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LBNE In the Precision Era of Neutrino Oscillation

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LBNE (Long-Baseline Neutrino Experiment) is an accelerator-based neutrino oscillation experiment. LBNE will produce a muon-neutrino beam using protons from Fermilab's Main Injector and will detect electron-neutrino appearance and muon-neutrino disappearance using a Liquid Argon TPC located at a distance of 1300 km at Sanford Underground Research Facility in South Dakota. The primary physics motivation of LBNE is to determine the neutrino mass hierarchy, to determine the octant of the neutrino mixing angle θ_{23}, to search for CP violation in neutrino oscillation, and ultimately, to precisely measure the size of any CP-violating effect that is discovered. This presentation reports the status of LBNE, the first phase of which is currently in the detailed-design stage of planning, and the physics potential of the LBNE research program.

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1. Introduction

It is well-established experimentally that the flavor composition of neutrinos change as they propagate[1]. In the three-neutrino framework, the three flavor states $(\nu_e, \nu_\mu, \nu_\tau)$ are superpositions of the three mass states (ν_1, ν_2, ν_3). The PMNS[2, 3] matrix describes this mixing with three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$, which have all been measured experimentally, and a CP-violating phase, δ_{CP}, which is unknown. Measurement of a value of δ_{CP} not equal to zero or pi would be the first observation of CP violation in the neutrino sector. The measured value of θ_{23} is near to 45°; if it is exactly 45°, which would indicate that ν_μ and ν_τ have equal contributions from ν_3, that could be evidence for a previously unknown symmetry. The θ_{23} octant, i.e., whether θ_{23} is less than, greater than, or equal to 45°, is unknown. The differences between the mass states, Δm^2_{21} and $|\Delta m^2_{32}|$, have also been measured, though the true mass hierarchy is unknown. The case in which Δm^2_{32} is greater than zero is referred to as "normal hierarchy" (NH) and the opposite case is called "inverted hierarchy" (IH).

Since the mixing angle θ_{13} is now known to be non-zero[4, 5, 6, 7, 8, 9], it is possible to probe neutrino oscillations via the appearance of electron neutrinos in a muon neutrino beam. The appearance probability is

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \tag{1.1}$$

$$\alpha\sin(2\theta_{13})\cos\delta\frac{\sin(aL)}{(aL)}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\cos\Delta_{32} - \tag{1.2}$$

$$\alpha\sin(2\theta_{13})\sin\delta\frac{\sin(aL)}{(aL)}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\sin\Delta_{32},$$

where $a = G_F N_e \sqrt{2}$ and $\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$. Figure 1 shows the ν_e appearance probability at 1300 km for various values of δ_{CP}. The value of $\sin^2(2\theta_{13})$ determines the size of the ν_e-appearance sample, the value of δ_{CP} affects the amplitude of the oscillation, the value of Δ_{31} affects the frequency of the oscillation, the mass hierarchy affects both the amplitude and frequency of the oscillation, and the value of θ_{23} enters unambiguously. So ν_e appearance is sensitive to δ_{CP}, the θ_{23} octant, and the mass hierarchy, as well as matter effects.

Figure 2 compares the neutrino-antineutrino asymmetries for different baselines. As seen in the left panel of Fig. 2, the asymmetry due to the matter effect, arising from the different effective masses of neutrinos and antineutrinos as they propagate in matter and entering Eq. 1.1 as aL, dominates the CP asymmetry at long baselines. In comparing the asymmetries for baselines of 290 km and 1300 km (right panel of Fig. 2), it is clear that for the first oscillation node, at 290 km, there are degeneracies in which the value of δ_{CP} might be very different for NH and IH given the same asymmetry measurement. These degeneracies are not present at 1300 km; this allows a long-baseline experiment to both determine the mass hierarchy and measure the CP phase.

2. The Long-Baseline Neutrino Experiment

The Long-Baseline Neutrino Experiment (LBNE) will consist of a muon-neutrino beam from Fermilab to Sanford Underground Research Facility (SURF), a baseline of 1300 km, and a massive

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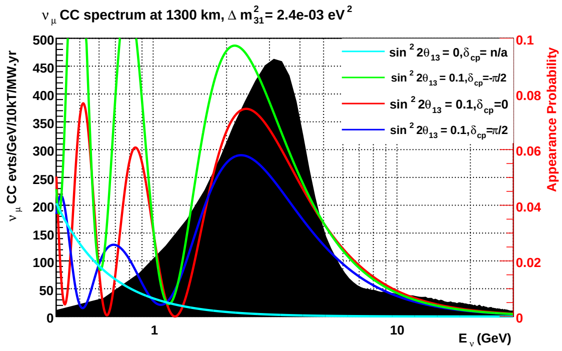

Figure 1: ν_e appearance probability at a distance of 1300 km as a function of energy. The green (red,blue) curve indicates a value of $\delta_{CP} = -\pi/2$ (0, $\pi/2$). The cyan curve shows the appearance probability if $\sin^2(2\theta_{13})$ were zero. The black histogram shows the unoscillated ν_μ spectrum. The spectrum is well-matched to the first oscillation maximum.

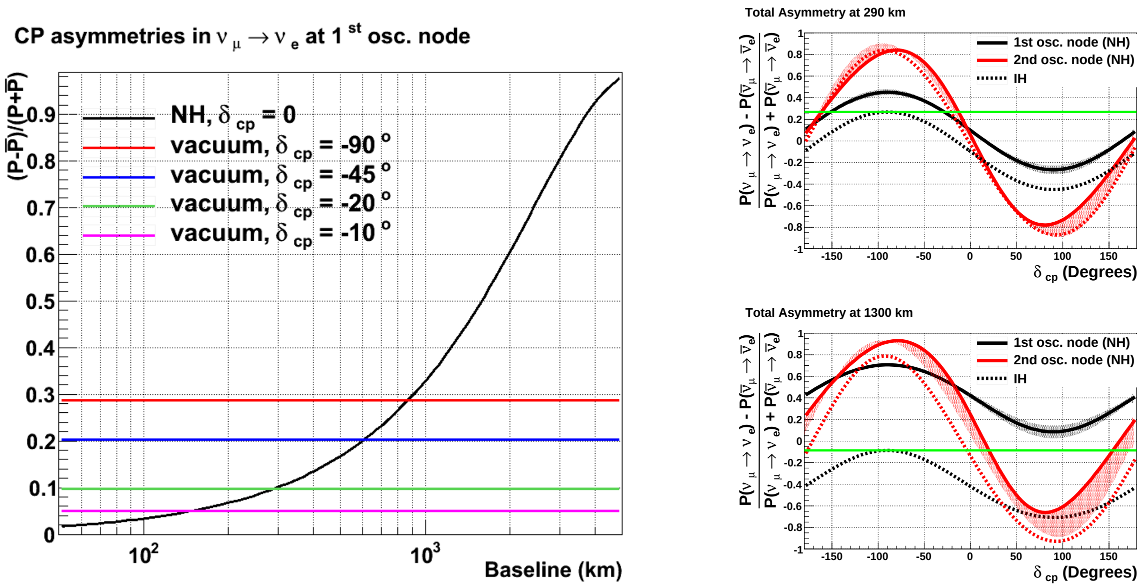

Figure 2: **Left:** Neutrino-antineutrino asymmetry in $\nu_\mu \to \nu_e$ appearance probability as a function of baseline at the first oscillation node. **Right:** Neutrino-antineutrino asymmetry as a function of δ_{CP} for the first and second oscillation nodes at baselines of 290 km (top) and 1300 km (bottom).

underground far detector. The experiment will make use of protons from Fermilab's Main Injector and a new muon-neutrino beam line will be constructed. The far detector will be a liquid argon time projection chamber (LAr TPC) with an integrated photon detection system. SURF is located in western South Dakota and is an active underground research lab, currently housing the LUX and MAJORANA experiments. At the time of this presentation, the LBNE collaboration consisted of about 370 members at 61 institutions. Since that time, the collaboration has grown significantly with the addition of sixteen new collaborating institutions from outside the U.S.

LBNE10 refers to the experiment design that currently has funding approval from the U.S.

Department of Energy: a 10-kt LAr TPC and a 700-kW, 120-GeV proton beam. It is the goal of the collaboration to achieve higher exposures with a higher mass far detector and upgrades to the beam. Higher proton beam power at lower energies and upgrades to the design of the neutrino beam line both provide increased sensitivity. It is the intention of the collaboration to place the far detector underground, enabling greater physics reach and breadth for the experiment. As an international collaboration, LBNE will be able to meet these goals.

Figure 3 shows the sensitives of LBNE10 to the determination of the mass hierarchy and the discovery of CP violation. LBNE10 represents a significant step forward in sensitivity relative to current experiments; in combination with NOvA and T2K, LBNE10 determines the mass hierarchy at better than 3σ for all values of δ_{CP} and can discover CP violation at the 3σ level for many values of δ_{CP}, where σ is simply $\sqrt{\Delta\chi^2}$. The left panel of Fig. 4 shows the ability of LBNE10 to determine the θ_{23} octant as a function of the true value of θ_{23}. The sensitivities presented here are calculated using GLoBES[10, 11] and are described in greater detail in [12].

The experimental sensitivity becomes more significant with higher exposure. Figure 4 (right panel) and Fig. 5 show the increase in sensitivity that will be possible with a higher power beam and a larger far detector in one possible staging scenario. In these plots, the three levels of exposure correspond to LBNE10 and the first and second phases of Project X[13, 14].

Observation of ν_e appearance in atmospheric neutrinos, which requires that the detector be underground, provides additional sensitivity to neutrino oscillation parameters, particularly the mass hierarchy. This is because the MH sensitivity from atmospheric neutrinos is independent of the true value of δ_{CP}. At $\delta_{CP} \approx \pi/2$ $(-\pi/2)$ in NH (IH), the sensitivity from atmospheric neutrinos is approximately equal to that from the beam, and the systematic uncertainties are largely independent. Other physics topics that are possible with an underground far detector include proton decay, particularly the $p \to \nu K^+$ decay mode, and the detection of supernova burst neutrinos if there is a galactic supernova during the lifetime of the experiment.

3. Summary

The 1300-km baseline between FNAL and SURF provides the opportunity to measure the remaining unknown neutrino oscillation parameters using $\nu_\mu \to \nu_e$ oscillations. LBNE10 represents a significant improvement in sensitivity over current experiments and there is a clear path forward for detector and accelerator upgrades to reach the ultimate LBNE sensitivity. LBNE is building an international collaboration and embarking on a program of precision measurements which will produce exciting physics for decades to come.

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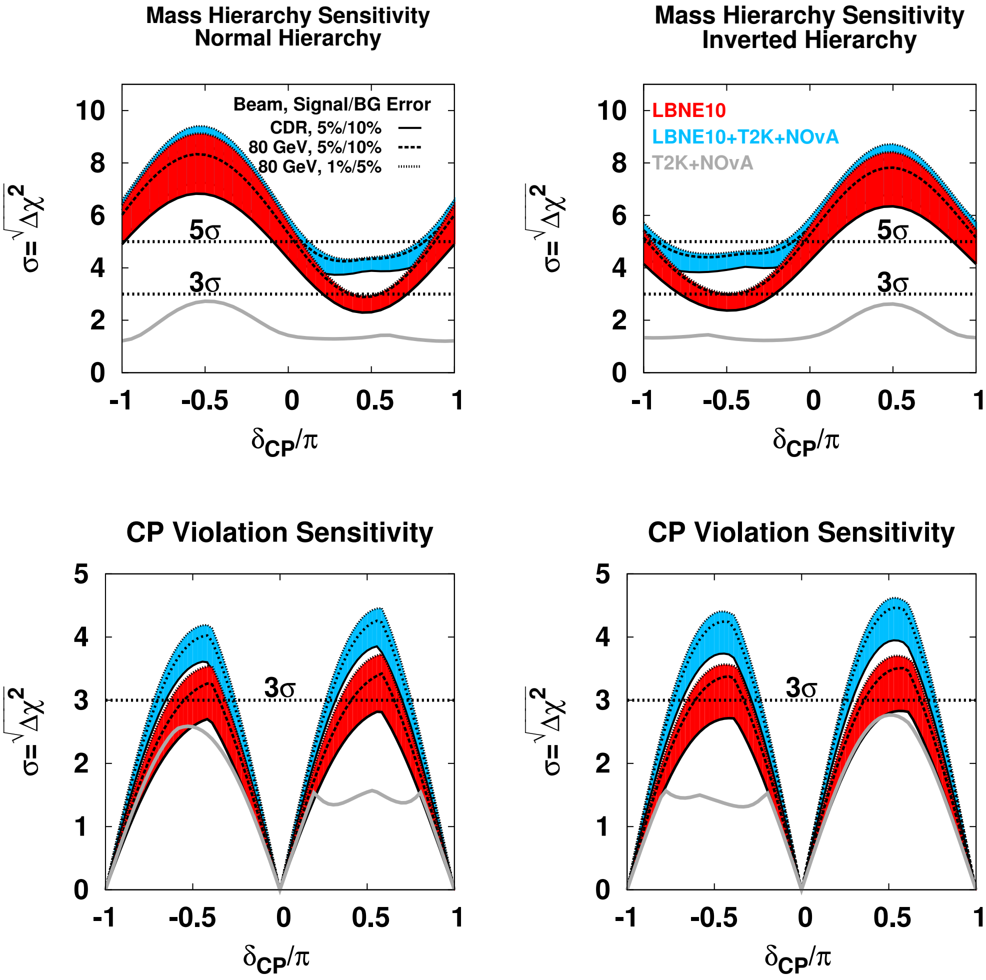

Figure 3: Sensitivity of LBNE10 to determination of mass hierarchy (top) and discovery of CP violation (bottom) for NH (left) and IH (right). The bands represent a range of possible sensitivities from variations in beam design and assumptions about the uncertainty of signal and background normalizations. NOvA and T2K are shown in grey, LBNE10 in red, and all three combined in blue.

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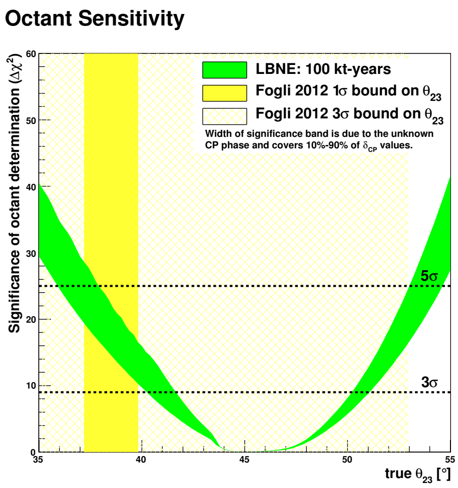

Figure 4: Sensitivity of LBNE10 (left) and higher exposures (right) to determination of the θ_{23} octant, as a function of the true value of θ_{23}. The Fogli 2012[15] 1σ and 3σ bounds on the true value of θ_{23} are shown.

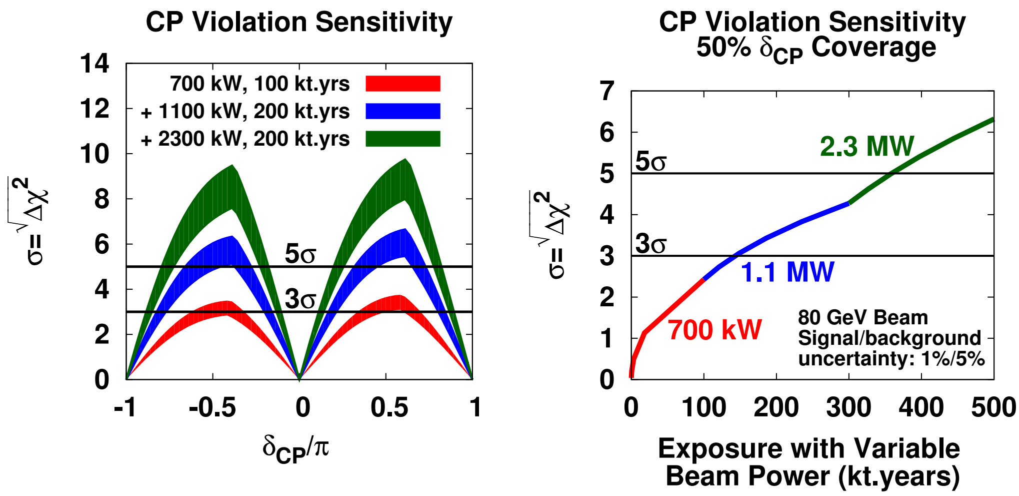

Figure 5: **Left:** Sensitivity of LBNE to discovery of CP violation, as a function of the true value of δ_{CP}, for increasing exposure. The width of the bands represent a range of possible beam configurations. **Right:** Significance with which CP violation can be observed for 50% of possible δ_{CP} values, as a function of exposure in kt-years. This curve assumes the best beam configuration considered in the left panel.