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Status of the US Long Baseline Neutrino Experiment Study

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Abstract. The US Long Baseline Neutrino Experiment Study was commissioned jointly by Brookhaven National Laboratory and Fermi National Accelerator Laboratory to investigate the potential for future U.S. based long baseline neutrino oscillation experiments beyond the currently planned program. The Study focused on MW class conventional neutrino beams that can be produced at Fermilab or BNL. The experimental baselines are based on two possible detector locations: 1) off-axis to the existing Fermilab NuMI beamline at baselines of 700 to 810 km and 2) NSF's proposed future Deep Underground Science and Engineering Laboratory (DUSEL) at baselines greater than 1000km. Two detector technologies are considered: a megaton class Water Cherenkov detector deployed deep underground at a DUSEL site, or a 100kT Liquid Argon Time-Projection Chamber (TPC) deployed on the surface at any of the proposed sites. The physics sensitivities of the proposed experiments are summarized. We find that conventional horn focused wide-band neutrino beam options from Fermilab or BNL aimed at a massive detector with a baseline of > 1000km have the best sensitivity to CP violation and the neutrino mass hierarchy for values of the mixing angle θ_{13} down to 2.2°.

Keywords: neutrino,oscillation,mixing,long baseline
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INTRODUCTION

There are three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) made up of a superposition of three mass eigenstates (ν_1, ν_2, ν_3). It is believed that mixing between the flavor states is responsible for the phenomenon of neutrino oscillations. The two mass squared differences (Δm^2_{32} and Δm^2_{31}) govern how the oscillations evolve over time. The three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) govern the amount of mixing between the different flavor states. As there are at least three generations mixing, a complex phase (δ_{CP}) determines the amount of violation of charge-parity (CP) symmetry. Our current knowledge of the parameters governing neutrino oscillations comes from observations of atmospheric, solar, and reactor neutrinos and is summarized in ref. [1]. Currently, the value of the mixing angle, θ_{13} is unknown, but is expected to be $< 10^\circ$ at the 90% C.L. The sign of the mass difference Δm^2_{31} which determines the ordering of the mass eigenstates is also unknown and the value of δ_{CP} is unknown. The current generation of neutrino oscillation experiments have no sensitivity to the value of δ_{CP} - and hence cannot determine whether CP is violated in the neutrino sector - and very limited sensitivity to the mass hierarchy only if the true value of θ_{13} is close to the current limit of 10°. The goal of the next generation of neutrino oscillation experiments is to determine whether CP is violated in the neutrino sector and unambiguously determine the mass hierarchy.

The US Long Baseline Neutrino Experiment Study

Early in 2006, the management of Fermi National Accelerator Laboratory (FNAL, Fermilab) and Brookhaven National Laboratory (BNL) formed a joint task force charged with studying the physics capabilities and technical feasibility of future U.S. based long baseline neutrino oscillation experiments. The US Long Baseline Neutrino Experiment Study (hereby referred to as the Study) task force was charged to consider the following experimental options: 1) A broad-band proposal using a new neutrino beamline aimed at a detector in the National Science Foundation's proposed Deep Underground Science and Engineering Laboratory (DUSEL) 2) An upgrade to the proposed NOνA experiment [2] utilizing the NuMI beamline [3] and massive surface detectors located off-axis (narrow-band). In addition, the Neutrino Scientific Assessment Group (NuSAG), which advises the the U.S. Department of Energy (DOE) and the National Science Foundation (NSF), has requested input from the Study to aid NuSAG in addressing the American Physical Society's (APS) neutrino study's [4] recommendation for a "next-generation neutrino beam and detector configurations". In this report, we summarize the status of the Study's current findings which are discussed in detail in reference [5].

TABLE 1. Baseline options considered by the U.S. Long Baseline Neutrino Experiment Study using the Fermilab Main Injector (MI) and the Brookhaven Alternating Gradient Synchrotron (AGS) as neutrino sources.

Beam source	Far detector location	Baseline
FNAL MI	NuMI off-axis	$\leq$ 810 km *
FNAL MI	DUSEL-Homestake Mine, SD	1297 km
FNAL MI	DUSEL-Henderson Mine, CO	1480 km
BNL AGS	DUSEL-Homestake Mine, SD	2540 km
FNAL MI	DUSEL-Cascades, WA	2600 km

* This is the furthest distance from the NuMI beam a detector can be placed within the continental US.

Baseline options within the continental U.S.

Previous studies have demonstrated that excellent sensitivity to CP violation and the mass hierarchy can be achieved by searching for $\nu_\mu -> \nu_e$ appearance using very long baseline experiments with conventional broad-band neutrino beams and massive detectors [6]. In these studies, the sensitivity to CP violation and the mass hierarchy as a function of baseline were determined using a broad-band neutrino beam with a peak energy of around 2 GeV and assuming a massive water Cherenkov detector with a fiducial mass of 300 to 500 kT. We find that the sensitivity to CP violation is roughly the same for baselines between 500 - 1500km and worsens slightly for baselines > 1500km [6]. Sensitivity to the mass hierarchy improves by almost an order of magnitude when the baseline is increased from 500km to 1500km and is almost constant for baselines greater than 1500km. The baseline options considered by the Study are constrained to lie within the continental U.S. and are summarized in Table 1. Based on the results in reference [6], we conclude that the baseline options available within the continental U.S. can meet the goals of the next generation of long baseline neutrino experiments when matched to neutrino beams with peak energies in the range 1.5-5 GeV.

NEUTRINO BEAM SOURCES

The Study considered three possible sources of conventional horn-focused neutrino beams in the U.S.:

1. The existing NuMI neutrino beamline [3] at Fermilab, with upgrades to the 120 GeV Main Injector proton beam power to produce a 1-2 MW beam.
2. A *new* 1-2 MW neutrino beamline at Fermilab pointed towards DUSEL, utilizing an upgraded Main Injector.
3. A new neutrino beamline from an upgraded 28 GeV BNL Alternating Gradient Synchrotron with a beam power of 1-2MW.

A key ingredient in the design of any next generation neutrino oscillation experiment, is producing a MW class neutrino beam. For conventional horn-focused neutrino beams, increasing the beam power from the Fermilab or BNL proton accelerators necessitates upgrades to the current accelerator complexes. The Study demonstrated that modest upgrades to the existing Fermilab complex can increase the Main Injector beam power from the current 300 kW (NuMI) to 1.2 MW at 120 GeV. The upgrades needed, described in detail in [7] are summarized as follows:

Proton Plan for NuMI The proton plan for NuMI involves raising the beam power up to 430 kW using the technique of slip stacking proton batches from the 15 Hz booster such that up to 12 booster batches can be accommodated in the Main Injector during one acceleration cycle (currently 2 to 2.4 seconds).

Recycler Upgrades The 8 GeV recycler synchrotron at Fermilab currently stores excess anti-protons produced after the stack size in the anti-proton accumulator increases beyond the optimal level. When the Tevatron program shuts down in 2008-2009, the recycler can be used to store 8 GeV protons from the booster to further increase the proton intensity injected into the Main Injector while reducing the cycle time. This increases the power to 700 kW at 120 GeV.

Accumulator Upgrades A further upgrade envisioned uses the anti-proton accumulator to also store booster protons for injection into the Main Injector. This upgrade would raise the proton beam energy to 1.2 MW at 120 GeV.

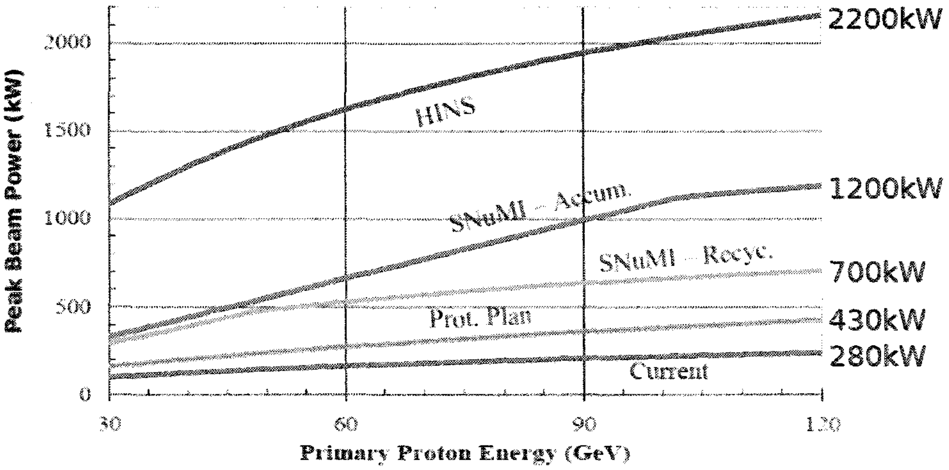

FIGURE 1. The Fermilab Main Injector proton power achievable as a function of proton beam energy for different accelerator upgrade options.

The upgrades of the Main Injector to operate at 700 kW are already planned as part of the NOνA project. Further upgrades beyond 1.2 MW have been proposed and require replacing the 8 GeV booster with a super-conducting linac and extensive Main Injector upgrades [8]. The Fermilab beam power achievable for each upgrade option as a function of beam energy is shown in Figure 1. In addition to upgrades at Fermilab, a conceptual design has been proposed for upgrading the BNL AGS to 1 MW using a super-conducting linac [9]. The maximum stable AGS proton beam energy achievable is 28 GeV.

The design specifications of the neutrino beams proposed by the Study are driven by the physics of $\nu_\mu \rightarrow \nu_e$ oscillations:

- Maximal possible neutrino fluxes to encompass the 1st and 2nd oscillation nodes. Measuring the oscillation parameters at different baseline/energy values helps to resolve the degeneracies between the values of θ_{13}, δ_{cp}, and the mass hierarchy. The first two oscillation maxima for normal hierarchy are at 1.6 and 0.5 GeV for a baseline of 810 km, at 2.4 and 0.8 GeV for a baseline of 1300km, and at 5 and 1.6 GeV for a baseline of 2500km.
- A high purity ν_μ beam (or $\bar{\nu_\mu}$) with negligible ν_e contamination is required.
- Its highly desirable to minimize the flux of neutrinos with energies greater than that at which the first oscillation maxima occurs to minimize the neutral-current feed-down contamination at lower energies.

Beamline design and simulations

To achieve the neutrino beam design specifications outlined above, we conducted detailed simulations and studies of the targeting design and materials, and optimization of the decay tunnel geometries.

The current NuMI design and simulations as used by the MINOS experiment to measure neutrino oscillations [10] are used to generate the neutrino energy spectra at different baselines and off-axis locations. We find that the low or medium energy tunes of the NuMI beamline produce spectra at baselines of 700-810km and off-axis angles of 0.8° and 3° that peak at the energies of the 1st and 2nd oscillation maxima respectively. The spectrum of neutrino events at the 1st and 2nd oscillation maxima at 810 km is shown in Figure 2 (A) and (B) respectively. The spectrum is normalized to an exposure of 1MW beam power, 10^7 seconds of running, and a mass of 1 kiloton. The oscillation probability is overlaid for a value of $\theta_{13} = 0.04$ and several values of δ_{CP} . The NuMI off-axis spectra are narrow-band spectra with a FWHM < 1 GeV. To measure $\nu_\mu - > \nu_e$ oscillations at the 1st and 2nd oscillation maxima using NuMI, two detectors need to be deployed at the different off-axis locations.

A quick survey of the Fermilab site determined that a new neutrino beamline directed towards DUSEL sites in the western U.S. can be accommodated on site. Site restrictions dictate that the maximum length of the target and decay region that can be accommodated is 400m. A wide-band low-energy (WBLE) target and horn design [9] was selected

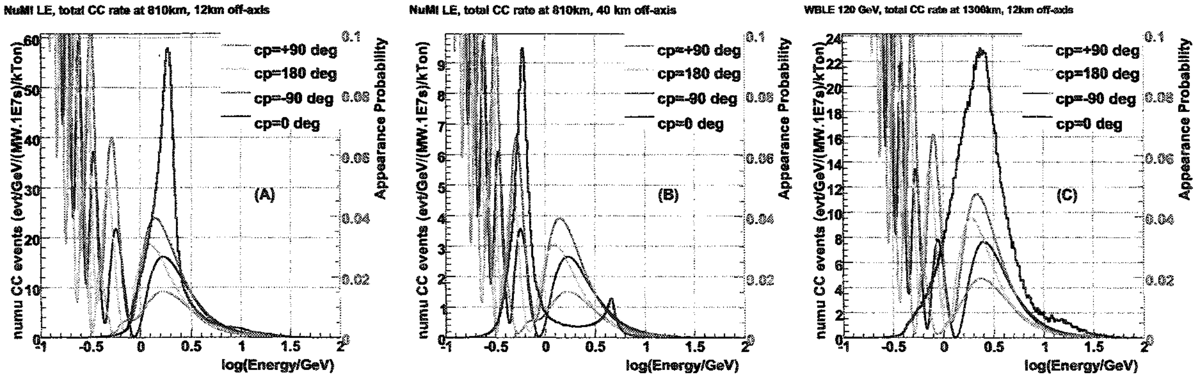

FIGURE 2. The total CC ν spectra (histogram) from (A) the NuMI LE tune at 0.8° off-axis, (B) 3° off-axis and, (C) the WBLE 120 GeV beam at 0.5° off-axis. Overlaid are the oscillation probabilities for different values of δ_{cp} at 810km (NuMI) and 1300 km (WBLE) for normal mass hierarchy with $\sin^2 2\theta_{13} = 0.04$.

for the design of a new Fermilab-DUSEL neutrino beamline. The simulation of the new beamline was implemented into the NuMI simulation framework. We studied the neutrino spectra produced using different proton energies and decay pipe geometries. The highest power proton beam from Fermilab is achieved at proton energies of 120 GeV. We selected a decay pipe with a diameter of 4m and a length of 380m (the NuMI decay pipe is 2m in diameter and 677m in length) and an off-axis angle of 0.5°. The spectra of neutrino events from the WBLE 120 GeV beamline at 0.5° off-axis is shown in Figure 2 with the oscillation probability at a 1300km baseline overlaid. The WBLE 120 GeV spectrum is a wide-band spectrum with a FWHM = 2.7 GeV, peaked near the 1st oscillation maxima and with significant flux at the 2nd oscillation maxima at the same far detector location. The WBLE 120 GeV spectrum is well matched to the spectrum obtained from the 28 GeV AGS beamline design that has been used in previous studies [6].

Neutrino event rates

The ν_e appearance event rate, R, at a given location $\vec{L}$, and for different values of $(\text{sign}(\Delta m^2_{31}), \theta_{13}, \delta_{cp})$ is as follows:

$$R(\vec{L}, \text{sign}(\Delta m^2_{31}), \theta_{13}, \delta_{cp}) = \int \mathscr{F}^{\nu_\mu}(\vec{L}, E_\nu) \cdot P^{\nu_\mu -> \nu_e}(\text{sign}(\Delta m^2_{31}), \theta_{13}, \delta_{cp}, E_\nu) \cdot \sigma^{CC}(E_\nu) dE_\nu \tag{1}$$

where $\mathscr{F}^{\nu}$ is the flux of ν_μ obtained from the beamline simulation, P, is the probability of $\nu_\mu -> \nu_e$ oscillation, and σ^{CC} is the total charged-current ν_e interaction probability. The values of the other neutrino oscillation parameters that govern the appearance probability are as follows

$$\sin^2(2\theta_{12}) = 0.86, \Delta m^2_{21} = 8.6 \times 10^{-5}\text{eV}^2, \sin^2(2\theta_{23}) = 1.0, \Delta m^2_{32} = 2.5 \times 10^{-3}\text{eV}^2 \tag{2}$$

The average density profile of the earth used to compute the matter effect on the oscillation probability is implemented using the Reference Earth Model [11].

Table 2 summarizes the event rates expected at select far detector locations using the Fermilab neutrino beam designs described in the previous section. The rates are given for normal/reversed (+/-) mass hierarchy and for different values of θ_{13} and δ_{CP}. The table indicates the rates for $\nu_\mu -> \nu_e$ oscillations as well as the charge conjugate $\bar{\nu}_\mu -> \bar{\nu}_e$ rates produced by reversing the horn currents to preferentially select $\bar{\nu}_\mu$. The oscillation probabilities for ν_μ and $\bar{\nu}_\mu$ are expected to be different due to the matter effect. The event rates are given in units of 100kT.MW.10^7s.

PROPOSED FAR DETECTOR DESIGNS

The neutrino event rates shown in Table 2 for values of θ_{13} of 0.02 ($\theta_{13} = 4°$) indicate the need for very massive, efficient detectors and MW class beams to achieve the event rates needed to push the sensitivity to low values of θ_{13}.

TABLE 2. Signal and background interaction rates for various Fermilab conventional neutrino beam configurations and baselines. Rates are given per 100 kT.MW.10^7s. The irreducible background rates from beam ν_e are shown integrated over the signal region (*=0-3 GeV, **=0-5 GeV). No detector model is used.

		$\nu_\mu \to \nu_e$ rate				$\bar{\nu}_\mu \to \bar{\nu}_e$ rates			
(sign of Δm^2_{31})	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	-90°	180°	+90°	0°	-90°	180°	+90°
NuMI LE beam tune at 810km, per 100kT. MW. 10^7s									
0.8° off-axis		Beam $\nu_e = 43^*$				Beam $\bar{\nu}_e = 17^*$			
(+)	0.02	76	108	69	36	20	7.7	17	30
(-)	0.02	46	77	52	21	28	14	28	42
3° off-axis		Beam $\nu_e = 11^*$				Beam $\bar{\nu}_e = 3.4^*$			
(+)	0.02	5.7	8.8	5.1	2.2	2.5	1.6	0.7	3.3
(-)	0.02	4.2	8.0	5.7	2.0	2.3	2.2	0.8	3.6
WBLE 120 GeV beam at 1300km, per 100kT. MW. 10^7s									
0.5° off-axis		Beam $\nu_e = 47^{**}$				Beam $\bar{\nu}_e = 17^{**}$			
(+/-)	0.0	14	N/A	N/A	N/A	5.0	N/A	N/A	N/A
(+)	0.02	87	134	95	48	20	7.2	15	27
(-)	0.02	39	72	51	19	38	19	33	52

The proposed far detector locations considered impose another set of constraints on the detector technology that can be used:

Locations off-axis to the NuMI beamline: These locations necessitate the use of a surface detector with limited overburden, but can accommodate several detectors at different locations. A massive detector deployed at the surface has to handle a very high rate of cosmic muon events - 500 kHz for a tank 50m in diameter and 50m in height (100kT of water) - while incurring low dead-time [1]. The surface restriction excludes the use of massive water Cherenkov detectors.

DUSEL based locations: When considering the longer baselines of a Fermilab-DUSEL or BNL-DUSEL program, on-axis or nearly on-axis beams are preferred to utilize the maximum possible flux at both oscillation maxima in the same detector. This increases the background contamination from neutral-current neutrino interactions that produce π^0s. Therefore, DUSEL based detectors require excellent neutral current background rejection. Both surface and deep underground detectors, including massive water Cherenkov detectors, can be accommodated at a DUSEL site.

The two detector technologies considered by the study are 1) a fully active finely grained liquid Argon time-projection-chamber (LAr-TPC) with a total mass of $\sim$ 100 kT which is suitable for both NuMI and DUSEL based locations, and 2) a massive water Cherenkov detector with a mass 300-500 kT which can be deployed at DUSEL locations.

Liquid Argon TPC

The Study group has conducted preliminary simulation studies of a finely segmented liquid Argon time-projection-chamber (LAr-TPC). Preliminary reconstruction and manual scanning studies of the simulations have indicated that a finely-segmented LAr-TPC could achieve a very high efficiency for selecting neutrino interactions (80% of all ν_e charged-current events) with the excellent π^0 identification needed to reject neutral current backgrounds. Preliminary results also indicate that excellent neutrino energy resolution in such a detector could be achieved: $20\%\sqrt{E}$ for charged-current inelastic events and $5\%\sqrt{E}$ for quasi-elastic ν_e interactions. The ν_e appearance smeared signal and background obtained from a parameterized simulation of a 100 kT LAr-TPC implemented in the GLoBeS [12]

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[1] For a 10 μ second proton beam spill time this corresponds to 4 muon tracks in the detector.

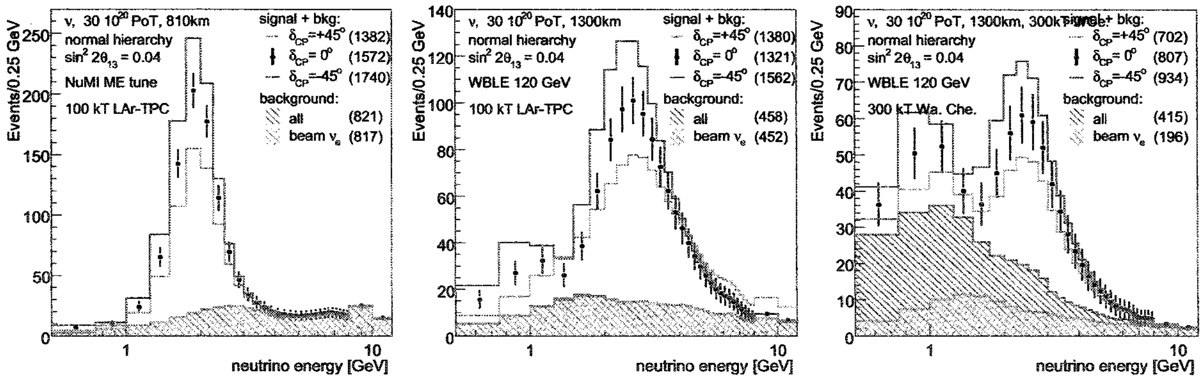

FIGURE 3. The simulated ν_e appearance spectra from the NuMI ME beam at 810 km and 0.8° off-axis as seen in a 100 kT LAr-TPC (left), the appearance spectra from a WBLE 120 GeV beam 0.5° off-axis at 1300 km as seen in a 100 kT LAr TPC (middle), and in a 300 kT water Cherenkov detector (right). The spectra shown are for normal mass hierarchy with $\sin^2 2\theta_{13} = 0.04$ and an exposure of 3.4 MW.yr

package is shown in Figure 3. The points with error bars are the observed signal+background events from a NuMI off-axis beam at 810 km (left plot) and the WBLE beam from Fermilab-DUSEL at 1300 km (middle plot). The oscillation parameters used are $\delta_{cp} = 0, \sin^2(2\theta_{13}) = 0.04$ and an exposure of 30×10^{20} protons. The shaded histogram is the total background. For LAr-TPC the background is predominantly the irreducible background from ν_e originating in the beam. The solid histograms are for data+background with different values of δ_{cp}. In addition, such a detector has excellent detection efficiency for the proton decay mode $p- > k\nu$. The main challenges facing the LAr-TPC technology are associated with the construction of a massive detector on the scale needed for the next generation of neutrino or proton decay experiments ($\sim$ 100 kT). The largest LAr-TPC built is the ICARUS T600 module [13] which has a mass of 600 tonnes. The Study has identified the following challenges to the construction of a massive LAr-TPC that need to be addressed:

Construction of the drift wires and Argon purity: The active volume of a massive 50 kT TPC proposed for this Study has a cylindrical diameter of 40m and a height of 30m, with 36 wire planes extending the height of the detector. R&D programs are ongoing on assembling such long wire planes, and designing the electronics needed to handle noise from long wires. The long electron drift times in such a massive detector require higher Argon purity than is available commercially. Other designs that avoid long wire planes and drift times are under study.

Operation at surface locations: The Study identified a massive LAr-TPC as the best candidate technology for a surface detector off-axis to the NuMI beam. The long drift times associated with some of the designs proposed pose a significant challenge to pattern recognition, and live-times on the surface. For a 50 kT module with signal collected over 3 drift times after each beam pulse, the rejection required is $\sim 10^8$ for cosmic muons and $10^3 - 10^4$ for photons from cosmics. Achieving such rejection factors has not yet been demonstrated in simulations.

Operation underground: Operating a LAr-TPC underground would ameliorate the challenges posed by backgrounds from cosmics and would allow the detector to be used for proton decay experiments [2], but would require more expensive liquefied gas storage solutions as well as extensive safety systems. More R&D is required to design the underground cavities needed for such a detector.

Understanding cost and schedule: Two of the primary cost drivers for a LAr-TPC are the cost of the liquid Argon and the containment tank. For surface operation, the Study estimates that for a 50kT TPC the cost is \$68M for the material and the containment tank. Other costs such as the wire planes, electronics, argon purification system, labour...etc have not been reliably determined yet, nor have the additional costs for operation underground.

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[2] Proton decay searches may still be possible in a surface detector with very high bandwidth data-acquisition systems but this has yet to be demonstrated.

Massive Water Cherenkov Detector

The massive water Cherenkov detector designs considered by the Study are based on well known technology and scaled up from the largest existing detector - Super-Kamiokande (SuperK) [14]. The SuperK water Cherenkov detector is a cylindrical detector 41.4m in height and 39.3m in diameter with 50 kT in total mass. Conceptual designs for a 400kT fiducial detector at DUSEL-Henderson mine and a 300 kT modular detector design at DUSEL-Homestake have been proposed. The modular detector design at DUSEL-Homestake involves 3-5 detector modules, each 100 kT in fiducial mass (53 m in height and 53 m in diameter) in separate caverns 4850 feet underground [15]. Each module is thus a modest scale-up of the existing SuperK detector and cavern. The challenge for water Cherenkov detectors located at DUSEL is demonstrating that adequate background suppression of neutral current interactions produced by the higher energy neutrinos in the wide-band on-axis beams can be achieved. A study of improved techniques used to suppress the π^0 backgrounds using the SuperK full detector simulation and reconstruction is reported in these proceedings [16]. This study indicates that for a wide-band long baseline beam the total signal efficiency is $\sim 14\%$ of all ν_e charged current and $\sim 0.4\%$ of all neutral current. The energy dependent ν_e signal and background efficiencies, and the detector smearing functions obtained from the SuperK simulation were implemented in GLoBeS. The appearance spectrum and background from the WBLE 120 GeV is shown in Figure 2 on the right, assuming a detector mass of 300 kT and the same beam exposure as with the 100 kT LAr-TPC shown in the same figure. The preliminary cost for a 300 kT fiducial modular water Cherenkov detector at DUSEL-Homestake has been estimated. The cost, including cavern excavation and a 30% contingency, is $335M [15].

PHYSICS SENSITIVITIES

The oscillation physics sensitivities of the different beam+baseline+detector combinations are determined by generating the ν_e appearance spectra and backgrounds for many combinations of δ_{cp} and θ_{13} and the oscillation parameter values listed in Equation 2 [3], with detector smearing and efficiency included as shown in Figure 3. The sensitivities to various oscillation physics hypothesis are then determined as follows:

Determining whether θ_{13} is non-zero: Fit the appearance spectrum generated for a particular θ_{13}, δ_{cp} to the oscillation hypothesis with $\theta_{13} = 0$.

Excluding CP-violation: Fit the appearance spectrum to the oscillation hypothesis with $\delta_{cp} = 0$ and π while allowing θ_{13} is allowed to float in the fit. Take the worst χ^2.

Determining the sign of Δm^2_{31}: Fit the appearance spectrum to the oscillation hypothesis with the opposite mass hierarchy while allowing both θ_{13} and δ_{cp} to float in the fit.

The Study group considered many beam+baseline+detector combinations in the sensitivity calculations, in this section we will summarize the three scenario's with the best sensitivities that were identified: Scenario 1 is the NuMI 0.8° off-axis beam at a baseline 810km with the 20 kT NOνA detector coupled with a 100kT LAr detector at the same location. Scenario 2 is the WBLE 120 GeV wide-band beam at the Fermilab-DUSEL baseline of 1300km coupled with a 100 kT LAr detector. Scenario 3 is the WBLE 120 GeV wide-band beam at the Fermilab-DUSEL baseline of 1300km coupled with a 300 kT water Cherenkov detector. The sensitivities for Scenario 1 were estimated using negligible uncertainties on the oscillation parameters, a 5% uncertainty on the background estimate, and allowing the sign of Δm^2_{31} to float when determining the sensitivity to non-zero θ_{13} CP violation. The 90%, 3σ, and 5σ confidence level exclusion limits for determining a non-zero value for θ_{13}, for excluding CP violation, and for excluding the opposite mass hierarchy in $\sin^2 2\theta_{13}$ versus δ_{CP} are shown in Figure 4 for Scenario 1. The LAr-TPC beam exposure assumed is 30×10^{20} protons in the neutrino running mode and 30×10^{20} in anti-neutrino (reversed horn current) running mode. For Scenarios 2 and 3 the following assumptions on systematic uncertainties were used: a 5% uncertainty on the values of $\sin^2 2\theta_{12}$ and Δm^2_{21}, the uncertainties on the values of $\sin^2 2\theta_{23}$ and Δm^2_{32} are obtained from the fit to the ν_μ disappearance mode in the same experiment, and the background uncertainty is assumed to be 10%. The mass hierarchy is fixed when determining the sensitivity to non-zero θ_{13} and CP violation in Scenarios 2 and 3. The 3σ,

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[3] For the sensitivity calculations a slightly different value of Δm^2_{32} is used: 2.7×10^{-3} eV^2, which corresponds to the best fit value from the MINOS experiment.

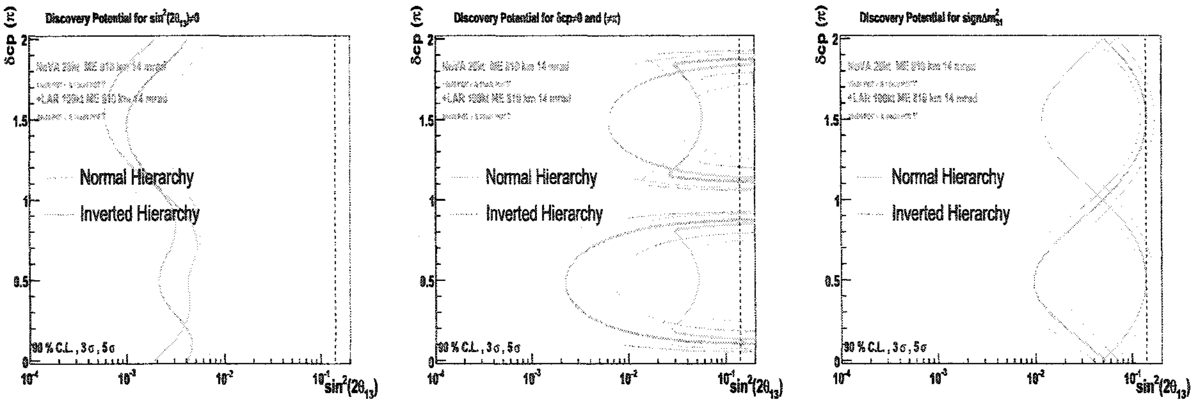

FIGURE 4. 90%, 3σ, and 5σ confidence level exclusion limits for determining a non-zero value for θ_{13} (left), for excluding CP violation (center) and for excluding the opposite mass hierarchy (right) in $\sin^2 2\theta_{13}$ versus δ_{CP}. These plots (blue for normal and red for reversed hierarchy) are for a 20 kTon NOνA detector placed at the off-axis location on the NuMI beamline with a total exposure of 30×10^{20} protons in addition to a 100 kT LAr detector placed the same location. The beam exposure is 60×10^{20} protons for the LAr-TPC divided equally between neutrino and anti-neutrino running. A 5% systematic uncertainty on the background is assumed.

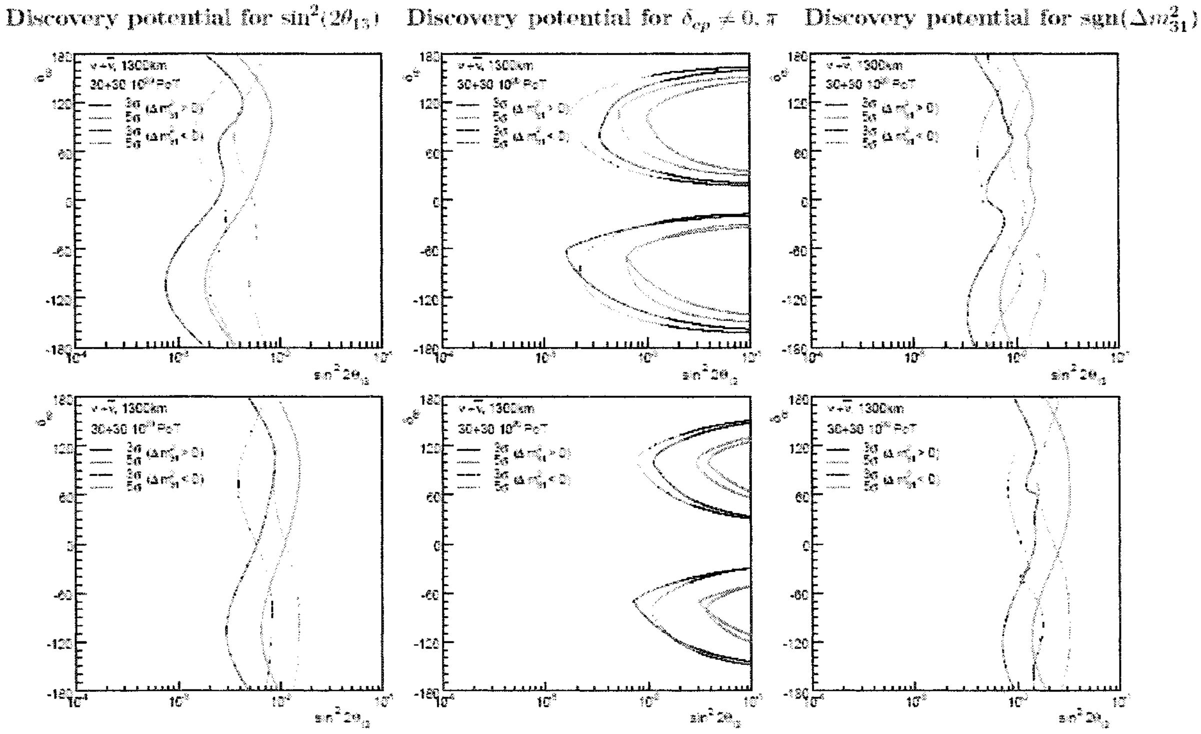

FIGURE 5. 3σ, and 5σ confidence level exclusion limits for determining a non-zero value for θ_{13} (left), for excluding CP violation (center) and for excluding the opposite mass hierarchy (right) in $\sin^2 2\theta_{13}$ versus δ_{CP}. These plots (solid for normal and dashed for reversed) are for a WBLE 120 GeV wide-band beam from Fermilab to DUSEL at a baseline of 1300km. The top set of plots is for a 100 kT LAr TPC and the bottom set of plots are for a 300 kT water Cherenkov detector. The total beam exposure is 60×10^{20} protons divided equally between neutrino and anti-neutrino running. A 10% systematic uncertainty on the background is assumed.

TABLE 3. Comparison of the sensitivity reach of different long baseline experiments. The sensitivity is given as the minimal value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach for the choice of mass hierarchy with worst sensitivity. We assume equal amounts of ν and $\bar{\nu}$ running in the total exposure.

Option	Beam	Baseline	Detector	Exposure (MW.yr)*	$\theta_{13} \neq 0$	CPV	$sgn(\Delta m^2_{31})$
(1)	NuMI ME, 0.9°	810 km	NOνA 20 kT	6.8	0.015	> 0.2	0.15
(2)	NuMI ME, 0.9°	810 km	LAr 100 kT	6.8	0.002	0.03	0.05
(3)	NuMI LE, 0.9°, 3.3°,	810,700 km	LAr 2 × 50 kT	6.8	0.005	0.04	0.04
(4)	WBLE 120GeV, 0.5°	1300km	LAr 100 kT	6.8	0.0025	0.005	0.006
(5)	WBLE 120GeV, 0.5°	1300km	WCe 300 kT	6.8	0.006	0.03	0.011
(6)	WBLE 120GeV, 0.5°	1300km	WCe 300 kT	13.6	0.004	0.012	0.008

* 1 yr = 1.7×10^7 seconds.

and 5σ confidence level exclusion limits for determining a non-zero value for θ_{13}, for excluding CP violation, and for excluding the opposite mass hierarchy in $\sin^2 2\theta_{13}$ versus δ_{CP} are shown in Figure 5 for Scenarios 2 and 3.

A summary of the sensitivity reach for non-zero θ_{13}, CP violation and the sign of Δm^2_{31} for 6 different combinations of beams, baselines, detector technologies, and exposure is presented in Table 3. The sensitivity reach is defined as the lowest $\sin^2 2\theta_{13}$ value at which at least 50% of δ_{cp} values will have $\geq 3\sigma$ reach. For this table we use the mass hierarchy with the worst sensitivity to determine the minimal value of $\sin^2 2\theta_{13}$ for which $\geq$ 50% of δ_{cp} values will have $\geq 3\sigma$ sensitivity to a particular measurement. We note that different options are sensitive to different values of δ_{cp}, such that being sensitive to 50% δ_{cp} values does not necessarily imply that a given experimental option is sensitive to the same region of oscillation parameter phase space as another.

We compare the wide-band Fermilab to DUSEL program, option (4), with the narrow-band off-axis NuMI-based program, option (2), for the same exposure of 6.8 MW.yr (1 experimental year is defined as 1.7×10^7 seconds). This is equivalent to an integrated exposure of 60×10^{20} protons-on-target for proton beam energies of 120 GeV. We assume equal amounts of exposure for neutrinos and anti-neutrino (reverse horn current) running. A liquid Argon TPC with a total mass of 100 kT is assumed as the detector technology of choice for the purpose of the comparison. We note that slightly different assumptions on the systematic uncertainties on the oscillation parameters and backgrounds went into the sensitivity estimates for NuMI off-axis (5% uncertainty on the background) and the wide-band Fermilab to DUSEL options (10% uncertainty on the background). The effect of the different assumptions is $\leq$ 15% variation on the value of $\sin^2 2\theta_{13}$ at which the sensitivity reaches 50% of δ_{CP}. We find that for the same exposure of 6.8 MW.yr, and the same liquid Argon TPC detector technology, the wide-band Fermilab to DUSEL approach has significantly better sensitivity to CP violation, the sign of Δm^2_{31}, and comparable sensitivity to non-zero values of θ_{13}. To illustrate the improvement in sensitivity over the existing program, the sensitivities of the current NOνA experiment at the same exposure, are summarized as option (1) in Table 3. Option (5) summarizes the Fermilab to DUSEL sensitivity when the 100 kT LAr TPC of option (4) is replaced by a 300 kT water Cherenkov detector. We find that the sensitivity worsens due to the lower signal statistics and higher NC backgrounds in a water Cherenkov detector. We can recover some of the lost sensitivity by doubling the exposure of the water Cherenkov detector as shown in option (6). For the same exposure, the Fermilab to DUSEL program with a 300 kT water Cherenkov detector, option (5), has the same sensitivity to CP violation as the NuMI based program with a 100 kT LAr TPC in options (2) and (3) and significantly better sensitivity to the sign of Δm^2_{31}. We find the Fermilab to DUSEL program with a 300 kT water Cherenkov detector has similar sensitivity to non-zero θ_{13} as the NuMI based program with two 50 kT LAr TPC's at the 1st and 2nd oscillation maxima, option (3).

SUMMARY AND CONCLUSIONS

The US Long Baseline Neutrino Experiment Study has concluded its survey of future long baseline neutrino oscillation experiments in the U.S. using conventional neutrino beams. The physics sensitivities and technical challenges of different experimental options were considered. We summarize the findings of the Study as follows:

- Values of $\sin^2 2\theta_{13}$ down to 0.02 can be measured by the currently planned Phase I (NOνA, T2K) experiments. Phase I experiments however, have limited or no sensitivity to determining the mass hierarchy, and essentially no sensitivity to δ_{CP} .

- The experimental options considered by the Study (Phase II experiments) will all improve the sensitivity to CP violation by at least an order of magnitude over the existing Phase I program.
- A NuMI off-axis program with two 50 kT LAr-TPCs at the 1st and 2nd oscillation maxima at baselines of 810 and 700 km respectively has marginally better sensitivity to the sign of Δm^2_{31} but significantly worse sensitivity to non-zero θ_{13} when compared with putting the full 100 kT mass at the 1st oscillation maxima.
- Given the same exposure and detector technology (LAr-TPC), the Fermilab to DUSEL program with a wide band beam has significantly better overall sensitivity to neutrino oscillations when compared to a shorter baseline NuMI based program with an off-axis beam (see Table 3). The technical challenges for building a massive LAr-TPC have been identified. Currently, the feasibility and cost of building a massive LAr-TPC - particularly one that can operate on the surface - has not been demonstrated and requires long term R&D efforts.
- The Fermilab to DUSEL program with a 300 kT water Cherenkov detector has similar sensitivity to CP violation when compared to a NuMI off-axis program with a 100 kT LAr TPC, and significantly better sensitivity to the sign of Δm^2_{31}. The modular water Cherenkov detector proposed is a modest scale up from the existing Super-Kamiokande detector and the technical feasibility is considered low-risk. A preliminary cost estimate exists for such a detector and is approximately $335M for 300 kT fiducial, including cavern costs and a 30% contingency factor.
- Although the Fermilab-DUSEL approach has the best physics sensitivities (both with a LAr-TPC and a water Cherenkov detector), it requires a new neutrino beamline to be built. Such a beamline can be accommodated on-site using part of the existing NuMI beamline but constitutes an additional cost to the project.
- A DUSEL based underground neutrino detector can support a wider physics program including but not limited to proton decay, supernova neutrinos, and geo-neutrinos. It has yet to be demonstrated that a massive surface detector can accommodate a broader physics program.

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REFERENCES

1. G.L. Fogli *et al.*, *Prog. Part. Nucl. Phys.* **57** 742-795 (2006), hep-ph/0506083v2.
2. D.S. Ayres *et al.* (The NOνA Collaboration), *NOνA Proposal to Build a 30 Kiloton Off-Axis Detector to Study Neutrino Oscillations in the Fermilab NuMI Beamline* March (2005), hep-ex/0503053.
3. J. Hylen *et al.*, *NuMI Facility Technical Design Report,* Fermilab-TM-2018, Sept. (1997).
4. Stuart Freedman and Boris Kayser (chairmen), *APS Multi-Divisional Study of the Physics of Neutrinos,* sponsored by the American Physical Society Divisions of Nuclear Physics, Particles and Fields, Astrophysics, and Physics of Beams.
5. V. Barger *et al.*, *Report of the US long baseline neutrino experiment Study*, Fermilab-0801-AD-E, BNL-77973-2007-IR, May 2007.
6. V. Barger *et al.*, *Phys. Rev.* **D** 74, 073004 (2006), hep-ph/0607177v2.
7. D. Bogert *et al.*, *SNuMI conceptual design report,* ProtonPlan2-doc-101, 9 Nov (2006).
8. R. Alber, *et al.*, *Proton Driver Study Group*, FNAL-TM-2136, FNAL-TM-2169.
9. J. Alessi *et al.*, *The AGS-Based Super Neutrino Beam Facility Conceptual Design Report*, BNL-73210-2004-IR, October 2004.
10. D.G. Michael *et al.* (The MINOS Collaboration), *Phys.Rev.Lett.* **97**, 191801 (2006), hep-ex/0607088.
11. Dziewonski and Anderson, *Phys. Earth. Planet. Int.*, **25**, 297-356 (1981).
12. P. Huber, M Lindner and W. Winter, *Simulation of long-baseline neutrino oscillation experiments with GLoBeS*, hep-ph/0407333 (2004).
13. S. Amerio *et al.* (The ICARUS collaboration), *Nucl. Instrum. Meth.* **A** 527, 329 (2004).
14. S. Fukuda *et al.* (The Super-Kamiokande collaboration), *Nucl. Instrum. Meth.* **A** 501, 418-462 (2003).
15. M. Diwan *et al.* (The Homestake Collaboration), *Proposal for an Experimental Program in Neutrino Physics and Proton Decay at the Homestake Laboratory* July (2006), hep-ex/0608023.
16. C. Yanagisawa, *Background Study on Nue Appearance in a Very Long Baseline Neutrino Oscillation Experiment with a Large Water Cherenkov Detector* as reported in these proceedings.