BNL-107720-2015-JA

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Submitted to Nuclear Physics B
Proceedings Supplement

March, 2015

Physics Department

Brookhaven National Laboratory

U.S. Department of Energy
DOE Office of High Energy Physics (SC-25)

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Nuclear Physics B Proceedings Supplement 00 (2015) 1–3

Nuclear Physics B Proceedings Supplement

Precision Measurements of Long-Baseline Neutrino Oscillation at LBNF

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Abstract

In a long-baseline neutrino oscillation experiment, the primary physics objectives are 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 to precisely measure the size of any CP-violating effect that is discovered. This presentation provides a brief introduction to these measurements and reports on efforts to optimize the design of a long-baseline neutrino oscillation experiment, the status of LBNE, and the transition to an international collaboration at LBNF.

Keywords: neutrino oscillation

In a long-baseline neutrino oscillation experiment, the amplitude of $\nu_\mu \to \nu_e$ oscillation is dependent upon the neutrino mixing parameters θ_{13}, θ_{23}, δ_{CP}, and matter effects. Given the non-zero value of θ_{13}[1, 2, 3, 4, 5], it is possible to simultaneously determine three unresolved issues in neutrino physics – mass hierarchy (MH), θ_{23} octant, and CP violation (CPV) – via the appearance of electron neutrinos in a muon neutrino beam. As seen in Fig. 1, which shows the neutrino-antineutrino asymmetry in the $\nu_\mu \to \nu_e$ oscillation probability at the first oscillation maximum as a function of baseline, the asymmetry due to the matter effect, arising from the different effective masses of neutrinos and antineutrinos as they propagate in matter, dominates the CP asymmetry at long baselines. The result of this is that while at short baselines there are degeneracies in which the asymmetry from non-zero δ_{CP} is identical to the asymmetry from the matter effect at the first oscillation maximum, these degeneracies are not present at 1300 km. This allows a long-baseline experiment to simultaneously determine the mass hierarchy and measure the CP phase. CPV effects are larger than matter effects at the second oscillation maximum, so study of events from the second maximum is particularly useful in determining the mass hierarchy.

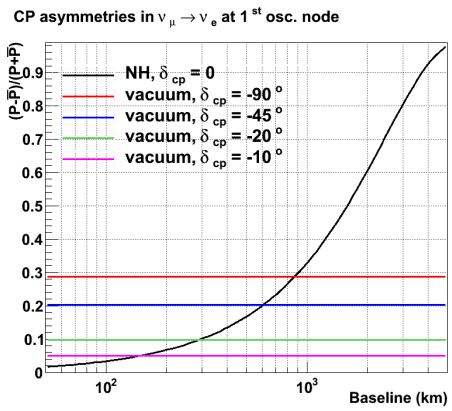

Figure 1: Neutrino-antineutrino asymmetry in the $\nu_\mu \to \nu_e$ appearance probability as a function of baseline at the first oscillation node for the matter effect (black line) and CPV effects (colored lines).

For experiment optimization studies, a joint fit to four samples ($\nu_e/\bar{\nu}_e$ appearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance) is performed using GLoBES[6, 7]. To approximate the effect of systematic uncertainties, signal and background normalization uncertainties are applied for each of the four samples; these uncertainties are treated as 100%

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uncorrelated among the four samples, so that there are eight total parameters, each of which represents the residual uncorrelated normalization uncertainty for a given sample. The nominal values are 5% signal and 10% background uncertainty on the $\nu_\mu/\overline{\nu}_\mu$ samples and 1% signal and 5% background uncertainty on the $\nu_e/\overline{\nu}_e$ samples.

Figure 2 shows the results of a study in which a horn-focused ν_μ beam based on the NuMI design is individually optimized for a range of baselines to determine the optimal baseline for MH and CPV sensitivity[8]. The top panel shows the ratio of the simulated flux relative to a perfect focus flux for three representative baselines. The bottom panel shows the exposure required to achieve a given sensitivity to MH and CPV as a function of baseline. The study concludes that a baseline of 1300 km is sufficient for MH determination and near optimal for CPV sensitivity.

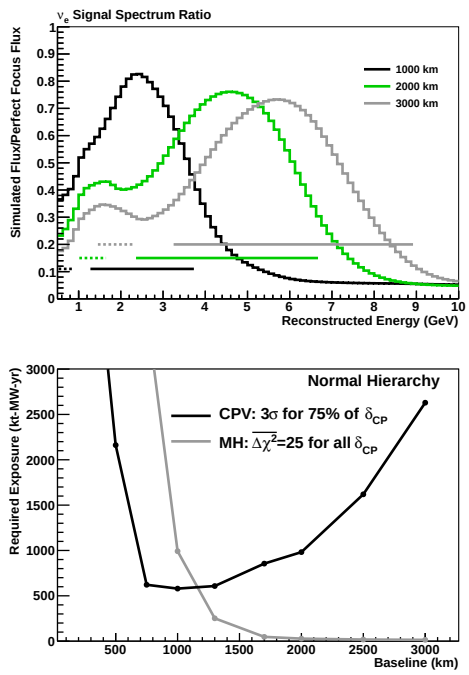

Figure 2: **Top:** Ratio of simulated flux to perfect focus flux for baselines of 1000 km (black), 2000 km (green), and 3000 km (gray) as a function of energy. The solid (dashed) horizontal bars show the energy range of the first (second) oscillation maximum at each baseline. **Bottom:** The exposure required to reach 3σ sensitivity to CPV for 75% of δ_{CP} values (black) and $\overline{\Delta\chi^2} > 25$ sensitivity to MH for all δ_{CP} values as a function of baseline.

Optimization of the beam design is a critical aspect of the experiment and is in progress. The beam used in the baseline optimization study and in most LBNE sensitivity studies to date is based on the NuMI design[9]. Within this basic design, it is possible to optimize the flux by adjusting such parameters as proton beam energy, target composition, focusing horn current, and decay pipe length. Design choices leading to enhancements of up to 50% at both the first and second oscillation maxima relative to the beam described in the LBNE CDR have been identified. Consideration of designs beyond NuMI may allow for even more significant improvements in sensitivity.

The Long-Baseline Neutrino Experiment (LBNE) is a collaboration consisting of more than 500 members from 90 institutions and 8 countries. Plans for LBNE consist of a neutrino beam from Fermi National Accelerator Laboratory (FNAL) to Sanford Underground Research Facility (SURF), a baseline of 1300 km, a precision near detector, and a massive underground far detector, which is a Liquid Argon TPC (LArTPC) with an integrated photon detection system located at the 4850-ft level of SURF. The beam line will make use of protons from the upgraded Main Injector at FNAL, providing 1.2 MW at 120 GeV, and a new muon neutrino beam line. SURF is located in Lead, South Dakota and is an operational underground physics laboratory, currently housing the Majorana Demonstrator and LUX experiments. Figure 3 shows the expected LBNE sensitivity to MH and CPV as a function of the true value of δ_{CP}. LBNE is capable of making precise measurements of neutrino oscillation parameters, which are comparable to ($\sin^2 2\theta_{13}$) or superior to ($\sin^2\theta_{23}$ and δ_{CP}) existing measurements.The scientific capabilities of LBNE, including underground physics, are detailed in [10].

The LBNE collaboration is actively performing hardware R&D and developing simulation, reconstruction, and analysis tools. A 35-ton LArTPC prototype is under construction; the 35-ton cryostat performance was successfully demonstrated in 2013 and the upcoming run, planned for 2015, will include first LBNE demonstrations of the full cold electronics readout chain, the wrapped-wire TPC design, and integration of the TPC and photon detection system. LBNE uses LArSoft[12] for simulation and reconstruction of interactions in the LArTPC; a full Monte Carlo simulation is available and significant progress is being made on three-dimensional reconstruction. Additionally, simulation and fitting tools such as the LBNE Fast Monte Carlo, VALOR, and MGT have been developed to study LBNE sensitivity and systematic uncertainties.

Excellent control of systematic uncertainty is critical to LBNE's sensitivity to CPV, as demonstrated in Fig. 4, in which the signal and background normalization uncertainties described above are varied. Evaluation of how more detailed treatment of systematic uncertain-

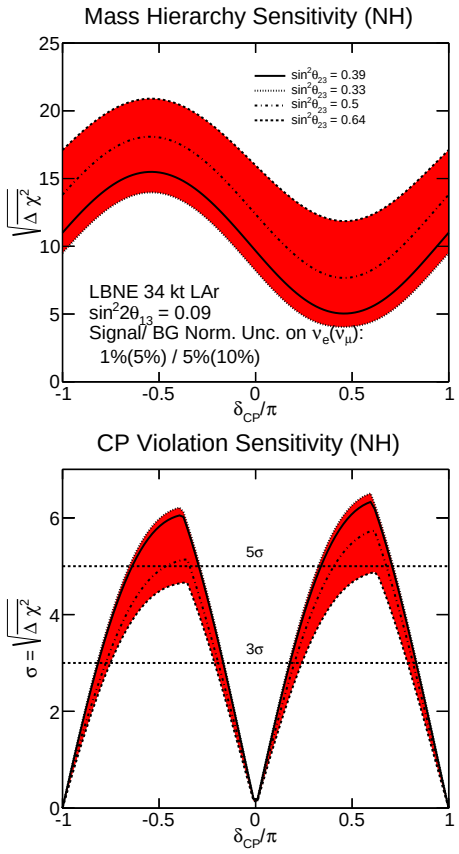

Figure 3: LBNE sensitivity to neutrino mass hierarchy (top) and CP violation (bottom) for a nominal exposure of 245 kt-MW-years as a function of the true value of δ_{CP}. Sensitivity is shown for four values of θ_{23}, covering the range allowed by [11].

ties may affect experimental sensitivity and the extent to which these uncertainties may be constrained by event samples in the near and far detectors are currently underway. Preliminary studies show significant constraint on flux and cross-section uncertainties using near and far detector data. Design of the experiment is ongoing and it is expected that systematics-driven performance requirements will guide the experiment design.

The Particle Physics Project Prioritization Panel (P5) has recommended that neutrino physicists should "form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S." The LBNE collaboration welcomes this recommendation and is enthusiastically engaging with all interested parties to realize this vision. To facilitate formation of the new collaboration, an interim international Executive Board (iiEB) was formed with the goal of producing a letter of intent by the end of 2014 and a CDR by mid-2015. Since the time of the presentation, the iiEB has had several successful meetings and the new collaboration has been dubbed ELBNF.

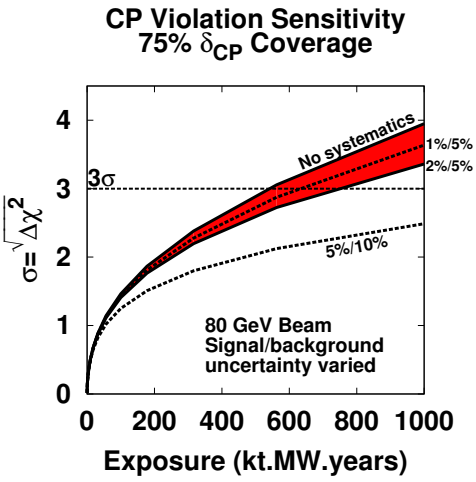

Figure 4: LBNE sensitivity to CP violation as a function of exposure in kt-MW-years for no systematic uncertainty (upper solid line), 1% or 2% signal and 5% background uncertainty (dashed lines), and 5% signal and 10% background uncertainty (lower solid line). As discussed in the text, these normalization uncertainties reflect the uncorrelated residual uncertainty on ν_e appearance, with the uncorrelated uncertainty on ν_μ disappearance of 5% signal and 10% background also included.

References

[1] F. An, et al., Spectral measurement of electron antineutrino oscillation amplitude and frequency at Daya Bay, Phys.Rev.Lett. 112 (2014) 061801. arXiv:1310.6732.

[2] Y. Abe, et al., Improved measurements of the neutrino mixing angle θ_{13} with the Double Chooz detector, JHEP 1410 (2014) 86. arXiv:1406.7763.

[3] New Results from RENO and The 5 MeV Excess (2014). arXiv:1410.7987.

[4] P. Adamson, et al., Electron neutrino and antineutrino appearance in the full MINOS data sample, Phys.Rev.Lett. 110 (17) (2013) 171801. arXiv:1301.4581.

[5] K. Abe, et al., Observation of Electron Neutrino Appearance in a Muon Neutrino Beam, Phys.Rev.Lett. 112 (2014) 061802. arXiv:1311.4750.

[6] P. Huber, et al., Comput. Phys. Commun. 167 (2005) 195.

[7] P. Huber, et al. (2007). arXiv:hep-ph/0701187.

[8] M. Bass, et al., Baseline optimization for the measurement of CP violation and mass hierarchy in a long-baseline neutrino oscillation experiment (2013). arXiv:1311.0212.

[9] V. Papadimitriou, R. Andrews, J. Hylen, T. Kobilarcik, A. Marchionni, et al., Design of the LBNE Beamline (2014).

[10] C. Adams, et al., The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe (2014). arXiv:1307.7335.

[11] G. Fogli, et al., Phys. Rev. D 86 (2012) 013012.

[12] `https://cdcvs.fnal.gov/redmine/projects/larsoft`.