds. This requires a high resolution, magnetized near neutrino detector with high efficiency for identifying and measuring electrons and muons. To measure the small ν_e contamination in the beam with greater precision, the

detector would need to be able to distinguish e^+ from e^- ; this would require a low-density detector with a commensurately long physical radiation length. Use of a target nucleus similar to the far detector would allow cancellation of systematic errors and inclusion of other target nuclei would provide constraints for accurate modeling of nuclear effects. Such a detector, [Ref. DPR, LBNE-doc-6704] placed in the high- intensity neutrino beam needed for the oscillation measurements, will collect a vast sample of neutrino interactions, which will enable a rich program in neutrino scattering physics addressing many non-oscillation topics, such as precision electroweak measurements and searches for new physics.

2.3 Non-Accelerator Physics

A large liquid argon TPC, when sited underground, has significant capabilities for addressing diverse physics topics, including proton decay, atmospheric and supernova neutrinos. These opportunities are described in detail in reference [1, 2]. For non-beam physics, no external trigger will be available, and suitable triggering will be required, possibly involving photon collection. Table I 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. Supernova neutrino events have few tens of MeV of energy and will create small lepton tracks involving only a few adjacent wires. Although these low-energy events are likely to be relatively difficult to select from background, the high-rate pulse of low-energy events all arriving within \sim 30 seconds results in promising signal relative to a (well-known) background. In contrast, “relic” supernova events arrive singly and very low expected signal rate will make their selection difficult; nevertheless a deep underground location may make the measurement feasible. Solar neutrinos, due to < 15 MeV energies, are also a challenging physics target, but conceivable to pursue in a low-background underground location.

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

2.3.1 Searches for baryon number non-conservation

Baryon number conservation is an unexplained symmetry in the Universe with

deep connections to both cosmology and particle physics. As one of the conditions underlying the observed matter-antimatter asymmetry of the Universe, baryon number should be violated. Nucleon decay, which is a manifestation of baryon number violation, is a hallmark of many Grand Unified Theories (GUTs), theories that connect quarks and leptons in ways not envisioned by the Standard Model. Observation of proton or bound-neutron decay would provide a clear experimental signature of baryon number violation.

A large LArTPC's superior detection efficiencies for decay modes that produce kaons will outweigh its relatively low mass compared with multi-100-kt water Cherenkov detectors. Because the LArTPC can reconstruct protons that would otherwise be below Cherenkov threshold, it can reject many atmospheric neutrino background topologies by vetoing on the presence of a recoil proton. Due to its high spatial resolution, it also performs better for event topologies with displaced vertices, such as $p \rightarrow K + \bar{\nu}$ (for multi-particle K^+ decay topologies) and $p \rightarrow K^0 \mu^+$. The latter mode is preferred in some SUSY GUTs.

Figure 1 shows the expected limit as a function of time for $p \rightarrow K + \bar{\nu}$. According to this plot, approximately 10 kton of LAr will improve the limits significantly beyond current Super-K limits. Other modes for which LArTPCs have an advantages are $n \rightarrow e^- K^+$, $p \rightarrow K^+ \mu^- \pi^+$, $n \rightarrow e^+ \pi^-$, $p \rightarrow e^+ K^0$.

2.3.2 Atmospheric neutrinos:

Atmospheric neutrinos are unique among sources used to study oscillations: the oscillated ux contains neutrinos and antineutrinos of all avors, and matter effects play a significant role. The expected interaction rate is a few hundred events per kton-year, enabling the collection of a very large-statistics sample. The excellent CC/NC separation, angular resolution, and the ability to fully reconstruct the hadronic final state in CC interactions, unimpeded by a Cherenkov threshold, would enable the atmospheric neutrino 4-momentum to be fully determined. 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.

The atmospheric sample will provide good sensitivity to mass hierarchy (see Fig. 2) and to the octant of Θ_{23} on its own, and will improve overall sensitivity when combined with beam measurements. Since the oscillation phenomenology plays out over several decades in energy and path length, 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.

2.3.3 Core Collapse supernova neutrinos:

A nearby core-collapse supernova will provide a wealth of information via the time, energy and flavor structure of its intense neutrino emission. A supernova neutrino burst contains information not only on the astrophysics of the core collapse (e.g. neutronization, black hole formation, shock wave effects, standing accretion shock instability effects, turbulence effects, proto-neutron star cooling) but also on neutrino properties related to neutrino oscillation. A particularly interesting example is the collective effects due to neutrino-neutrino interactions in super-dense matter, which will have observable signatures which depend on the neutrino mass hierarchy.

Core-collapse 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 $\bar{\nu}_e$ 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 flavor component of the flux via the absorption interaction on ^{40}Ar , $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$. In principle, this interaction can be tagged via the de-excitation gamma cascade although more work needs to be done to understand efficiencies for a given detector configuration. Some thousands of events would be expected in a 40kton of liquid argon for a supernova at 10kpc; estimates vary by model over a fairly wide range. The number of signal events scales with mass and inverse square of distance as shown in figure XX. For a collapse in the Andromeda galaxy, a 40-kton detector would expect a few events.

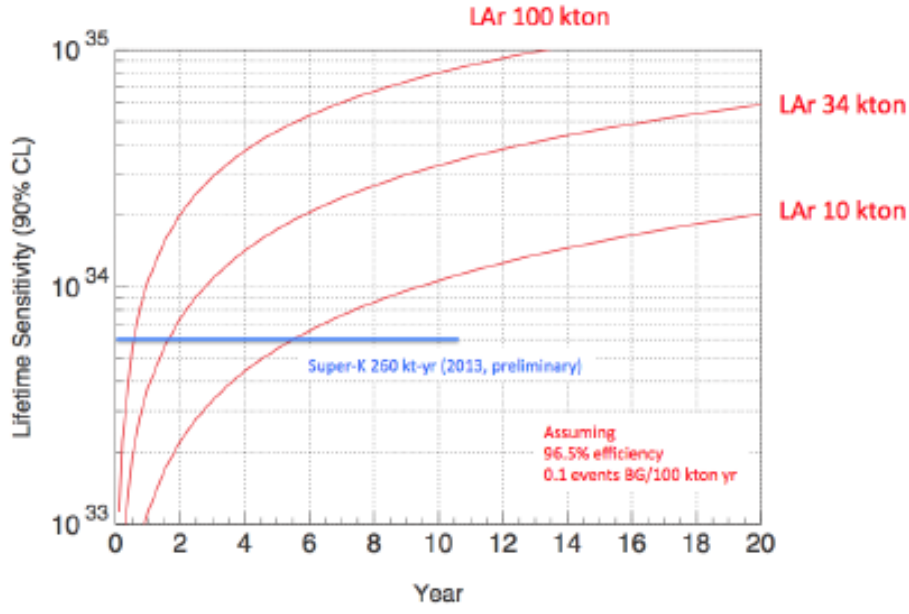


FIG. 1. Proton decay lifetime limit for $p \rightarrow K^+ \bar{\nu}$ as a function of time for underground LArTPCs of fiducial masses 10, 34 and 100 kt. For comparison, the current limit from SK is also shown. The limits are at 90% C.L., calculated for a Poisson process including background, assuming that the detected events equal the expected background.

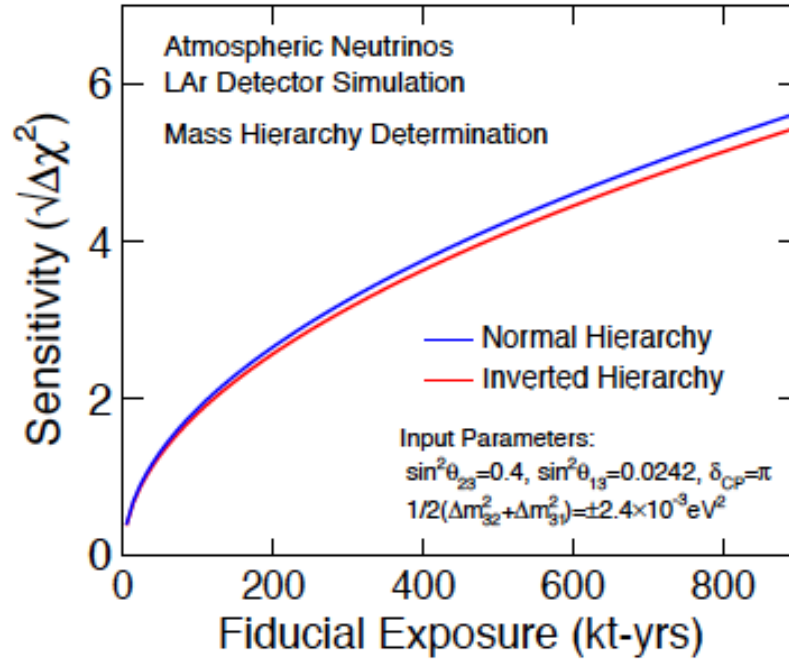


FIG. 2. Sensitivity to mass hierarchy using atmospheric neutrinos as a function of fiducial exposure in a liquid argon detector.

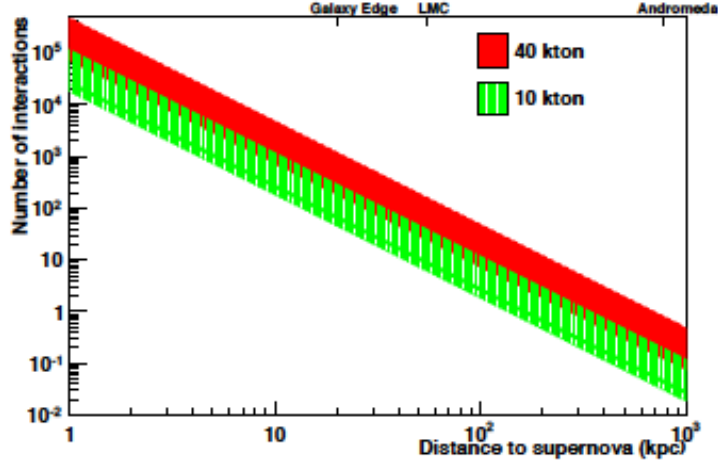


FIG. 3. Estimated numbers of supernova neutrino interactions in a LAr detector as a function of distance to the supernova, for different detector masses (ν_e events dominate). The red dashed lines represent expected events for a 40-kton detector and the green dotted lines represent expected events for a 10-kton detector. The lines limit a fairly wide range of possibilities for “Garching-parameterized” supernova flux spectra (e.g., [4]) with luminosity 0.5×10^{52} ergs over ten seconds. The optimistic upper line of a pair gives the number of events for average ν_e energy of $\langle E_{\nu_e} \rangle = 12$ MeV, and “pinching” parameter $\alpha = 2$; the pessimistic lower line of a pair gives the number of events for $\langle E_{\nu_e} \rangle = 8$ MeV and $\alpha = 6$. (Note that the luminosity, average energy and pinching parameters will vary over the time frame of the burst, and these estimates assume a constant spectrum. Oscillations will also affect the spectrum.) The solid lines represent the integrated number of events for the specific time-dependent neutrino flux model in [5] (see Fig. 4; this model has relatively cool spectra and low event rates). Core collapses are expected to occur a few times per century, at a most-likely distance of about 10-15 kpc.

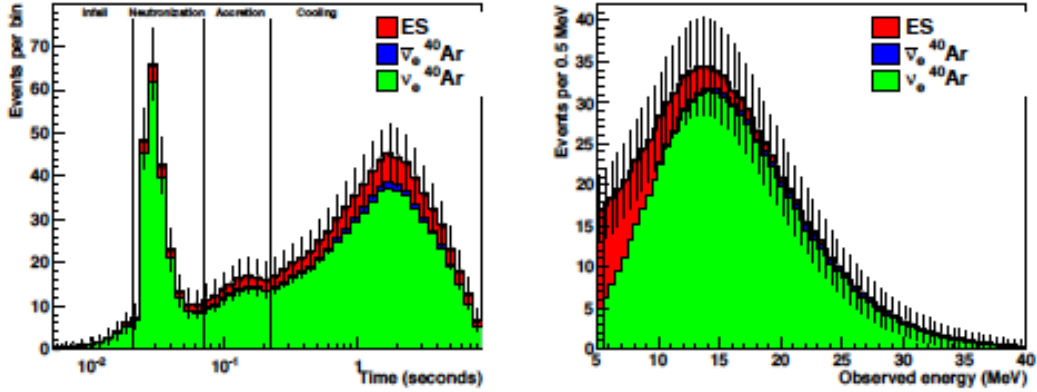


FIG. 4. Left: Expected time-dependent signal in 40 kt of liquid argon for a specific flux model for an electron-capture supernova [5] at 10 kpc, calculated using SNoWGLoBES [6]. Note the logarithmic binning in time; the plot shows the number of events expected in the given bin for three detection channels and the error bars are statistical. The vertical dashed line at 0.02 seconds indicates the time of core bounce, and the vertical lines indicate different eras in the supernova evolution. The leftmost time interval indicates the infall period. The next interval, from core bounce to 50 ms, is the neutronization burst era, in which the flux is composed primarily of ν_e . The next period, from 50 to 200 ms, is the accretion period. The final era, from 0.2 to 9 seconds, is the proto-neutron-star cooling period. Right: expected measured event spectrum for the same model, integrated over time.

2.4 The physics Reach with an Initial 10 kton LAr Detector

A preliminary phase of ELBNF, planned to commence data collection in 2021 would use a 10 kt fiducial mass LArTPC and a 700 kW FNAL beam. We will assume 4 years of data taking, with a neutrino plus antineutrino beams or running in neutrinos only. This experimental configuration, which will have an exposure of 28 MW-kton-yrs and will be denoted here ELBNF28, would be a milestone towards the ELBNF project. Here we highlight the important physics results that could be obtained both for accelerator neutrinos and for non-accelerator physics from this first module. For the latter, the location underground is essential.

Run Mode	Signal Events			Background Events				
	δ							
	$\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC	
Neutrino	117	94	71	8	9	20	6	
Antineutrino	18	23	25	4	5	12	4	

Table 1: Expected number of ν_e appearance signal and background events in the energy range 0.5–10.0 GeV at the far detector after detector smearing and event selection. The signal events are shown for $\delta = \pi/2$, 0, and $\pi/2$, for a 10-kt fiducial mass LAr TPC and an 80-GeV, 700-kW beam from FNAL to SURF with two years of running in neutrino and two years in antineutrino mode. Neutrino and antineutrino events are combined for both signal and background. Normal hierarchy is assumed.

2.4.1 Accelerator neutrino physics

The preliminary setup ELBNF28 will have a significantly smaller number of events compared to the completed ELBNF, due to the reduced beam power, smaller detector and fewer years of running. This configuration will be strongly statistically limited as can be seen in Table 1. Nevertheless, it will be able to provide some information on the mass ordering and CP violation. It is particularly interesting to consider the case of maximal CP violation. Combined analysis of current neutrino oscillation data show a preference for close-to-maximal CP violation in the negative half: the current best fit values are $\delta = 304^\circ$ for NO and $\delta = 254^\circ$ for IO and the CP conserving values $\delta = 0, \pi$ are excluded at more than 1σ (except for $\delta = \pi$ which is excluded at slightly less than 1σ for IO) [Gonzalez-Garcia:2014bfa]. Although these hints of CP violation are not yet statistical significant, it is interesting to consider

the physics reach of ELBNF28 if they were to be confirmed, in addition to the general case of $0 \leq \delta < 2\pi$.

Mass ordering.

While at present no information on the mass ordering is available, in the next few years thanks to the 800 km baseline the NOvA experiment will have some sensitivity to it, which could be improved if combined with T2K results, for $\delta < 0$ and NO ($\delta > 0$ and IO). ELBNF has a 1300 km baseline and consequently stronger matter effects which help in mass hierarchy determination. Even for the limited exposure of 28 MW-kton-yrs, for 2 years of neutrinos and of antineutrino running, in the region of maximal CP violation and negative δ , ELBNF28 achieves a median sensitivity of around $\Delta\chi^2 > 4$, depending on the specific experimental configuration, see Fig. 1. The addition of NOvA and T2K data improves slightly the reach in this region of δ and gives a significant contribution for $\delta \geq 0$.

CP-violation determination

Given the number of events and the large backgrounds at low energy, the sensitivity of ELBNF28 alone to CP violation is comparable to that of NOvA+T2K, reaching 2σ for close-to-maximal CP violation independently from the sign of δ (it should be noted that for $\delta > 0$ NOvA and T2K loose sensitivity due to the mass ordering degeneracy). In this preliminary phase of the experiment, the sensitivity is strongly determined by the number of events as it can be understood by comparing the lines corresponding to different experimental configurations, 80 GeV versus 120 GeV beams. Systematic errors play a subdominant role as the results are very similar for the two choices of 5%/10% and 1%/5% signal/background normalization uncertainty. Therefore, adding information from NOvA and T2K improves very significantly the physics reach: for maximal CP violation and 2+2 years of neutrino and antineutrino run, nearly 3σ can be reached. This would be a very interesting result which could be confirmed rapidly by the subsequent run of the full experiment with higher power and larger detector. Moreover, at 2σ CP violation could be established for approximately 50% of the values of the δ phase. It should be noted that for the CP violation determination, the combination of neutrino and antineutrinos runs is superior to the one of neutrinos only.

2.4.2 Non-accelerator physics

A 10 kton fiducial mass LArTPC located underground at the SURF site would be the first large-scale and low threshold LAr detector available in the world and could provide new physics opportunities. Given the size of the detector, an

unprecedented sensitivity to proton decay, supernova neutrinos, atmospheric neutrinos would become available.

Proton decay

As discussed in the dedicated section, a 10 kton LAr detector would be able to already improve the Super-Kamiokande bound in the $p \rightarrow K+\nu$ channel and would provide the first limits on $n \rightarrow e-K^+$, $p \rightarrow e+K^0$, $n \rightarrow \mu+\pi^-$, $p \rightarrow \mu+K^0$, $n \rightarrow e+\pi^-$, for which Water Cherenkov detectors have limited reconstruction capabilities.

SN neutrinos

The detection of supernova neutrinos can shed light on the evolution of these extreme astrophysical environments and on neutrino properties. Currently, most experiments are sensitive only or mainly to the $\bar{\nu}e$ component of the flux. The ELBNF28 detector would constitute a step-change in the field, by allowing to detect νe via $\nu e + 40\text{Ar} \rightarrow e + 40\text{Ar}$. Depending on the supernova model considered, between 180 and 1200 events would be expected for a core-collapse supernova located at 10 kpc of distance. In Fig. ?? we show the dependence of the number of events on the supernova distance. Differently from the other flavours, electron neutrinos are emitted early on in the supernova evolution in conjunction with the neutronization burst. Therefore their observation in the 10 kton LAr ELBNF detector would constitute a prompt supernova alert for the astronomers and other detectors. Moreover, combining the information on the neutrino component of the flux with that which can be achieved from Water Cherenkov and Liquid scintillator detectors on the other flavors and on antineutrinos would play an important role in understanding SN evolution.

Atmospheric neutrinos:

The operation of the 10 kton LAr detector for 4 years would provide around 2000 νe CC events for which, even in the sub-GeV energy region, not only the lepton produced in an interaction but also the hadronic part could be reconstructed. These capabilities would be fundamental to develop a detailed understanding of the reconstruction of νe CC events and of detector systematic in the GeV range.

Reference

[Gonzalez-Garcia:2014bfa] M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, "Updated fit to three neutrino mixing: status of leptonic CP violation," JHEP **1411**, 052 (2014), [arXiv:1409.5439 [hep-ph]]

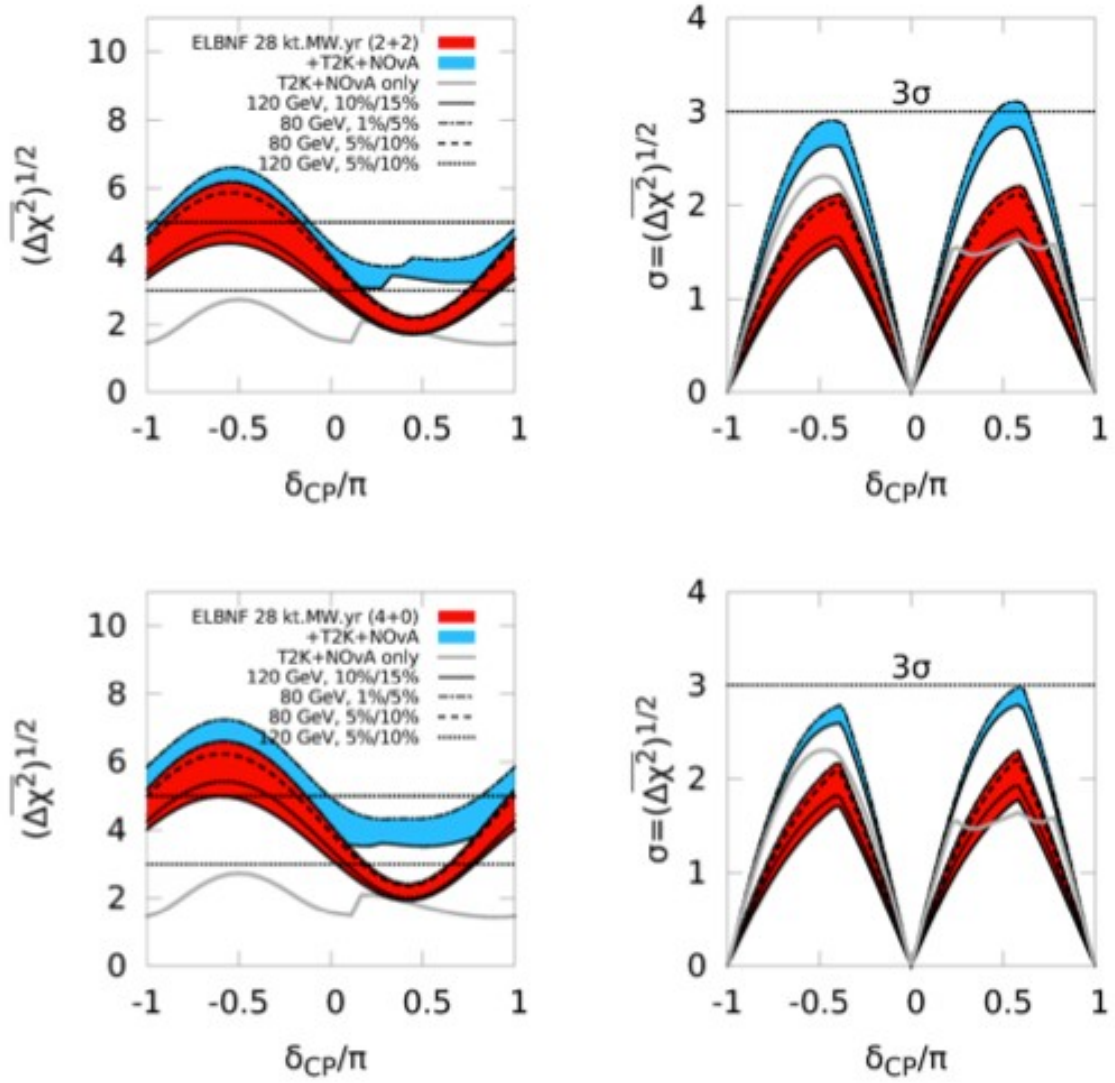


Figure 1: Expected sensitivity of ELBNF28 to the determination of the neutrino mass ordering (left) and discovery of CP violation, i.e. $\delta \neq 0, \pi$, (right), alone (red) and in combination with NOvA and T2K (blue). In the top panels, the ELBNF data is divided equally between neutrino and antineutrino mode while for the bottom panels data is in neutrino mode only for the same exposure. Expected sensitivity for a combination of NOvA and T2K without ELBNF28 is indicated by the gray line. The T2K sensitivity is based on 7.8×10^{21} protons-on-target (POT) in neutrino mode. The NOvA sensitivity is based on three years of running in neutrino and three years in antineutrino mode, where 6×10^{20} POT per year are expected. The systematic uncertainties quoted for ELBNF are the uncorrelated signal/background normalization uncertainties for the e and \bar{e} samples; each configuration also includes 5%-10% signal/background normalization uncertainty on the muon neutrino and antineutrino samples. The curves on each band represent a range of ELBNF beam designs and levels of systematic uncertainty, ranging from the 120-GeV FNAL beam with 10%-15% uncertainty to the 80-GeV FNAL beam with 1%-5% uncertainty.

Sensitivities are for true normal ordering; neutrino mass ordering is assumed to be unknown in the CPV fits.

3.0 Design of the Experiment

3.1 Overview:

To address this broad and exciting physics program, a number of key elements are required:

- A high-intensity, megawatt class, wide-band, sign-selected muon neutrino beam.
- A massive, high-precision neutrino detector, placed deep underground.
- A baseline sufficiently long to simultaneously determine the mass hierarchy and measure CP-violating effects.
- A highly capable precision near detector located close to the neutrino source.

Access to this potentially groundbreaking science is now possible because of the important opportunity provided by the expected availability of a new intense neutrino beam at Fermilab and of underground infrastructures at the Sanford Underground Research Facility, which is at a distance of 1300 km from Fermilab. These facilities will make viable the experimental physics program needed for the elucidation of the fundamental questions described above.

Fermilab is prepared to host the Long-Baseline Neutrino Facility (LBNF), strongly recommended by the P5. As host, Fermilab will provide the infrastructure required to carry out a long-baseline neutrino oscillation experiment with the combination of the required accelerators, beamline, target and horn. The LBNF will include:

- A conventional horn-focused neutrino beam, including a proton transfer line target, horns, decay pipe and absorber, capable of operating at 1.2 MW initially, and with the potential to be upgraded to 2.4 MW. This beam will be driven by the existing Fermilab Main Injector complex, including the planned PIP-II injector upgrades.
- The LBNF far site infrastructure with newly expanded underground space at the SURF, which is foreseen to be created after the complete

refurbishing of the Ross shaft in 2017 and other site improvements necessary to house the massive LAr-TPC experimental apparatus.

- The LBNE near site infrastructure required to house the near detector complex.
- The conventional infrastructure, including the primary technical infrastructure such as the cryostat and associated cryogenics for the liquid argon detector.

To address the groundbreaking physics program made possible by the LBNF, the large international collaboration (referred to here as ELBNF), identified in the author list presented in Appendix A, proposes to construct a deep-underground neutrino observatory based on a 40 kton liquid-argon (LAr) time-projection chamber (TPC) at the Sanford Underground Research Facility. Potential designs for the ELBNF far detector have been developed by a number of groups, who now have come together within ELBNF, including both single-phase and dual-phase readout technology. The far detector may employ just one of these technologies, or possibly different technologies in a phased implementation, depending on the performance and developing maturity of the candidate designs. These options are being explored by several groups at the CERN Neutrino Platform (e.g. WA105) as well as Fermilab's short-baseline neutrino program.

The collaboration also proposes to build a fine-grained highly-capable near detector located on the Fermilab site. The reference design of the Near Detector (see Fig. *FGT-Schematic*) has been developed by the Indian Institutions and Fermilab Collaboration (IIFC) [Ref. <http://iifc.fnal.gov/>], which is an integral part of the LBNE Collaboration. The design consists of a large-volume straw-tube tracking detector and electromagnetic calorimeter inside of a dipole magnet, and resistive plate chambers for muon identification located in the magnet yoke and upstream and downstream steel absorbers. High-pressure argon gas targets and other nuclear targets are embedded in the upstream part of the tracking volume. This system may be augmented by a magnetized LAr or GAr TPC.

3.2 Liquid Argon Far Detector

ELBNF proposes to construct a deep-underground neutrino observatory based on a 40 kton liquid-argon (LAr) time-projection chamber (TPC) [LAr1] at the Sanford Underground Research Facility. The LAr TPC combines fine-grained tracking with total absorption calorimetry to provide a detailed view of particle interactions,

making it a powerful tool for neutrino physics and underground physics such as proton decay and supernova-neutrino observation. It provides millimeter-scale resolution in 3D for all charged particles. Particle types can be identified both by their dE/dx and by track patterns, e.g., the decays of stopping particles. The modest radiation length (14 cm) is sufficiently short to identify and contain electromagnetic showers from electrons and photons, but long enough to provide good e/γ separation by dE/dx (one versus two minimum ionizing particles) at the beginning of the shower. In addition, photons can be distinguished from electrons emanating from an event vertex by the flight path before their first interaction. These characteristics allow the LArTPC to identify and reconstruct signal events with high efficiency while rejecting backgrounds to provide a high-purity data sample.

Potential designs for the ELBNF far detector have been developed by a number of groups, who now have come together within ELBNF, including both single-phase and dual-phase readout technology. The far detector may employ just one of these technologies, or possibly different technologies in a phased implementation, depending on the performance and developing maturity of the candidate designs. These options are being explored by several groups at the CERN Neutrino Platform (e.g. WA105) as well as Fermilab's short-baseline neutrino program.

The strategy for integrating these efforts and deciding on the type and configuration of the LBNF far detector system, including the possibility of phased implementation which may involve modules of different design, will be developed and presented in the full LBNF proposal that is anticipated to be submitted in mid-2015.

3.2.1 Dual Phase Option

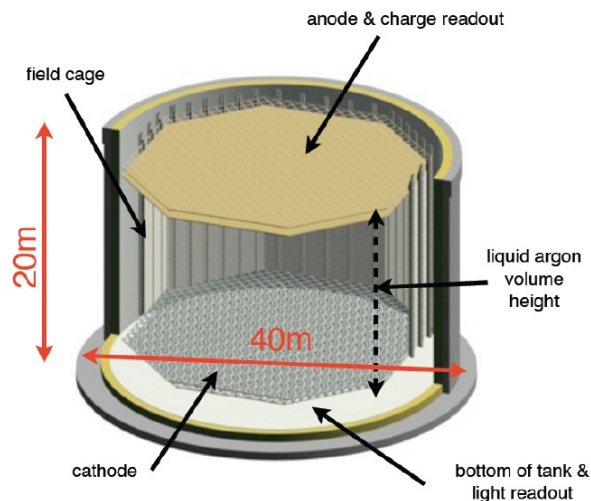
The LBNO Collaboration is developing a dual-phase readout LAr-TPC in which the ionization electrons are drifted vertically in the liquid, extracted into the gas phase, and gas-amplified in with a Large Electron Multiplier (LEM) stage before collection on the anode. The anode is assembled from modules that can be combined to produce a detector of any size[LAr2, LAr3]. The LAr detector has the shape of a vertically standing cylinder, where electrons are drifted vertically towards the liquid-vapor interface (See Figure *LAGUNA1*). The uniform drift field is created by an octagonal field cage composed of several equally-spaced stainless-steel tubes, supported by insulating mechanical structures which are suspended with stainless-steel ropes linked to the outer deck. The bottom field is closed by a transparent cathode and the top field by an anode, which also serves as the charge readout. Fully engineered and costed conceptual designs have been developed for the three mass options: 20, 50 and 100 kton, but optimized for the Pyhäsalmi mine location.

All three configurations assume a 20 m long drift for the TPC, and are composed of modular charge and light readout located respectively at the top and bottom of the tank. The light readout consists of PMTs uniformly distributed below the cathode. A cost-optimized installation sequence for an underground location and associated logistics has been considered and developed. Work is presently ongoing to best implement the layout for a double-phase detector to the specificities of the SURF environment. In particular, the double-phase readout could be readily adapted to a different shape of the cryostat, such as the parallelepipedic membrane vessel embedded in the rock, proposed in the context of LBNE. With such a shape, a single unit double-phase detector with 23.3kton active mass could be achieved with a 20m(w)x16m(drift)x52m(l) instrumented argon volume.

This new type of LAr-TPC, operating in the double-phase (liquid-vapor) mode in pure argon, is characterized by its charge amplifying stage (LEM) and its projective anode charge readout system. Situated in the vapor phase on top of the active LAr volume, these latter provide an adjustable charge gain and two independent readout views, each with a canonical and optimal pitch of 3 mm, since the amplification stage produces sufficient charge to be shared among several readout electrodes operated in collection mode (smaller pitch sizes and more than two independent readout views could be considered), eliminating the drawbacks introduced by induction views. With t_0 time information provided by the LAr scintillation, they provide a real-time three-dimensional (3D) track imaging with dE/dx information and the detector acts as a high-resolution tracking-calorimeter. A high signal-to-noise ratio on 3 mm pitch or less, and a very low energy detection threshold (<100 keV) can be reached and maintained over very large active argon volumes in the LAr LEM-TPC thanks to the gas amplification stage, and therefore allows for long drift paths. The ionization charge is readout via cold-electronics embedded in the chimneys crossing the roof of the vessel. While cold because within the insulation layer of the cryostat, the front-end electronics remain accessible and upgradeable over the lifetime of the experiment without the necessity of emptying the main argon volume, removing the risk associated to failure of inaccessible active elements.

The performance of the double-phase readout has been extensively demonstrated with cosmic rays on small-scale devices up to 200 liters [LAr3a]. A test of a TPC with the scale of 1 m x 3 m anode plane and a 1-meter drift is currently under construction at CERN. It is planned to build a 6 m x 6 m x 6 m TPC demonstrator (WA105 approved experiment) [LAr4] inside a 8 m x 8 m x 8 m cryostat, illuminated by a charged particle test beam, in the CERN Neutrino Platform. Construction has started for an extension of the EHN1 building in the North Area at CERN to house this and potentially the LBNE test., with the goal of executing initial beam tests before the start of the next long shutdown for LHC upgrades. The

double-phase readout of the WA105 detector will be 36 m^2 or $\approx 1:30$ of the required area for the 23.3kton detector for SURF. Working as independent detector readout modules, scaling up from the $6\text{m} \times 6\text{m} \times 6\text{m}^3$ to the 23.3 kton will be straightforward and rely on the parallel production of 65 independent $4\text{m} \times 4\text{m}^2$ readout units (See Figure *LAGUNA1* right), to be assembled and tested offsite before installation at SURF. The WA105 team also plans to develop and test a cathode high-voltage system up to 600 kV. All components such as cables, connectors, etc. used in the 400kV industry standard are tested and must hold 600 kV. A 16 m drift considered for the 23.3 kton detector at SURF at a nominal drift field of 0.5 kV/cm and velocity of $1.5\text{mm}/\mu\text{s}$ would require an extrapolation to a cathode voltage of 800 kV. In the engineering design, a maximum field of 50 kV/cm for a conservative 2 MV has been imposed [LAr3] therefore one expects a discharge free operation at the nominal drift field. For additional safety, one could also operate efficiently with a drift field of 0.4 kV/cm or $\approx 600 \text{ kV}$, reducing the electron drift velocity to $1.4\text{mm}/\mu\text{s}$ and taking advantage of the adjustable charge amplification in the LEM stage. The requirements on liquid argon purity for the double-phase design are similar to those for the single-phase design, since the large S/N ratio guarantees that 100% efficiency in hit reconstruction on both readout views, even after electron cloud diffusion over long paths, and potential charge attenuation due to attachment to the remaining traces of electronegative impurities.



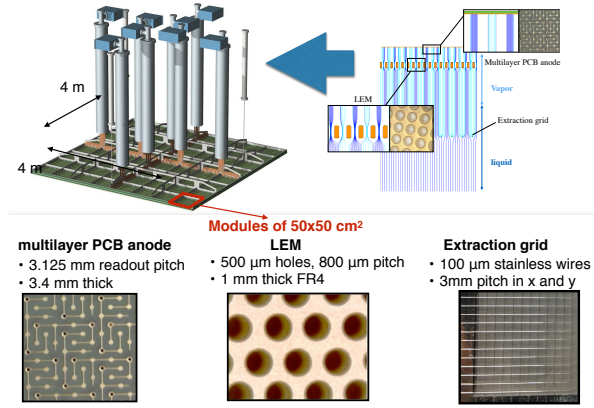


Figure *LAr1*. (left) Schematic view of the 20 kt double-phase LAr detector optimized for the Pyhäsalmi mine location. Engineering work is presently being performed to optimize the geometry to a SURF location (right) the basic $4 \times 4 \text{ m}^2$ double-phase readout unit with their extraction, LEM amplifying stage and anode layer. In total 65 such units of $4 \times 4 \text{ m}^2$ will be needed for the 23.3kton detector.

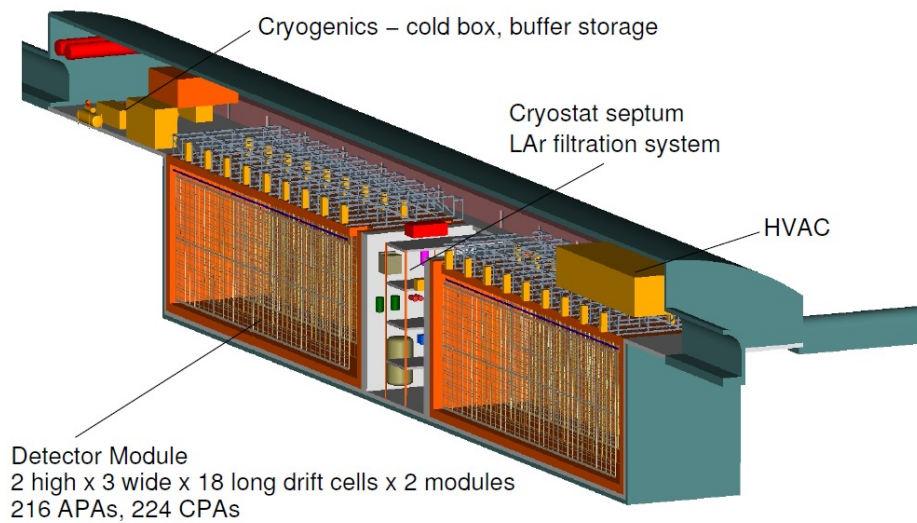
3.2.2 Single Phase Option

The LBNE Collaboration is developing a design for a single-phase LAr-TPC in which the ionization electrons are drifted horizontally and collected directly in the liquid on wire planes without amplification[LAr5, LAr5a]. This design is based on the successful INFN ICARUS detector[LAr6]. It takes a modular approach based on factory-built anode planes, which can be assembled in configurations and quantities depending on the total size of the far detector. Specific designs have been developed for 10 kt and 34 kt fiducial mass detectors.

The LAr TPC design (Fig. *LAr2*) utilizes a rectangular cryostat embedded directly in and supported by the rock in a dedicated cavern within SURF. This design maximizes the use of the excavated volume and therefore maximizes the detector mass within cost constraints. The cryostat is divided into two identical modules to aid with detector commissioning (one cryostat can serve as a storage vessel for the other, if an early intervention is required) and to enhance uptime in case one detector must be off-line.

The TPC itself consists of alternating rows of cathode plane assemblies (CPAs) and anode plane assemblies (APAs). The modular design allows flexibility in the choice of anode-cathode spacing. Based on considerations of expected purity, signal-to-noise requirements and diffusion of the electron cloud, the spacing between CPA and APA rows has been set to 3.7 m. With an electric field of 500 V/cm, the maximum drift time is 2.3 ms. The single-wire detection threshold is estimated to be $\leq 1 \text{ MeV}$.

The APAs and CPAs are designed in a modular fashion and have dimensions 2.5m long and 7m high. See the right side of Fig. *LAr2*. Three sense wire planes (two induction planes and one collection plane) with wire pitches of 4.8 mm are mounted on each side of an APA frame, providing three views both for redundancy and to aid in reconstructing complex events. Wire pitch as low as about 3 mm has been considered, and the final configuration of wire pitch and stereo angle of the three views will be determined through both physics and cost optimization exercises currently in progress. During installation, two APAs are connected end-to-end to form a 14m tall, 2.5m long unit, and pairs of CPAs are installed in a similar fashion. This system of 2.5m long detector elements is easily scalable to any desired detector size. A field cage for shaping the electric field covers the top, bottom, and ends of the detector. Scintillation light detectors, to provide the t_0 for the drift time measurement, consist of acrylic bars coated with wavelength shifter which are read out by silicon photomultipliers. These detectors are fitted within the gap between the wire planes on the two sides of the APA, thereby making efficient use of the space inside the cryostat.



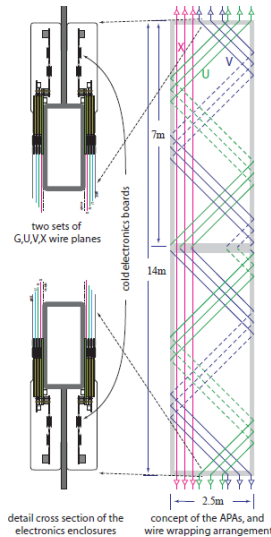


Fig. *LAr2*. Schematic of a 34-kt fiducial mass LArTPC design (left) The detector comprises two 17-kt fiducial mass LArTPC detectors. The design of a pair of Anode Plane Assemblies is shown in the right-hand figure.

Low-noise, low-power CMOS preamplifier and ADC ASICS have been developed for deployment on circuit boards mounted directly on the APA frames. This scheme minimizes the capacitance to ensure good signal-to-noise performance. It offers the possibility of digital signal processing, including multiplexing and zero suppression at the front end, thereby limiting the cable plant within the cryostat and the number of penetrations required, while also easing requirements on the downstream readout and DAQ systems located outside the cryostat. The ASICS have been laid out following design rules developed explicitly for long-term operation at cryogenic temperatures. The same cold preamplifier is used in the MicroBooNE detector[LAr6a], which will allow an early and robust test of this design.

A complete cost estimate and resource-loaded schedule for the development, design, construction, installation and commissioning of the detector has been developed[LAr6b], and thoroughly reviewed by independent external review committees reporting to the Fermilab Director [LAr6c] and the U.S. Department of Energy[LAr6d].

The design of this detector is based on extensive R&D done as part of an integrated program of LAr TPC R&D, which includes: the Material Test Stand[LAr7], which addresses issues related to argon purity; the Liquid Argon Purity Demonstrator[LAr8], which has demonstrated the ability to achieve long electron lifetime in liquid argon without evacuation of the cryostat and now serves as a vessel for performing R&D tests of TPCs and other detector components; the

ArgoNeuT detector[LAr9], a small LAr TPC which was exposed to the NuMI beam; and MicroBooNE[LAr6a], a 170 ton Liquid Argon Time Projection Chamber (LArTPC) which will begin taking data in the Fermilab Booster Neutrino Beam in early 2015.

A small-scale prototype, utilizing reduced-scale anode planes of the same conceptual design as those planned for the full detector, is currently being assembled inside a cryostat at Fermilab that can hold 35 tons of LAr. It will be tested with cosmic rays in the first half of 2015. An Expression of Interest [LAr10] contemplating a full-scale prototype for an engineering as well as a beam test has been reviewed by the CERN SPSC and they have invited submission of a full technical proposal.

3.2.3 Other Development Programs

Other world-wide efforts on LAr TPC development which will also benefit the development of the LBNF far detector include the upgrades of the ICARUS detector (WA104)[LAr11] for possible use in a short-baseline program at Fermilab, MicroBooNE[LAr6a], the proposed LAr1-ND experiment[LAr12] at Fermilab, the LArIAT test beam program[LAr13], ARGONCUBE[LAr14], and other smaller scale R&D programs.

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3.3 Fine Grained Near Detector

The LBNF Near Detector is required to:

- Measure the relative abundance and energy spectrum of all four species of neutrinos in the LBNF beam, muon-neutrino ($\nu\mu$), muon-antineutrino ($\bar{\nu}\mu$), electron-neutrino (νe), and electron-antineutrino ($\bar{\nu}e$), to a few percent;
- Determine the absolute neutrino and antineutrino flux to measure the cross sections to $\sim 3\%$, precision necessary to interpret the far detector signal and backgrounds;
- Quantify the asymmetries between neutrinos and anti-neutrinos, including energy scales and interaction topologies, for the CP-violating phase;
- Predict the FD flux relative to ND, FD/ND, to within a few percent for all four species;
- Measure the backgrounds to the oscillation signal, i.e. π^0 , π^- , and π^+ yields, both in charged-current (CC) and neutral-current (NC) interactions;
- Characterize various exclusive (semi-exclusive) channels such as Quasi-Elastic (QE), Resonance (Res), Coherent-mesons and Deep-Inelastic-Scattering (DIS);
- Quantify the neutrino-nucleus cross-sections by measuring interactions off nuclear targets, most notably Ar and Ca targets, to account for nuclear effects while interpreting the FD signal; and
- Provide rich physics, comprising a generational advance in the precision measurements and sensitive searches unique to neutrinos.

To meet the above requirements, a high resolution, magnetized ND capable of measuring negative & positive muons and electrons with high efficiency is needed. This would require a low-density detector with a commensurately long physical radiation length for the footprint of an event's constituent particles to be sufficiently distinct. The ND would include (1) high fidelity identifications of μ^- , μ^+ , e^- and e^+ to ID the four neutrino species, the e^-/e^+ ID also being necessary to measure the photons to reconstruct the π^0 ; (2) good momentum and dE/dx resolution to measure the charged hadrons (π^+ , π^- , p , K^+ , K^-) (see Fig. *PartID*), and neutral hadrons (π^0 , K^0 , Λ); (3) adequate containment to reconstruct the 3-momenta of the particles; (4) fast-readout to handle the event rates; (5) nuclear targets, including Ar & Ca, to not only empirically measure the ν -Ar effects but to precisely model these effects (see Fig. *Nuclear-Targets*); (6) sufficient target mass

to provide an order of magnitude higher systematic and statistical precision than in the current most precise experiment; (7) 4π calorimetric and muon coverage to measure neutral hadrons and muons, and to veto particles from outside. Requirement (5) is that one of the target nuclei the same as that in the far detector to allow cancellation of systematic errors, and inclusion of other target nuclei would provide constraints for accurate modeling of nuclear effects. Such a detector, placed in the high-intensity neutrino beam needed for the oscillation measurements, will collect a vast sample of neutrino interactions. This will enable a rich program in neutrino scattering physics addressing many non-oscillation topics, such as precision electroweak measurements.

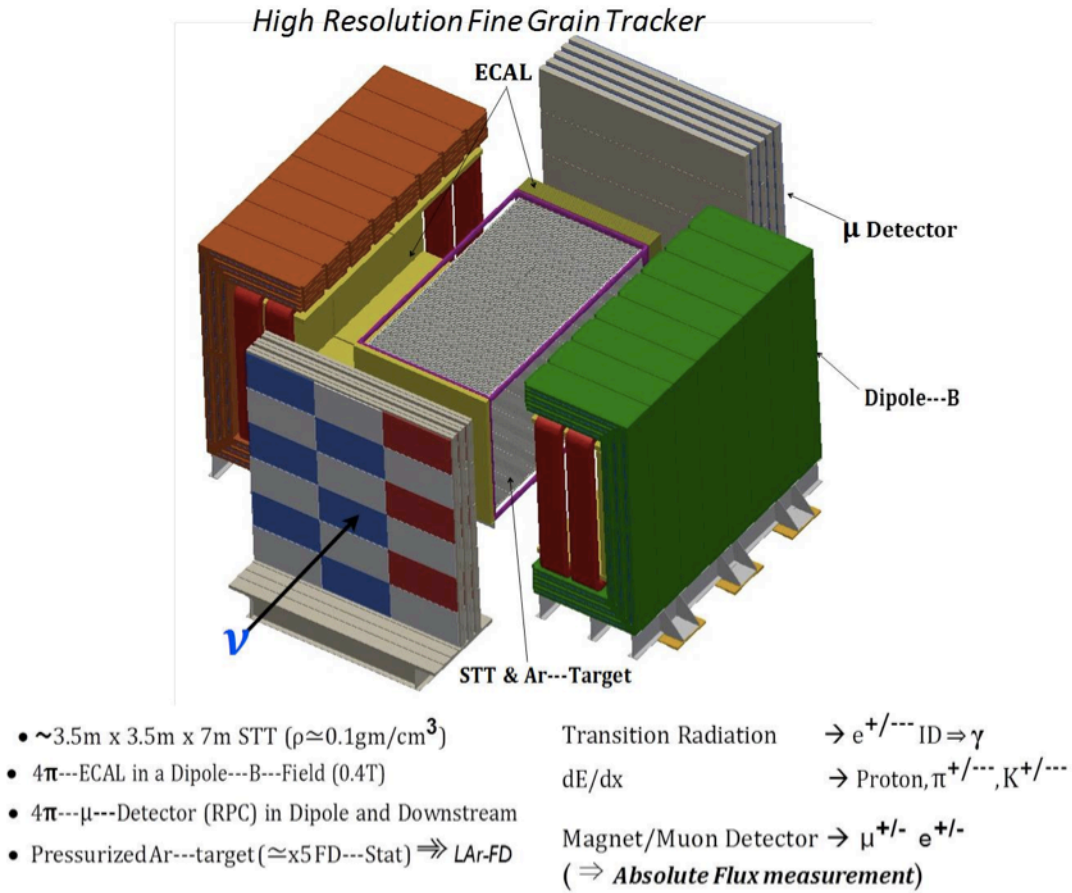


Figure *FGT-Schematic*: Schematic of the Fine-Grained Tracker Near Detector, with straw-tube tracker (STT), electromagnetic calorimeter (ECAL), large-aperture dipole magnet, and resistive plate chamber (RPC) muon detectors.

The active target is composed of the straw tube tracker (STT) equipped with the transition radiation (TR) capability to distinguish electron/positron (with Lorentz factor >1000) from muon/pions with high efficiency and purity. The low average density of the target, $\sim 0.1\text{gm/cm}^3$ (similar to that of liquid hydrogen), combined

with the granularity of the STT, provides excellent momentum and angular resolutions for μ^+ , μ^- , e^+ , e^- , π^+ , π^- , π^0 , proton, and K^0 produced in ν -induced interactions – see Figure [FGT-PartID]

The proposed FGT would fulfill the ND-requirements introduced above. In particular, the ND would: (1) Completely measure the neutrino source, allowing a precision on ν_e/ν_μ and ν_e/ν_μ Bar with 1% precision or better; (2) Measure the absolute neutrino flux using neutrino-electron scattering with 3% precision or better; (3) Determine the energy scale and topologies of neutrino and antineutrino interactions; (4) Accurately classify NC and CC interactions and determine the yields of $\pi^0/\pi^-/\pi^+$ dominant backgrounds to the oscillation signal from each; (5) Measure the (semi)exclusive processes such as QE, Resonance, Coherent-Meson; and (6) Conduct a rich panoply of measurements and searches unique to the neutrino physics engendering over 120 topics which over the lifetime of the experiment would create over two hundred papers and Ph.D. theses.

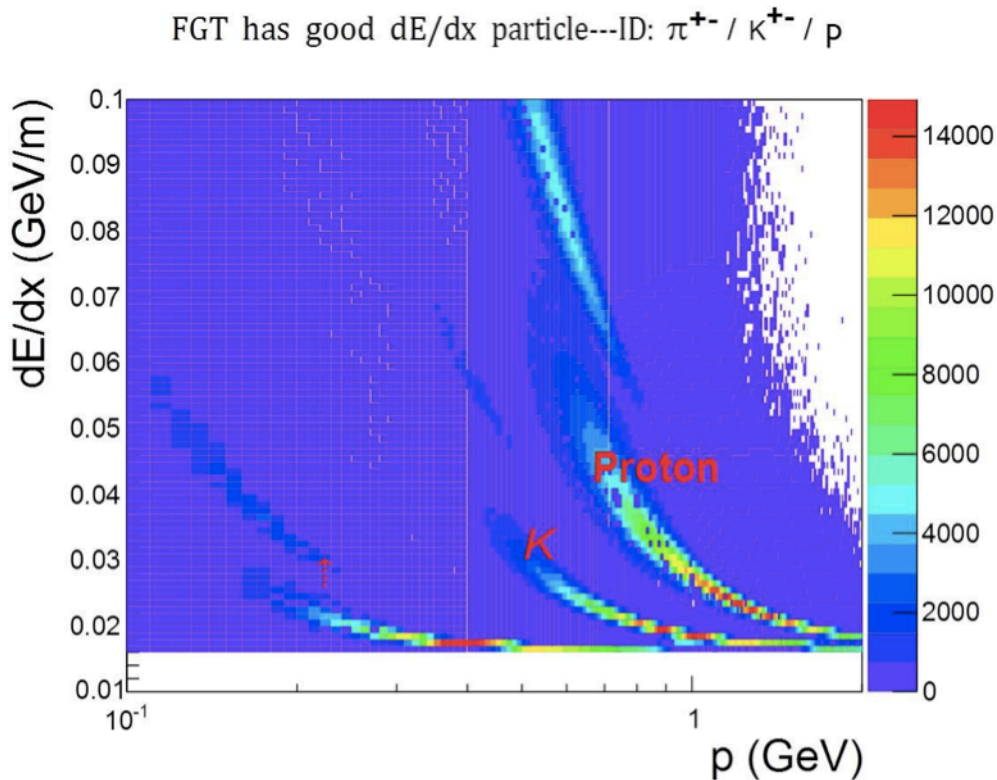


Figure *PartID*: Simulation of dE/dx versus momentum measured in the straw-tube tracker for hadrons produced in charged-current interactions.

(ANTI)NEUTRINO TARGETS

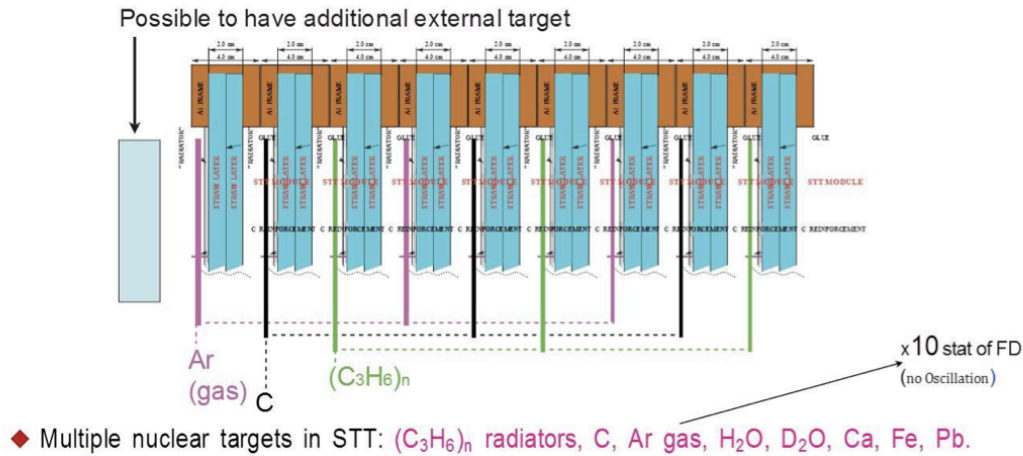


Figure *Nuclear Targets*: Schematic of nuclear targets (Ar, Ca, C, etc.) placed at the upstream end of the FGT. Note that pressurized Ar gas will be placed in aluminum tubes.

Not being identical to the FD, the one notable thing that FGT cannot do is 'cancel' the reconstruction inefficiency in FD. At the international NND workshop held at Fermilab (July 2014), the general sense was that the FGT offers a sound basis for moving forward and that a small liquid LAr detector placed upstream of the FGT would enhance the ND capability.

3.4 The Neutrino Beamline: Requirements and Conceptual Design

The Beamline is a central component of LBNF and its driving physics considerations are the long baseline neutrino oscillation analyses. It will aim a beam of neutrinos from Fermilab, with a 5.8° downward vertical bent, toward detectors placed at the Sanford Underground Research Facility (SURF) in South Dakota, about 1,300 km away. It is a wide band, sign selected beam, aiming to cover both the first and second oscillation maxima. The initial beam power is expected to be ~ 1.2 MW, however the facility is designed to be upgradeable for 2.4 MW operation. The Beamline design has benefited significantly from the design and operational experience of the NuMI beamline which is in operation since 2005.

The Beamline facility is expected to be fully contained within Fermilab property and its main elements are a primary proton beamline, a neutrino beamline, and conventional facilities to support the technical components of the proton and neutrino beamlines. The primary proton beam, in the energy range of 60-120 GeV, will be extracted from the Main Injector's (MI) MI-10 straight section using "single-turn" extraction. The beam is then transported with negligible losses to the target area within a beam enclosure embedded in an earthen, engineered filled embankment (hill) whose dimensions are commensurate with the bending strength of the required dipole magnets (see Figure 1). For 120 GeV operation and

with the MI upgrades implemented for the NOvA experiment as well as with the expected implementation of the accelerator Proton Improvement Plan, phase II (PIP-II), the fast, single turn extraction will deliver all the protons (7.5×10^{13}) in one MI machine cycle (1.2 sec) to the LBNE target in 10 ms. The accelerator complex and the primary beamline are planned to deliver about 11×10^{20} primary protons to the neutrino target per year for 1.2 MW operation for an uptime of 56%.

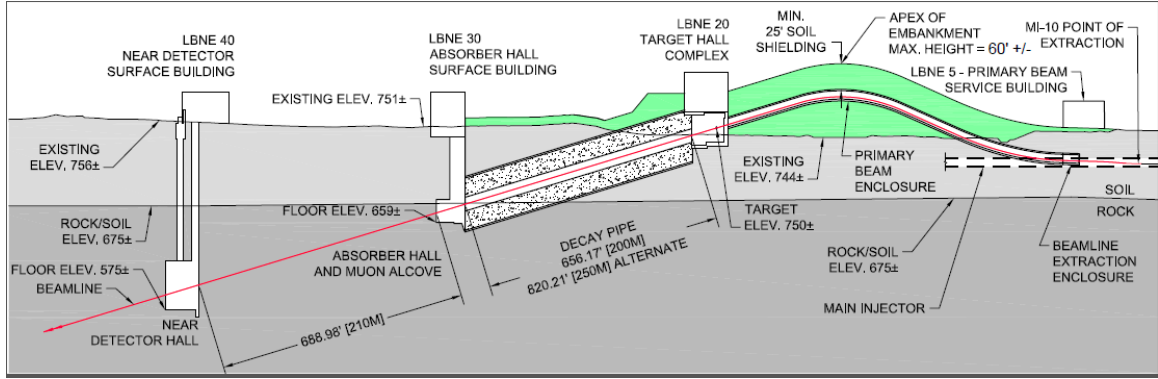


Figure 1: Longitudinal section of the LBNF beamline facility at Fermilab. The beam comes from the right, the protons being extracted from the MI-10 straight section of the MI.

Neutrinos are produced after protons from the Main Injector hit a solid target where approximately 85% of the protons interact producing pions and kaons which are subsequently focused by two magnetic horns into a decay pipe where they decay into muons and neutrinos. The neutrinos form a wide-band, sign-selected neutrino or anti-neutrino beam, designed to provide flux in the energy range of 0.5 to 5 GeV.

The reference target design for LBNF is an upgraded version of the NuMI-LE (Low Energy) target design that was used for 7 years to deliver beam to the MINOS experiment and was exposed to beam power up to 375 kW. The target is made out of graphite, it is segmented and about one meter long, and it is mounted together with a baffle on a carrier allowing for the flexibility to move the target with respect to the focusing devices, and therefore for a tunable neutrino energy spectrum. Focusing of charged particles is achieved by two magnetic horns in series, the first of which partially surrounds the target (See Figure 2). They are both NuMI/NOvA design horns with double paraboloid inner conductor profiles and currents of up to 230 kA.

The decay volume in the LBNF reference design is a helium-filled, air-cooled pipe of circular cross section with its diameter (4m) and length (204m-250m) optimized such that decays of the pions and kaons result in neutrinos in the energy range useful for the experiment. A 250m decay pipe is the maximum length that will allow the near neutrino detector complex to fit within the Fermilab site boundaries. At the end of the decay region, the absorber, a water cooled pile of aluminum and steel, is needed to remove the residual particles remaining at the

end of the decay pipe. An array of muon detectors in a small muon alcove immediately downstream of the absorber provide information on the direction, profile and flux of the neutrino beam.

In general, components of the LBNE beamline system which cannot be replaced or easily modified after substantial irradiation at 1.2 MW operation are being designed for 2.4 MW. Examples of such components are the shielding of the target chase and decay pipe, the absorber with its associated shielding and the remote handling.

In order to increase the neutrino event rates and before baselining the experiment we are considering:

- Development of more optimized horn designs which could boost the flux, especially in the low-energy region below the peak of the first oscillation maximum and down to the second oscillation maximum.
- Using materials for the target alternate to graphite (eg. Be) to increase the target longevity, as well as investigating different target shapes and dimensions. This would involve additional R&D effort.
- Increasing the length of the decay pipe up to 250 m (the maximum length allowed by the existing Fermilab site boundaries), and possibly the diameter of the decay pipe up to 6m.

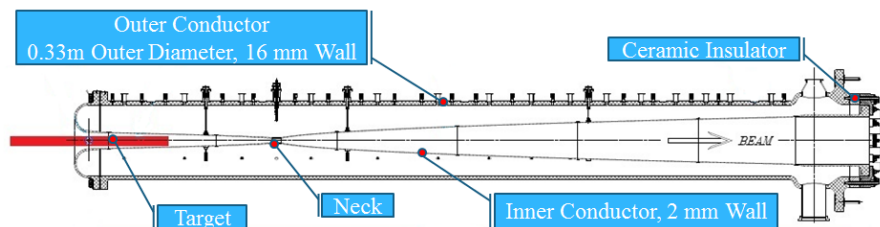


Figure 2: Longitudinal section of the first focusing horn with the target inserted into it. A current of 230 kA through the inner and outer conductors generates a toroidal field between the conductors (~ 3.4 T at the neck). A second horn, 6.6 m downstream, provides additional focusing to secondary particles.

3.5 Fermilab and SURF Facilities Requirements

The Sanford Underground Research Facility (SURF) in Lead, South Dakota, a dedicated deep underground research facility, has been selected as the location of the far detector for ELBNF. Figure 1 illustrates Sanford Laboratory's location within the region as a part of the northern Black Hills of South Dakota.

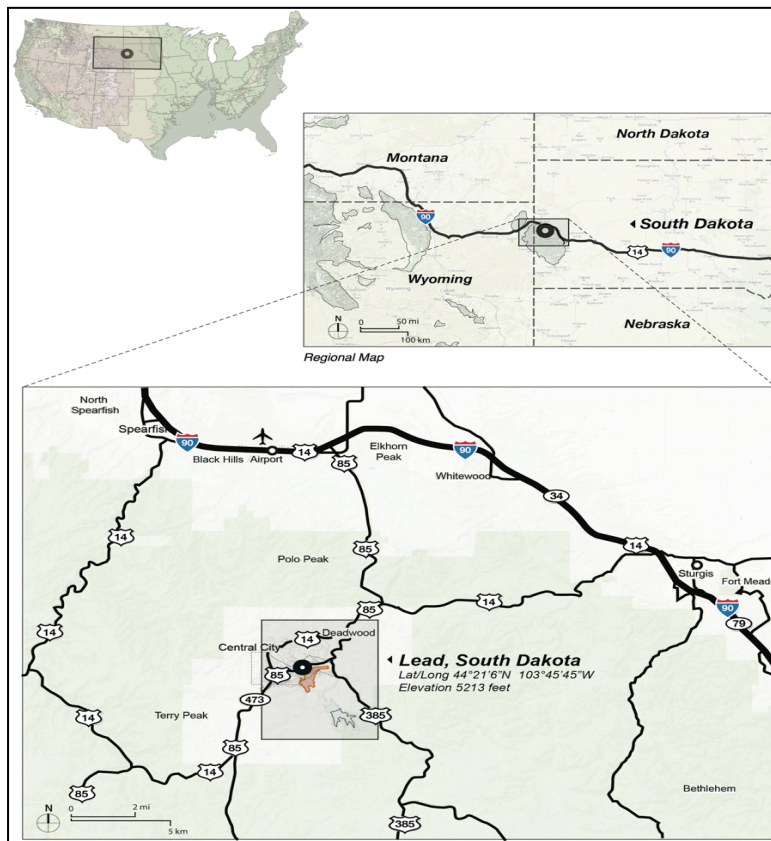


Figure 1. SURF's Regional context showing the city of Lead, South Dakota.

SURF is being developed in the former Homestake Gold Mine. Barrick Gold Corporation donated the site to the State of South Dakota in 2003, following over 125 years of mining. Mining operations created over 600 km of tunnels and shafts in the facility, extending from the surface to over 8000 feet below ground. The mining levels are distributed ~150 feet apart and are referenced by the feet below the entrance to the facility, therefore the level 4850 feet below ground is referred to as the 4850L. A historic cross section of the Homestake Mine is presented in Fig 2.

The South Dakota Science and Technology Authority (SDSTA) operates and maintains the Sanford Laboratory at the Homestake site in Lead, South Dakota through a contract managed and overseen by Lawrence Berkeley National Laboratory's (LBNL)'s SURF Operation's Office. The Sanford Laboratory property comprises 186 acres on the surface and 7,700 acres underground. The Sanford Laboratory Surface Campus includes approximately 253,000 gross square feet of existing structures. Using a combination of private funds, South Dakota Legislature-appropriated funding, a US Federal HUD Grant, and funding from NSF and DOE, the SDSTA has made significant progress in stabilizing and rehabilitating the Sanford Laboratory facility to provide for safe access and prepare the site for science experiments. The DOE now supports the operation of the facility, in addition to state and private funding. Both the NSF and the DOE support experiments at the

site.

The science program at SURF for the coming ~ five years is concentrated at two campuses located near the two main access shafts at the 4850L, the Davis Campus – site of the former Homestake Neutrino Experiment, and the Ross Campus as shown in Figure 3. The near term scientific program at SURF consists of the MAJORANA DEMONSTRATOR (MJD) neutrinoless double beta decay experiment, the Large Underground Xenon (LUX) dark matter search, the Center for Ultralow Background Experiments at Dakota (CUBED), and the geoscience installations. Plans are being developed to host the ELBNF Far Detector, a nuclear astrophysics program involving underground particle accelerators (CASPAR and DIANA), and second and third generation dark matter experiments. Additional details concerning SURF can be obtained from the Homestake DUSEL Preliminary Design Reporti .

The ELBNF far detector will be located in new excavated spaces near the bottom of the Ross Shaft, about 1km from the Davis Campus as shown in Figure 3. The 4,850-ft depth (4300 mwe) makes it extremely an extremely competitive location in terms of cosmic-ray background suppression for undertaking the nucleon decay and supernova neutrino studies that ELBNF plans to address. Another advantage of the proposed 4850L location for the ELBNF far detectors at SURF is the low level of rock radioactivity that could contribute backgrounds to the supernova burst neutrino signal and other low-energy physics searches. It was found that the U/Th/K radioactivity for the underground bedrocks at SURF is in general very low when compared to common construction materials such as concrete and shotcrete ii.

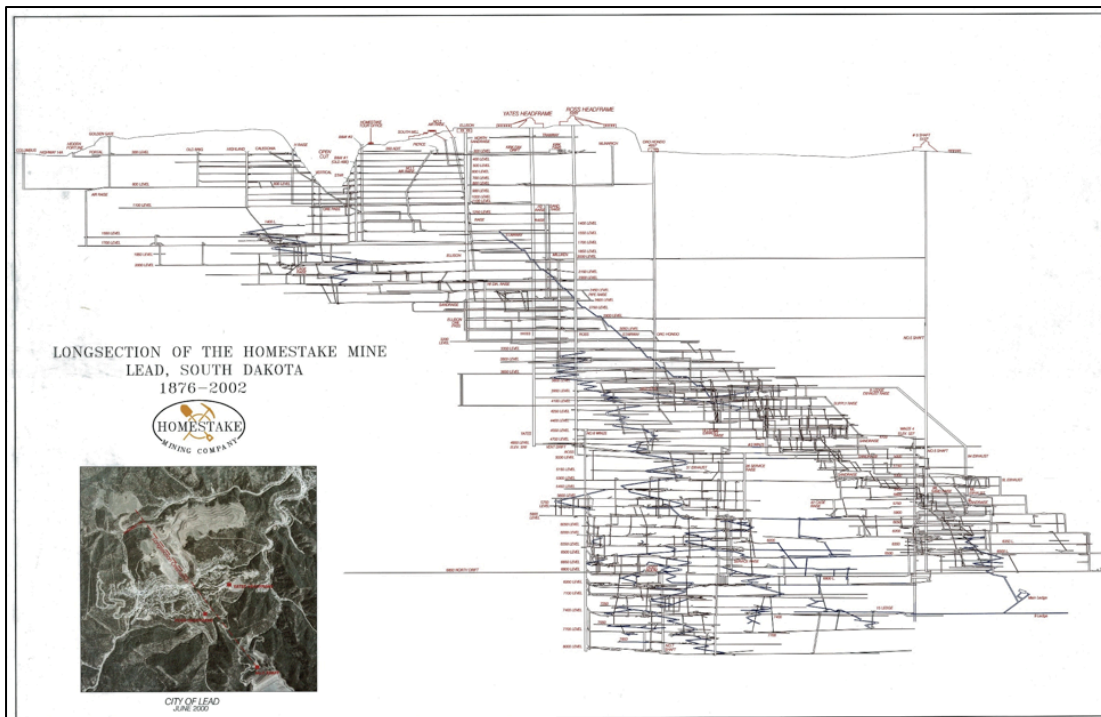


Figure 2. The long section of the former Homestake Gold Mine. This figure illustrates

the 60 underground levels extending to greater than 8,000 feet below ground. The location of cross section is indicated in the inset along a NW to SE plane. The projection extends for 5.2 km along this plane.

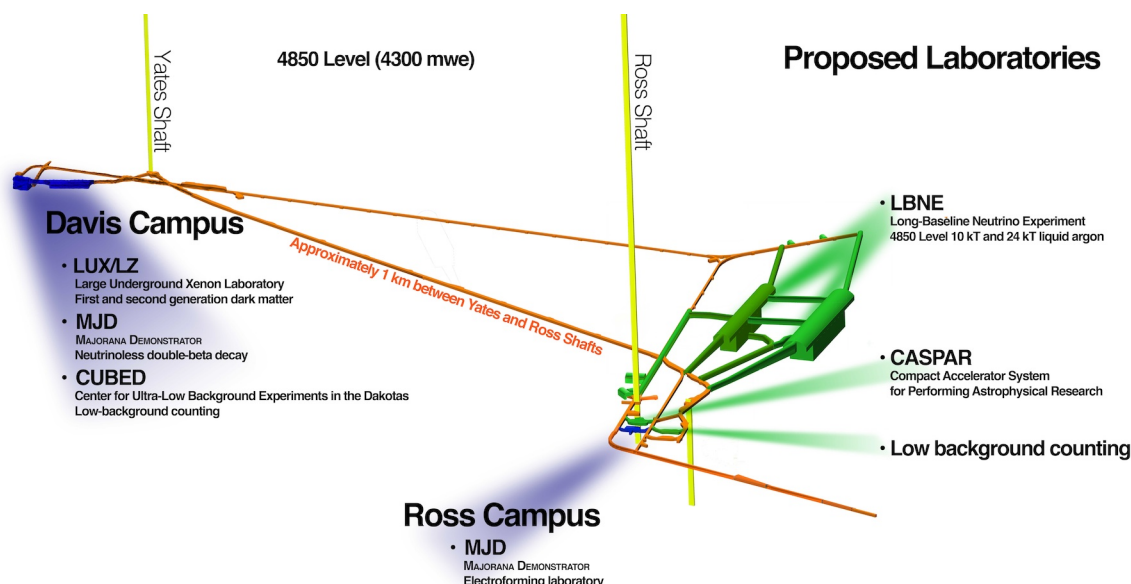


Figure 3. The 4850 (4300 mwe) level of SURF highlighting the existing and proposed experiments.

4.0 Organization ELBNF and LBNF

It is envisioned that the experiment proposed by the ELBNF detector collaboration in this LOI and the LBNF facility and the ELBNF detector collaboration would be two distinct entities. The international partners may contribute to either or both

The ELBNF Collaboration will be responsible for:

- The definition of the scientific goals and corresponding scientific and technical requirements on the detector systems and neutrino beam line.
- The design, construction, commissioning and operation of the detector systems.
- The scientific research program conducted with the ELBNF detectors and LBNF neutrino beam.

Fermilab will provide the high-intensity proton source that will drive the long-baseline neutrino beam, utilizing the existing Main Injector with upgraded injectors (PIP-II)[Ref. *get something from Steve Holmes*]. PIP-II is also being planned with significant international collaboration. Fermilab, working with and

with the support of international partners, will be responsible for the Long-Baseline Neutrino Facility, including:

- Design, construction and operation of the LBNF beamline, including the primary proton beam beamline and the neutrino beamline including target, focusing structure (horns), decay pipe, absorber, and corresponding beam instrumentation.
- Design, construction and operation of the conventional facilities and technical infrastructure on the Fermilab site required for the ELBNF Near Detector complex.
- Design, construction and operation of the conventional facilities and technical infrastructure within the Sanford site, including cryostat and cryogenic systems, required for the ELBNF Far Detector.
- Fermilab, as the host lab, will pay for the operating costs of the facility.

Close and continuous coordination between ELBNF and LBNF will be required to ensure the success of the combined enterprise. An Experiment-Facility Interface Group will be established (by Fermilab) to oversee and ensure the required coordination both during the design and construction and the operational phases of (E)LBNF. This Group will cover areas including

- Interface between the Near and Far Detectors and the corresponding conventional facilities.
- Interface between the detector systems provided by ELBNF and the technical infrastructure provided by LBNF.
- Design and operation of the LBNF neutrino beamline. This is a particularly important activity, since the neutrino-energy spectrum and other characteristics of the neutrino beam, and the ability to measure those characteristics, are a crucial part of the long-baseline experimental program.

The successful model used by CERN for managing the construction and exploitation of the LHC and its experiments will be used as a starting point for the joint management of LBNF and ELBNF. Fermilab, as the host laboratory, will have responsibility for the facilities, and for oversight of the experiment and its operations. Mechanisms to ensure input from and coordination among all of the funding agencies supporting ELBNF, modeled on the CERN Resource Review Board, will be adopted. The same (or similar) structure will be employed to coordinate among funding agencies supporting the LBNF construction and operation.

5.0 Scientific and Experimental Strategy

The above conditions are necessary for the previously independent worldwide experimental options to converge on a single facility and for the creation of a unique international collaboration with the necessary capabilities to develop a world-class experiment with FNAL acting as host. The new collaboration supporting this LOI includes key international players in ongoing supporting programs (such as the CERN Neutrino Platform) and this collaboration is in the unique position to propose a credible and effective experimental plan supported by a “Conceptual Design Report” (CDR) to be submitted in the summer of 2015, followed by a fully established cost and schedule (CD-2) by the end of 2017.

We are proposing a strong and timely strategy to benefit from the unique opportunity provided by LBNF:

- The ELBNF collaboration will rapidly establish itself as a world-class player in the deep underground physics field (accelerator and non-accelerator) through the construction of a modular set of detectors that are not necessarily identical but are of the similar mass.
- The construction of an initial 10-kton detector deep underground at Sanford laboratory on a timescale of 2021 is a top priority to begin the physics program and establish the collaboration in the neutrino landscape. This early first module installation will engage the collaboration, test all the aspects of the underground installation and operation, and will provide an early underground physics program as well as be ready for beam physics as soon as PIP-II is implemented.
- Remaining modules will follow in rapid succession in order to complete the 40 kton detector in a timely fashion.
- The new international collaboration will leverage the CERN Neutrino Platform as an important facility for detector design and development. The collaboration will also utilize the infrastructure of both its University partners and science laboratories located around the world.
- The collaboration will have the necessary expertise intellectual resources and critical mass to accrete the financial resources to design and implement this challenging plan.
- We expect to start data taking from accelerator operations in 2024 and extend until around 2035 (a decade of beam operations) in order to fully

exploit this remarkable facility.

- Our experiment offers a unique, exciting and challenging program that adopts a modular approach to get first science early and drive the establishment of the facility that will lead to the scientific discoveries that are core to the LBNF programme.

6.0 Plan and Questions in development of Conceptual Design Report

There are a number of key strategic decisions that will need to be addressed by the ELBNF collaboration as part of the writing of the CDR. For illustration, a sample of the issues to be addressed include:

- Examine the tradeoffs between a single large cavern as compared to multiple smaller, modular caverns.
- Determine the optimal construction strategy. Is it better to clone identical modules or to construct detectors with increasing volumes (as risks are mitigated)?
- Based on a given funding profile, how should the funds be allocated to optimize the scientific impact. When does a finely segmented near detector need to be in place?
- When does the neutrino beam line need to be completed – when PIP-II is ready or earlier in order to exploit 700 KW beam currently serving NOvA which could be deployed in the LBNF beamline as soon as the beamline is done?
- Define the final mix of technologies. Should the LAr technology be single phase, two-phase, or a combination of both?
- Consider the benefits of constructing a small (approximately 100 ton) demonstrator before 2021 in the underground laboratory at Sanford in order to retire technical/implementation risks.
- Determine the timeline for key decisions and establish milestones, such as CD-2/3 reviews to drive the program forward.
- Determine the roadmap to produce “CD-1 like” documentation (with detailed costing) within the coming year.

Immediate Plan Moving Forward

Given the scientific importance and urgency, the intention is to form the full EBLNF collaboration structure on a rapid timescale. In particular, as soon as possible, we as the newly forming collaboration intend to:

- Establish the collaboration, implement a governance model, and choose leadership for the collaboration.
- Determine the roadmap for the completion of the writing of a CDR and for the provision of the “CD-1 like” supporting material including a cost and schedule within the coming year.

7.0 Summary

This LOI establishes the first step in the creation of new, international collaboration that unifies the world’s two very long-baseline neutrino collaborations and other interested scientists from all over the world. It proposes to build a state-of-the-art liquid argon detector deep underground for the purposes of unraveling the mysteries of the neutrino, observing proton decay, and detecting thousands of neutrinos coming from a supernovae explosion, and a high-resolution near detector to support the measurements with the far detector and enable a rich program in neutrino scattering physics. This collaboration will exploit the major and expanded facilities foreseen at Fermilab and Sanford Underground Research Facility in order to carry out its science. To quickly establish itself on the world stage, the collaboration aims to have a 10-kton-module underground in 2021. The goal is to begin beam operations with the full scope detector in 2024 and the plan is to operate the experiment for more than a decade.

Appendix A – Signatures

To be added prior to presentation at the PAC

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- i Lesko, K.T., et al., “Deep Underground Science and Engineering Laboratory - Preliminary Design Report”, [arXiv:1108.0959](https://arxiv.org/abs/1108.0959), (2012)
 - ii C. Adams, et al., “The Long Baseline Neutrino Experiment. Exploring Fundamental Symmetries of the Universe”, arXiv:1307.7335 (2014)