Hierarchy and Octant Determination Potential of LBNE and LBNO

Sanjib Kumar Agarwalla

Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
E-mail: sanjib@iopb.res.in

Suprabh Prakash

Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 221019, Allahabad, India
E-mail: suprabhprakash@hri.res.in

S. Uma Sankar∗

Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India
E-mail: uma@phy.iitb.ac.in

Recent measurement of a moderately large value of θ_{13} is very good news for both current and future long-baseline experiments. It enables them to address the outstanding issues in neutrino oscillation physics: (a) Neutrino mass hierarchy, (b) Octant of θ_{23} and (c) CP violation. The current experiments, T2K and NOνA, can only give 90% C.L. hint of hierarchy and 95% hint of octant. Future facilities are imperative for making measurements at 3σ level or better. We compare the physics reach of two future superbeam facilities, LBNE and LBNO in their first phases of run, to resolve the above issues. LBNO, by itself, can determine the hierarchy at more than 10σ, even for the lowest allowed value of $\sin^2\theta_{23}(\text{true}) = 0.34$. For LBNE, the hierarchy reach is more modest. In particular, LBNE, by itself, will not be able to reach 3σ hierarchy determination, for the most unfavourable values of δ_{CP}. The sensitivities of these future facilities improve significantly with the addition of the projected data from T2K and NOνA. Thus, LBNE is able to achieve better than 3σ hierarchy determination in combination with T2K and NOνA. The addition of T2K and NOνA data also leads to (a) significant boost in the CP violation discovery and (b) a 3σ octant resolution for $\sin^2\theta_{23}(\text{true}) \leq 0.44$ or for $\sin^2\theta_{23}(\text{true}) \geq 0.58$ for all values of $\delta_{CP}(\text{true})$ for both LBNE and LBNO.

∗Speaker.

1. Introduction

The discovery of neutrino oscillations over the past decade provides firm evidence for new physics. Recently, the unknown 1-3 lepton mixing angle has been measured quite precisely by the reactor experiments [1, 2, 3]. They have found a moderately large value, not too far from its previous upper bound. This represents a significant milestone towards addressing the remaining fundamental questions, in particular determining the neutrino mass hierarchy and searching for CP violation in the neutrino sector. Another recent and crucial development is the indication of non-maximal 2-3 mixing by the MINOS accelerator experiment [4], leading to the problem of determining the correct octant of θ_{23}. It is possible to resolve all the above three issues by the observation of ν_e appearance via $\nu_\mu \to \nu_e$ oscillations. The determination of CP violation in particular requires the full interplay of three flavor effects in neutrino oscillations.

Oscillation experiments are insensitive to the value of the lowest neutrino mass. They measure the two independent mass-squared differences: $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{31}^2 = m_3^2 - m_1^2$. Solar neutrino data constrain Δm_{21}^2 to be positive but there is no experimental constraint on the sign of Δm_{31}^2. Hence, two patterns of neutrino masses are possible: $m_3 > m_2 > m_1$, called normal hierarchy (NH) where Δm_{31}^2 is positive and $m_2 > m_1 > m_3$, called inverted hierarchy (IH) where Δm_{31}^2 is negative. If CP violating phase δ_{CP} in the neutrino mixing matrix $\neq 0$ or $180°$, then CP violation in leptonic sector is established. So far, δ_{CP} is unconstrained and can take any value in the full range $[-180°, 180°]$. Regarding θ_{23}, global fits [5] point to a deviation from maximal mixing (MM) *i.e.* $(0.5 - \sin^2\theta_{23}) \neq 0$. This raises an additional question: Is θ_{23} in the lower octant (LO: $\theta_{23} < 45°$) or higher octant (HO: $\theta_{23} > 45°$)? Determining the mass hierarchy and the octant of θ_{23} is crucial for identifying the symmetries of the neutrino mass matrix and the pattern of symmetry breaking.

The combined data from the current ν_e appearance experiments, T2K [6] and NOvA [7], can provide a 90% confidence level hint for neutrino mass hierarchy [8] and a 95% confidence level hint for octant of θ_{23} [9]. They can determine these quantities at $> 99\%$ C.L. only for a very small range of favorable values of δ_{CP}. Discovery of leptonic CP violation is possible at 95% C.L. only for values of δ_{CP} close to $\pm 90°$, *i.e.* where CP violation is maximum [8]. Hence, future facilities consisting of intense, high power wide-band beams and large smart detectors are mandatory to cover the entire parameter space at a high confidence level. Here, we explore the capabilities of future superbeam experiments with liquid argon detectors, LBNE [10] and LBNO [11] towards resolving these unknowns. We first present the stand-alone performances of these setups in their first phases. Then we examine how the addition of projected data, from T2K and NOvA, can improve the sensitivity of these future facilities. We also study in detail how these sensitivities change as the true value of $\sin^2\theta_{23}$ varies in its allowed 3σ range of 0.34 to 0.67.

2. Physics with Bi-events Plot

The Tokai-to-Kamioka (T2K) experiment started taking data in 2010. In this experiment, a $2.5°$ off-axis ν_μ beam from J-PARC is directed to the Super-Kamiokande detector (fiducial volume 22.5 kt) at Kamioka, at a distance of 295 km [6]. The neutrino flux peaks sharply at the first oscillation maximum of 0.6 GeV and a five year run in neutrino mode with a beam power of 0.75

MW is envisaged. We consider such a run for mass hierarchy and CP violation studies. We assume equal neutrino and anti-neutrino runs of 2.5 years while exploring the octant sensitivity [9].

The NOvA experiment [7] is now under construction and will start taking data near the end of this year. Here, the NuMI beam will be sent towards a 14 kt totally active scintillator detector (TASD) placed at a distance of 810 km from Fermilab, at a location which is $0.8°$ off-axis from the beam. Due to the off-axis location, the flux is sharply peaked around 2 GeV, again close to the first oscillation maximum in $P(\nu_\mu \to \nu_e)$ channel. A three year neutrino run followed by a three year anti-neutrino run are planned with a beam power of 0.7 MW. After the discovery of moderately large value of θ_{13}, NOvA has reoptimized its event selection criteria. In our simulation, we use all these new features, the details of which are given in [12, 8].

The Long-Baseline Neutrino Experiment (LBNE10) [10], in its first stage, will have a high intensity, on-axis neutrino beam from Fermilab directed towards a 10 kt LArTPC located at Homestake with a baseline of 1300 km. It is scheduled to have five years each of ν and $\bar{\nu}$ runs. To have the LArTPC cross-sections, we have scaled the inclusive charged current (CC) cross sections of water by 1.06 (0.94) for the ν ($\bar{\nu}$) case. The Long-Baseline Neutrino Oscillation Experiment (LBNO) [11] plans to use a conventional wide-band beam, of power 750 kW, from CERN to a proposed 20 kt (in its first phase) LArTPC housed at the Pyhäsalmi mine in Finland, at a distance of 2290 km. For LBNO also, we consider five years each of ν and $\bar{\nu}$ runs. We assume the same detector properties as that of LBNE10. In our calculations, we also consider a LBNO configuration reducing the detector mass to 10 kt which we denote as 0.5*LBNO. The exposure for this setup will be quite similar to LBNE10 which will enable us to perform a comparative study between these two baselines on the same footing. The results presented in this paper are obtained using the GLoBES software [13, 14].

We attempt to understand the physics capabilities of 0.5*LBNO and LBNE10 setups with the help of bi-events plot. In figure 1, we have plotted ν_e vs. $\bar{\nu}_e$ appearance events, for 0.5*LBNO and LBNE10 for the four possible combinations of hierarchy and octant. Since δ_{CP} is unknown, events are generated for the full range $[-180°, 180°]$, leading to the ellipses. The event rates are calculated using the following oscillation parameters: $\Delta m_{21}^2 = 7.5 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.3$ [5], $\Delta m_{\text{eff}}^2 = \pm\, 2.4 \times 10^{-3}$ eV^2, and $\sin^2 2\theta_{13} = 0.089$ [1]. Δm_{eff}^2 is the effective mass-squared difference measured using the ν_μ survival probability and is a linear combination of Δm_{31}^2 and Δm_{21}^2. The value of Δm_{31}^2 is derived from Δm_{eff}^2 using the relation given in [15]. This relation leads to different magnitudes of Δm_{31}^2 for NH and for IH. For $\sin^2\theta_{23}$, we choose the two degenerate best-fit values of the global fit [5]: 0.41 in the lower octant (LO) and 0.59 in the higher octant (HO). Note that, here we have plotted the total number of events, whereas the actual analysis will be done based on the spectral information. Nevertheless, the contours in this figure contain very important information regarding the physics capabilities of the experiments. An experiment can determine both the hierarchy and the octant, if every point on a given ellipse is well separated from every point on each of the other three ellipses. The larger the separation, the better is the confidence level with which the above parameters can be determined.

One can see from figure 1 that for 0.5*LBNO, the two (LO/HO)-IH ellipses are well separated from the two (LO/HO)-NH ellipses, in number of ν_e events. This is a consquence of the LBNO baseline being close to the bimagic baseline [16, 17]. Hence, 0.5*LBNO has excellent hierarchy
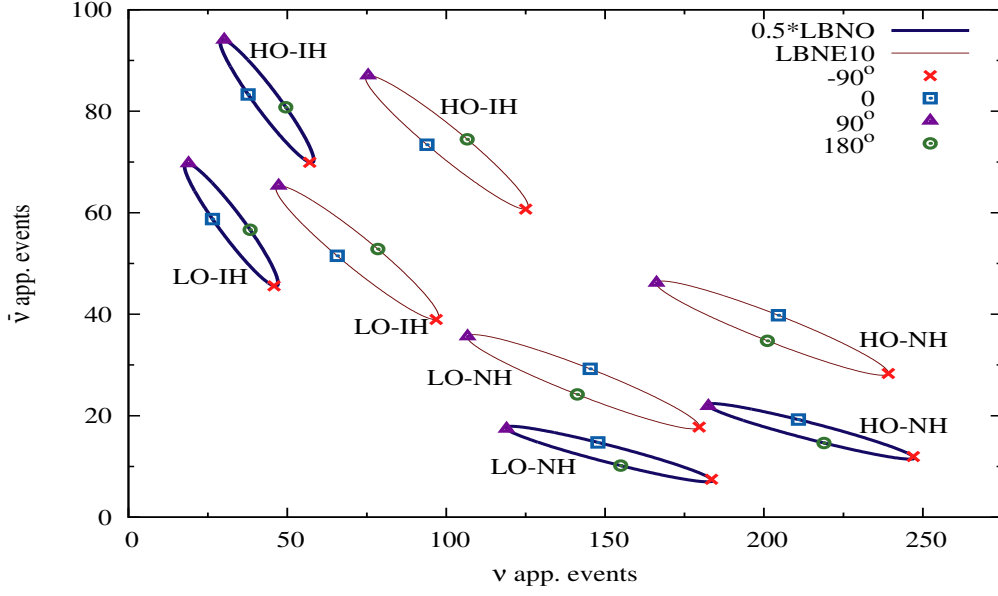
Figure 1: Bi-events (ν_e and $\bar{\nu}_e$ appearance) plot for the four possible octant-hierarchy combinations and all possible δ_{CP} values. The experiments considered are LBNE10 and 0.5*LBNO. Here $\sin^2 2\theta_{13} = 0.089$. For LO (HO), $\sin^2 \theta_{23} = 0.41(0.59)$.

determination capability with just ν data. However, ν data alone will not be sufficient to determine the octant in case of IH, because various points on (LO/HO)-IH ellipses have the same number of ν_e events. Likewise, only $\bar{\nu}$ data cannot determine the octant in case of NH. Therefore, balanced ν and $\bar{\nu}$ data are mandatory to make an effective distinction between (LO/HO)-IH ellipses and also between (LO/HO)-NH ellipses.

For LBNE10, ν data alone can not determine hierarchy because various points on LO-NH and HO-IH ellipses have the same number of ν_e events (see figure 1). Thus, $\bar{\nu}$ data is also needed. Even with $\bar{\nu}$ data, hierarchy determination can be difficult to achieve, if nature chooses LO and one of the two worst case combinations of hierarchy and δ_{CP} which are (NH, 90°) or (IH, −90°). In such a situation, the ν_e and $\bar{\nu}_e$ events are rather close to each other and it will be very difficult for LBNE10 to reject the wrong combination. Regarding octant determination, the capability of LBNE10 is very similar to that of 0.5*LBNO because the separations between the ellipses, belonging to LO and HO are very similar for these two experiments.

3. Results

In figure 2, the mass hierarchy capabilities of 0.5*LBNO, LBNE10 and LBNE10+T2K+NOνA are shown, for the lowest allowed value of $\sin^2 \theta_{23}$. We see that even 0.5*LBNO, by itself, has better than 7σ hierarchy determination capability for all δ_{CP}, whereas LBNE10 needs the help of T2K and NOνA data to achieve 3σ hierarchy determination for the most unfavourable values of δ_{CP}. The octant discrimination capability is shown in figure 3, where we see that LBNE10 and LBNO have similar sensitivity, both without and with the data from T2K and NOνA added. The fraction
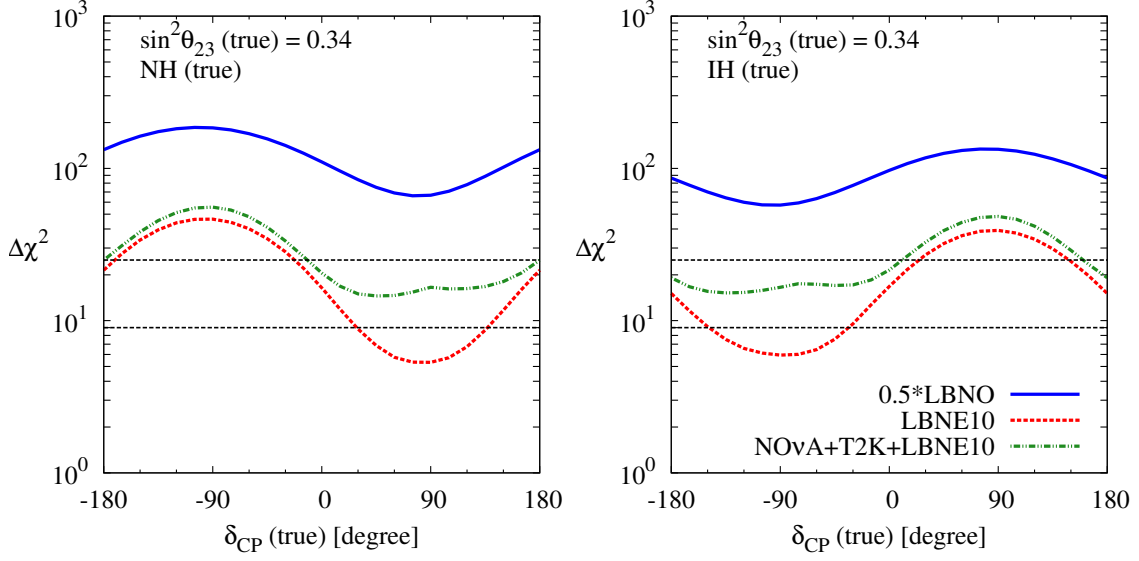
Figure 2: Left panel (right panel) shows the $\Delta\chi^2$ for the mass hierarchy discovery as a function of true value of δ_{CP} assuming NH (IH) as true hierarchy. Results are shown for 0.5*LBNO, LBNE10, and LBNE10+T2K+NOvA. Here we consider $\sin^2\theta_{23}$(true) = 0.34 (the lowest value in its allowed 3σ range).

Setups	Fraction of δ_{CP}(true)	
	2σ confidence level	3σ confidence level
LBNE10 (10 kt)	0.51	0.03
LBNE10 + T2K + NOvA	0.63	0.43
0.5*LBNO (10 kt)	0.40	0.0
0.5*LBNO + T2K + NOvA	0.63	0.37
LBNO (20 kt)	0.51	0.23
LBNO + T2K + NOvA	0.69	0.46

Table 1: Fraction of δ_{CP}(true) for which a discovery is possible for CP violation considering NH as true hierarchy. Here, we assume maximal mixing for the true choice of θ_{23}. The results are presented at 2σ and 3σ confidence level.

of values of δ_{CP} for which leptonic CP violation can be established is shown in table 1. We see from this table that the addition of T2K and NOvA data leads to a dramatic improvement in the sensitivity to establish leptonic CP violation at 3σ level.

References

[1] Daya Bay Collaboration: An, F. and others, Phys. Rev. Lett. **108**, 171803 (2012).

[2] RENO Collaboration: Ahn, J. and others, Phys. Rev. Lett. **108**, 191802 (2012).

[3] Double Chooz Collaboration: Abe, Y. and others, Phys. Rev. **D86**, 052008 (2012).

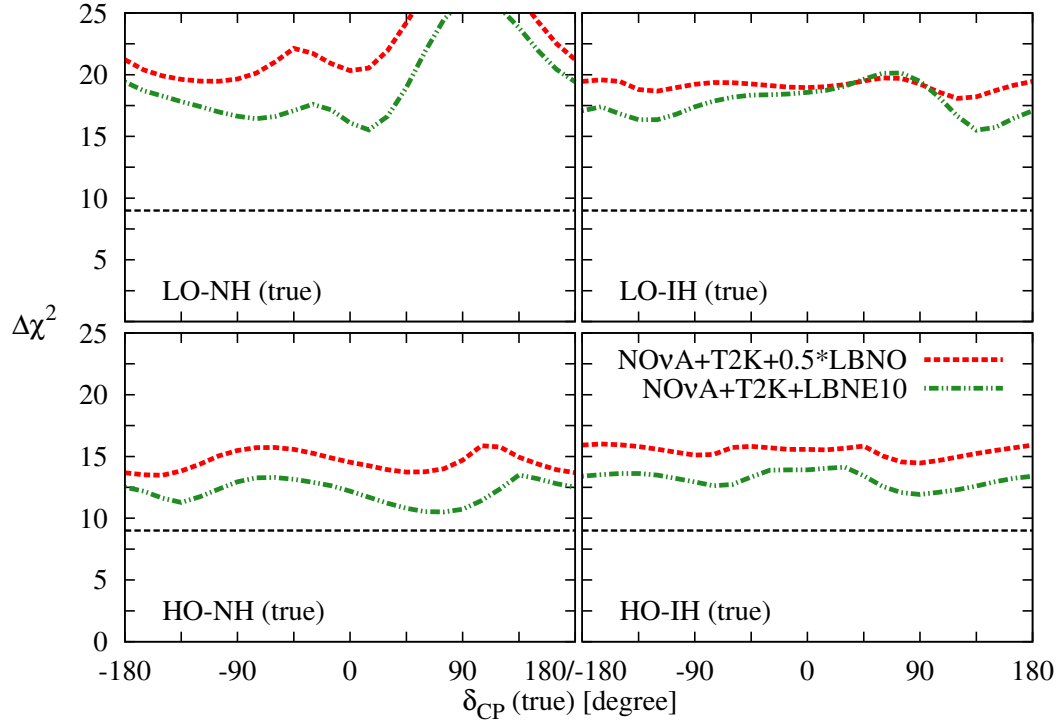[4] MINOS Collaboration: Adamson, P. and others, Phys. Rev. Lett. **110**, 251801 (2012).

Figure 3: $\Delta\chi^2_{\min}$ for octant discovery potential as a function of true δ_{CP} for 0.5*LBNO and LBNE10 adding the projected data from T2K and NOvA. Results are shown for the four possible true octant-hierarchy combinations. For LO (HO), $\sin^2\theta_{23}$(true) = 0.41 (0.59). Here $\sin^2 2\theta_{13}$(true) = 0.089.

[5] Gonzalez-Garcia, M. and Maltoni, M. and Salvado, J. and Schwetz, T., JHEP **1212**, 123 (2012).

[6] T2K Collaboration: Itow, Y. and others, arXiv:hep-ex/0106019.

[7] NOvA Collaboration: Ayers, D. and others, arXiv:hep-ex/0503053.

[8] Agarwalla, Sanjib and Prakash, Suprabh and Raut, Sushant and Umasankar, S., JHEP **1212**, 075 (2012).

[9] Agarwalla, Sanjib and Prakash, Suprabh and Umasankar, S., JHEP **1307**, 131 (2013).

[10] LBNE Collaboration: Adams, C. and others, arXiv:1307.7335.

[11] LBNO Collaboration: Rubbia, A and others, arXiv:1003.1921.

[12] Patterson, R. (for NOvA Collaboration) Nucl. Phys. Proc. Suppl. **235-236**, 151 (2013).

[13] Huber, P. and Lindner, M. and Winter, W., Comput. Phys. Commun. **167**, 195 (2004).

[14] Huber, P. and Lindner, M. and Rolinec, M. and Winter, W., Comput. Phys. Commun. **177**, 432 (2007).

[15] Nunokawa, H. and Parke, S. J. and Zukanovich Funchal, R., Phys. Rev. **D72**, 013009 (2005).

[16] Raut, Sushant and Singh, Ravi Shanker and Umasankar, S., Phys. Lett. **B696**, 227 (2011).

[17] Dighe, A. and Goswami, S. and Ray, S., Phys. Rev. Lett. **105**, 261802 (2010).