

A Second Detector Focusing on the Second Oscillation Maximum at an Off-axis Location to Enhance the Mass Hierarchy Discovery Potential in LBNE10

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Abstract. The Long Baseline Neutrino Oscillation Experiment (LBNE) is proposed to determine the neutrino mass hierarchy and measure the CP phase δ_{CP} in the leptonic sector. The current design of LBNE Phase I consists of a 10 kt liquid argon time projection chamber (LBNE10). The neutrino-antineutrino asymmetry in the electron-neutrino appearance probability has contributions from both the CP phase and the matter effect. For this reason, experimental sensitivity to the mass hierarchy depends both on the true value of the CP phase and the true mass hierarchy; LBNE10 will determine the mass hierarchy at high levels of significance for half of δ_{CP} phase space. We propose placing a second detector at an off-axis location. Such a detector will share the same beamline as the primary LBNE detector. The detector location is chosen such that this detector focuses on a measurement of electron (anti-)neutrino appearance at the second oscillation maximum. We will show that this configuration will enhance the ability of LBNE to determine the mass hierarchy and to discover CP violation in the leptonic sector.

The recent discovery of sizable θ_{13} with reactor electron anti-neutrino disappearance measurements [1, 2, 3, 4] and electron (anti-)neutrino appearance measurements [5, 6] opens door to the determination of the neutrino mass hierarchy (MH) and the CP phase δ_{CP} in the leptonic sector [7]. The neutrino mass hierarchy problem is to determine whether the third generation of neutrino is heavier (normal hierarchy/NH) or lighter (inverted hierarchy/IH) than the first two generations of neutrinos. Together with the next generation neutrinoless double beta decay experiments, the determination of the neutrino mass hierarchy may hold the key to the nature of neutrinos (Dirac or Majorana particles). A value of the CP phase not equal to zero or π may produce the CP-violation that is required for leptogenesis [8], which is a potential explanation for the apparent matter-anti-matter asymmetry in the universe. The determination of MH and the CP phase δ_{CP} will have profound significance not only within the neutrino physics, but in the larger field of high-energy physics.

The Long-Baseline Neutrino Experiment (LBNE) [9] is designed to determine the MH and δ_{CP} simultaneously. By placing an on-axis detector at a baseline of 1300 km, LBNE will measure the (anti-) ν_μ to (anti-) ν_e oscillation. As shown in Fig. 1, the ν_μ to ν_e oscillation probabilities are

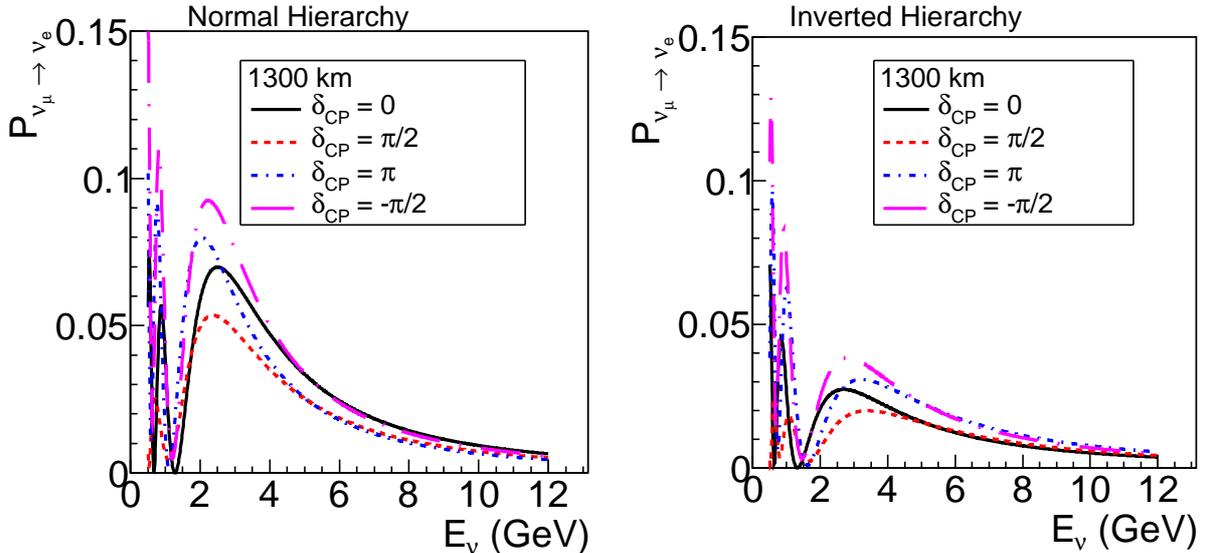


Figure 1. The ν_{μ} to ν_e oscillation probabilities at a 1300 km baseline are shown for the normal (left) and inverted (right) mass hierarchy. The value of $\sin^2 2\theta_{13}$ is assumed to be 0.092. On each panel, four curves corresponding to four values of δ_{CP} are shown.

sensitive to both the MH (through the matter effect) and the value of δ_{CP} . Commonly, the peaks around 2.5 GeV and 0.8 GeV are referred to as the first and the second oscillation maximum, respectively. For the first oscillation maximum, the neutrino appearance probability is higher in the case of the normal hierarchy than in the case of the inverted hierarchy, regardless of the value of δ_{CP} . With a wide-band (large energy coverage) beam, the LBNE on-axis detector will cover both the first and the second oscillation maximum (shown in Fig. 2) with the emphasis on the first oscillation maximum.

Due to the potential cancellation between the matter effect and the effect of δ_{CP} at the first oscillation maximum, the discovery potential of the MH strongly depends on the true value of δ_{CP} . For example, as seen in Fig. 3, at the first oscillation maximum, the asymmetry in the neutrino-antineutrino appearance probability for $\delta_{CP} = \pi/2$ with the normal hierarchy is close to that for $\delta_{CP} = -\pi/2$ with the inverted hierarchy. On the other hand, for the second oscillation maximum, the size of the CP asymmetry is larger and the size of the matter effect is smaller, so the degeneracy between the two solutions is broken. Therefore, coverage of the second oscillation maximum is important for LBNE and an improved measurement of electron (anti-)neutrino appearance at the second oscillation maximum will enhance sensitivities to the MH and CP violation.

In this whitepaper, *we propose a second detector, a 10 kt water Cerenkov detector, at an off-axis location dedicated to the second oscillation maximum to enhance the MH discovery potential and the overall performance of the LBNE program.*

Due to the two-body kinematics of the pion decay, the off-axis neutrino flux is narrow in energy [11, 12]. Fig. 2 shows the neutrino flux using the beam design described in Ref. [13] at 27 mrad off-axis. The peak of the off-axis neutrino beam approximately matches the location of the second oscillation maximum. Comparing to the on-axis neutrino beam, the off-axis beam flux is much higher at the second oscillation maximum. The narrow-band beam also provides advantages in reducing backgrounds, which are generated by high-energy neutrinos, but misidentified as being low-energy neutrinos due to imperfect reconstructions. These

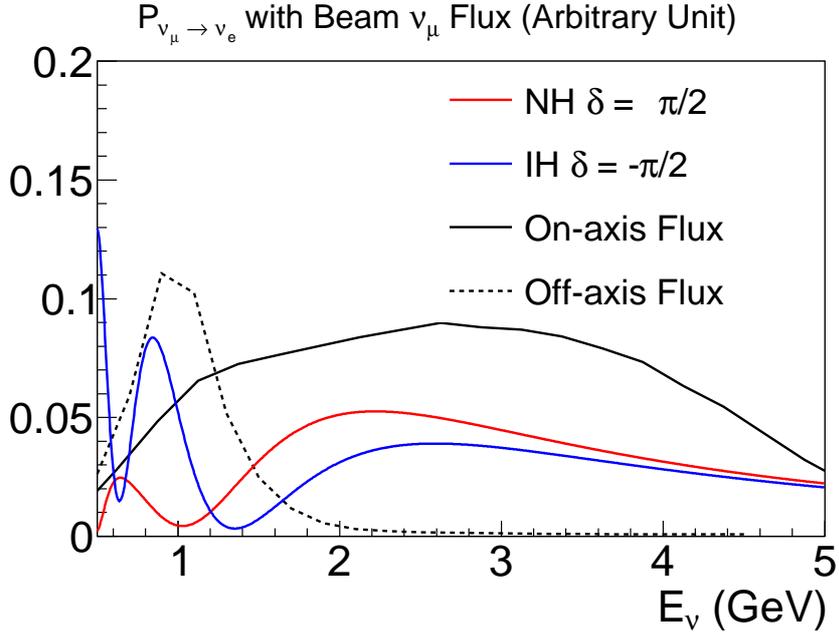


Figure 2. The on-axis and 27 mrad off-axis neutrino beam energy profile at a baseline of 1300 km are shown. Together, the ν_e appearance probability for two cases: i) normal hierarchy with $\delta = \pi/2$ and ii) inverted hierarchy with $\delta = -\pi/2$ are shown. While the cancellation happens at the first oscillation maximum, the matter effect and the effect of δ_{CP} will result in a distinctive feature at the second maximum [10]. Furthermore, at second oscillation maximum, the off-axis beam provides a much higher flux than the on-axis beam.

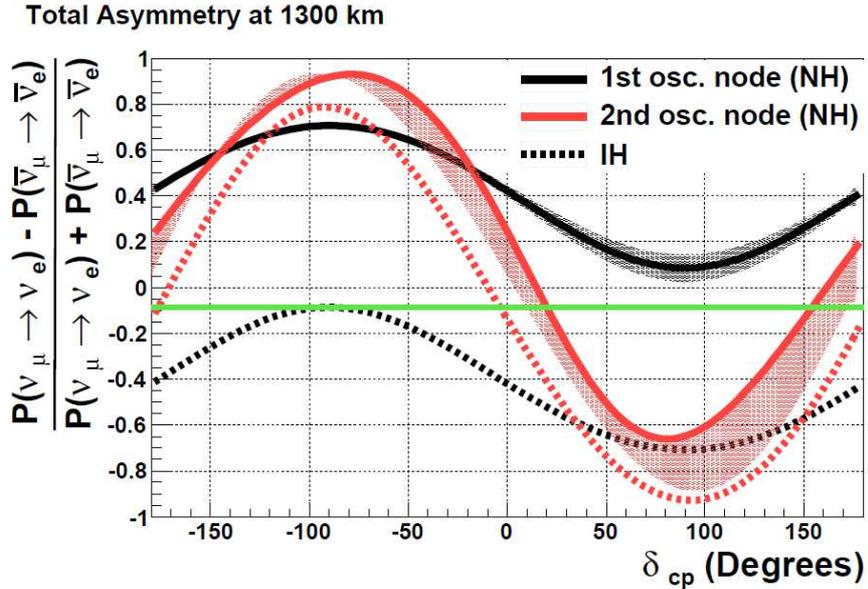


Figure 3. The asymmetry between the ν_e and anti- ν_e appearance at first and second oscillation maxima for both the normal and the inverted mass hierarchy.

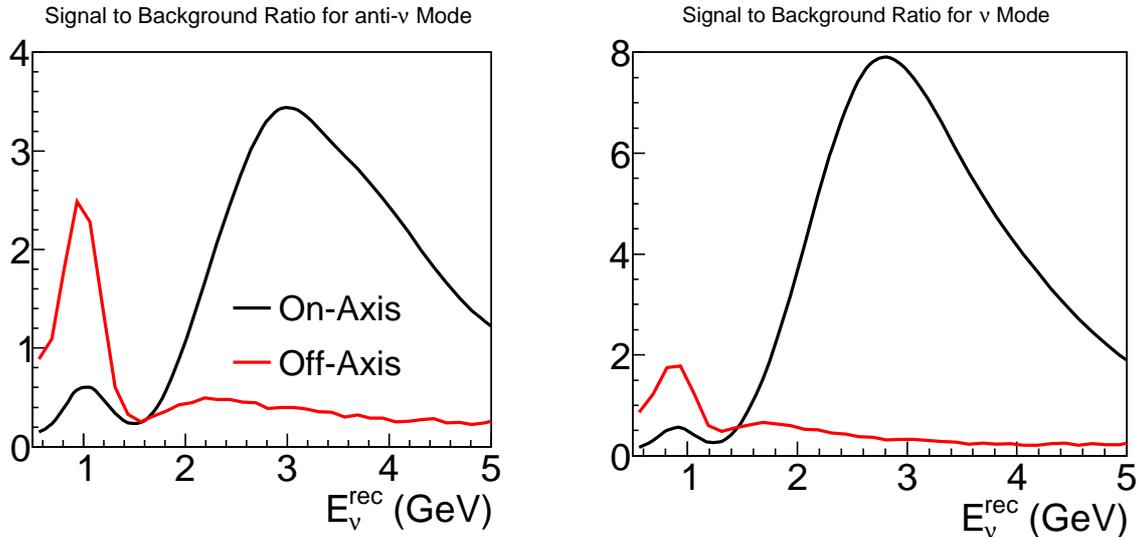


Figure 4. The signal-to-noise ratios for ν (right) and anti- ν (left) running are shown with respect to the reconstructed neutrino energy (E_{ν}^{rec}). A 10 kt liquid argon time projection chamber is assumed to be the on-axis detector. A 10 kt water Cerenkov detector is assumed to be the off-axis detector. The signal-to-noise ratio at the first (second) oscillation is excellent for the on-axis (off-axis) detector.

include neutral-current background and τ -neutrino (oscillated from the μ -neutrino) appearance background. Fig. 4 shows the expected signal-to-background ratio for the (anti-) ν_{μ} running (NH and $\delta_{CP}=0$) with a 10 kt off-axis water Cerenkov (WC) detector in which the performance is assumed to be the same as Super-Kamiokande (SK2 performance [14, 15] assumed). The expected signal-to-background ratios for the 10 kt LBNE on-axis liquid argon time projection chamber (LAr TPC) are also shown in Fig. 4 for comparison. The signal-to-background ratio is excellent at the first oscillation maximum for the on-axis LAr TPC detector, while the off-axis WC detector provides a cleaner signal at the second oscillation maximum. In addition, it has been pointed out in Ref. [16] that such a detector can work on surface to reduce cost with sufficient shielding.

The physics sensitivities to the determination of the mass hierarchy and the discovery of CP violation with the additional 10-kt, off-axis water Cerenkov detector, are calculated in GLoBES [17] using the 2010 LBNE beam design (Fig. 5). The input oscillation parameters to generate expected spectra are taken from Ref. [18]. The statistical interpretation of MH sensitivity is explained in detail in Ref. [19]. The off-axis detector will considerably improve the combined sensitivity of LBNE10 and T2K [20, 21, 22] in MH, with slight improvement in sensitivity to the CP violation. At the worst possible δ_{CP} values, the increment in the MH sensitivity ($\Delta\chi^2$) with the second 10 kt off-axis WC detector is equivalent to that of an additional 10 kt on-axis LAr TPC. Since the WC detector is much cheaper than the LAr TPC with the same target mass, adding the second off-axis WC detector is a more efficient way to enhance MH sensitivity at the bad half of δ_{CP} . In addition, the MH sensitivity can be further enhanced with a narrower off-axis neutrino beam [24] without increasing the total flux intensity or a larger target mass ¹.

¹ The newly proposed 100 kt water Cerenkov detector in mine pits (CHIPS) [23] could be re-deployed in Belle Fourche Reservoir, a lake located at about 27 mrad off-axis (1300 km) of the LBNE beam.

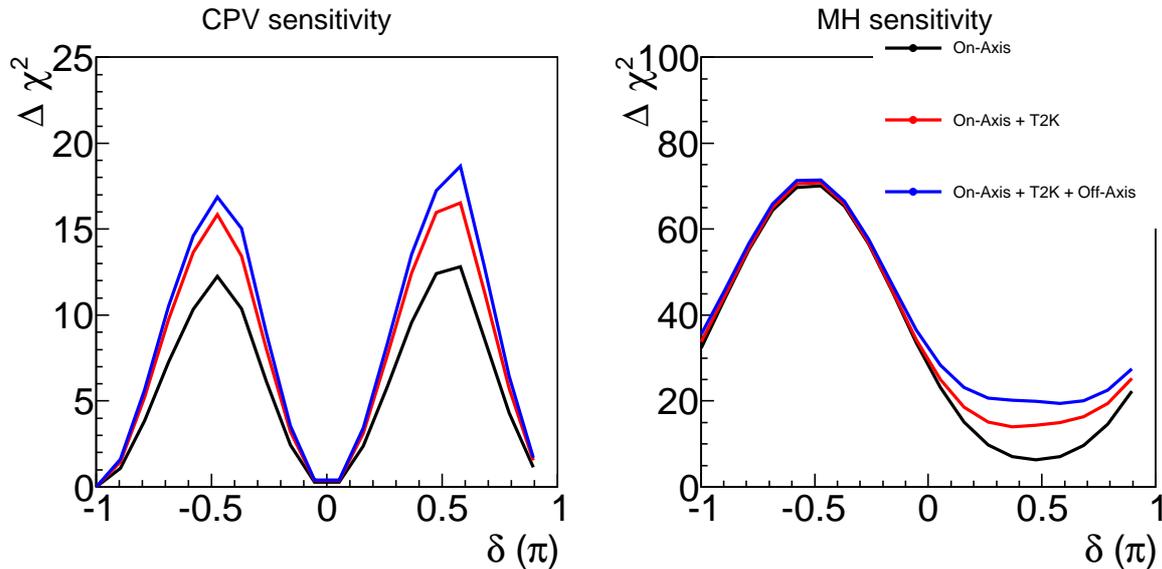


Figure 5. The physics sensitivity of LBNE10 to determine that the value of the CP-violating phase, δ_{CP} , is not zero or π (left) and to determine the neutrino mass hierarchy (right) are shown. Three cases are compared: i) LBNE10 with only the on-axis 10 kt LAr TPC, ii) combining the results of LBNE10 with those from the T2K experiment, and iii) combining the results of LBNE10 with T2K and a 10-kt water Cerenkov detector at a location 27-mrad off-axis from the LBNE beam line. The mass hierarchy sensitivity in the bad half of δ_{CP} is significantly improved with the second off-axis detector.

In summary, a second detector at an off-axis location focusing on the second oscillation maximum can enhance the ability of LBNE10 to determine the mass hierarchy and strengthen its potential to discover CP violation in the leptonic sector.

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