

Resolving octant degeneracy at LBL experiment by combining Daya Bay reactor setup

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Abstract. Long baseline Experiment (LBL) have promised to be a very powerful experimental setup to study various issues related to Neutrinos. Some ongoing and planned LBL and medium baseline experiments are- T2K, MINOS, NOvA, LBNE, LBNO etc. But, the long baseline experiments are crippled due to presence of some parameter degeneracies, like the Octant - degeneracy. In this work, we first show the presence of Octant degeneracy in LBL experiments and then combine it with Daya Bay Reactor experiment at different values of CP violation phase. We show that the Octant degeneracy in LBNE can be resolved completely with this proposal.

1. Introduction

In the quest to find the unknowns in neutrino sector, long baseline neutrino experiments (LBNEs) have an important role to play. But there is a major drawback of the LBNEs- the presence of parameter degeneracies [1, 2]. The appearance of several disconnected region in multi-dimensional space of oscillation parameters for a given experiment is due to the inherent structure of three flavour neutrino oscillation probabilities. Because of these, it is not exactly possible to pin-point, which one is the exact (true) solution. These degeneracies can be classified in three ways. Appearance of two disconnected regions in the $(\delta_{cp}, \theta_{13})$ plane for $\nu_\mu \rightarrow \nu_e$ channel in neutrino and anti neutrino mode leads to intrinsic or $(\delta_{cp}, \theta_{13})$ -degeneracy [3, 4]. Appearance of two solutions corresponding to two sign of Δm^2 gives hierarchy or sign (Δm^2) -degeneracy [5] and appearance of solutions corresponding to θ_{23} and $\pi/2 - \theta_{23}$ at different values of δ_{cp} and θ_{13} is called octant or (θ_{23}) -degeneracy [6]. In literature, various methods to resolve these degeneracies have been proposed. The use of spectral information [7], combining experiments at various baselines and/or (L/E)-values [2], combining $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\tau$ oscillation channels [8], combining long baseline (LBL) and reactor experiments [9, 10] and combination of LBNE and atmospheric experiments [11, 12] are a few of them.

Recent global fit of all neutrino oscillation parameters [13], points towards the lower octant [$\theta_{23} < \pi/4$], but its still not clear which octant is the true octant. Again, bounds on sterile oscillation parameters from Reactor experiments can be found on [14]. In this work, we have considered a LBNE like setup and combined it with Daya Bay [15] reactor setup with the help of simulation using Globes [16] to check what information we can get from it. We call it LBNE-like setup because LBNE collaboration is planning to reconfigure their setup with liquid argon detector. But still our work is relevant in the sense that this result can be implemented to any long baseline experiment having water Cherenkov detector at a baseline ~ 1300 km. LBNE



neutrino beamline is driven by the physics of different oscillation channels like $-\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$ etc. We have considered the $\nu_\mu \rightarrow \nu_e$ appearance channel in this study.

Presence of octant degeneracy, in LBNE like setup is confirmed by exclusion curves in Fig.1(1st column) in the $\theta_{13} - \delta_{CP}$ plane. Next, we combine LBNE like setup with Daya Bay reactor experiment, to resolve the above mentioned octant degeneracy as shown in Fig.1 (2nd column). We find that after combining, the degenerate exclusion curves disappear. With this proposed combination, it is possible to resolve octant degeneracy. In fig.2, we have pinpointed the octant after combining LBNE like setup with Reactor setup at $\delta_{CP} = 0^\circ$. We have done this analysis for a running time of 5 years in neutrino and 5 years of anti- neutrino. The results have been presented for different values of δ_{CP} phase = $0^\circ, 90^\circ, 150^\circ$. We have tested these results for a wide range of δ_{CP} , as we do not know the exact value of this parameter in leptonic sector, from experiments.

2. Experiment details

In our analysis, we have considered the LBNE to DUSEL beamline [17] of 1300 km baseline that is pointing from NuMI (Neutrino Main Injector). The Detector is a 300 kiloton water Cherenkov detector. Running time is 5 years for neutrinos and 5 years for anti-neutrinos. Power considered is 700 KW. Daya Bay [15] has three pairs of reactors at Daya Bay and Ling Ao I, which generate 11.6 GW of power. Daya Bay consists of three underground experimental halls, one far and two near, linked by horizontal tunnels. Eight identical cylindrical detectors are employed to measure the neutrino flux. The mass of each detector is about 20 tons. Equal mass of near and far detector will reduce the systematic errors. Four of these eight detectors are at the far zone while two detectors are kept in each near zone. The distance of the detectors from the reactor cores at the Daya Bay site is 363 m while this distance at the Ling Ao site is 481 m. The far detectors are at 1985 m and 1615 m respectively from the Daya Bay and Ling Ao reactor sites. Energy resolution used is 5%. In this work, we have used only two pairs of reactors.

3. Results and analysis

Using above details of LBNE experiment, we have produced exclusion curves in the $\delta_{CP} - \theta_{13}$ plane. The best fit values of oscillation parameters [13] used are: $\sin^2 \theta_{12} = 0.307$, $\sin^2 \theta_{23} = 0.427$, $\sin^2 \theta_{13} = 0.0241$ and $\Delta m_{21}^2 = 7.54 \times 10^{-5} eV^2$ and $\Delta m_{31}^2 = 2.43 \times 10^{-3} eV^2$.

Energy resolution used is 10% for the electrons, and 5% for the muons. 1% systematic errors for the signal, and 5% systematic error for the background has been used. While searching for degenerate curves, we give the global best-fit values (true hierarchy, true octant) as true values. Then a chi-square analysis is done, to search for true hierarchy, and wrong octant for the minima of χ^2 function. We have used the $P_{\mu e}$ channel in our calculation and we have marginalised over δ_{CP} , $\sin^2 2\theta_{13}$, Δm_{31}^2 and θ_{23} in their 3σ ranges. We are only showing plots for normal hierarchy cases. In the plots we abbreviated true hierarchy- true octant as THTO, true hierarchy- wrong octant as THWO.

From these figures, following observations are in order :

- (i) Appearance of THTO and THWO (true hierarchy and wrong octant) contours in Fig.1 (1st column, top six panels), indicates the presence of octant degeneracy in the LBNE like experimental setup.
- (ii) It may be noted that the regions inside the contours are the allowed regions of the neutrino oscillation parameters θ_{13} and δ_{CP} .
- (iii) Occurrence of THTO and THWO curves nearly at same δ_{cp} affects the measurement of θ_{13} but not of δ_{cp} . It means that we can pinpoint the value of δ_{cp} even in the presence of octant degeneracy.

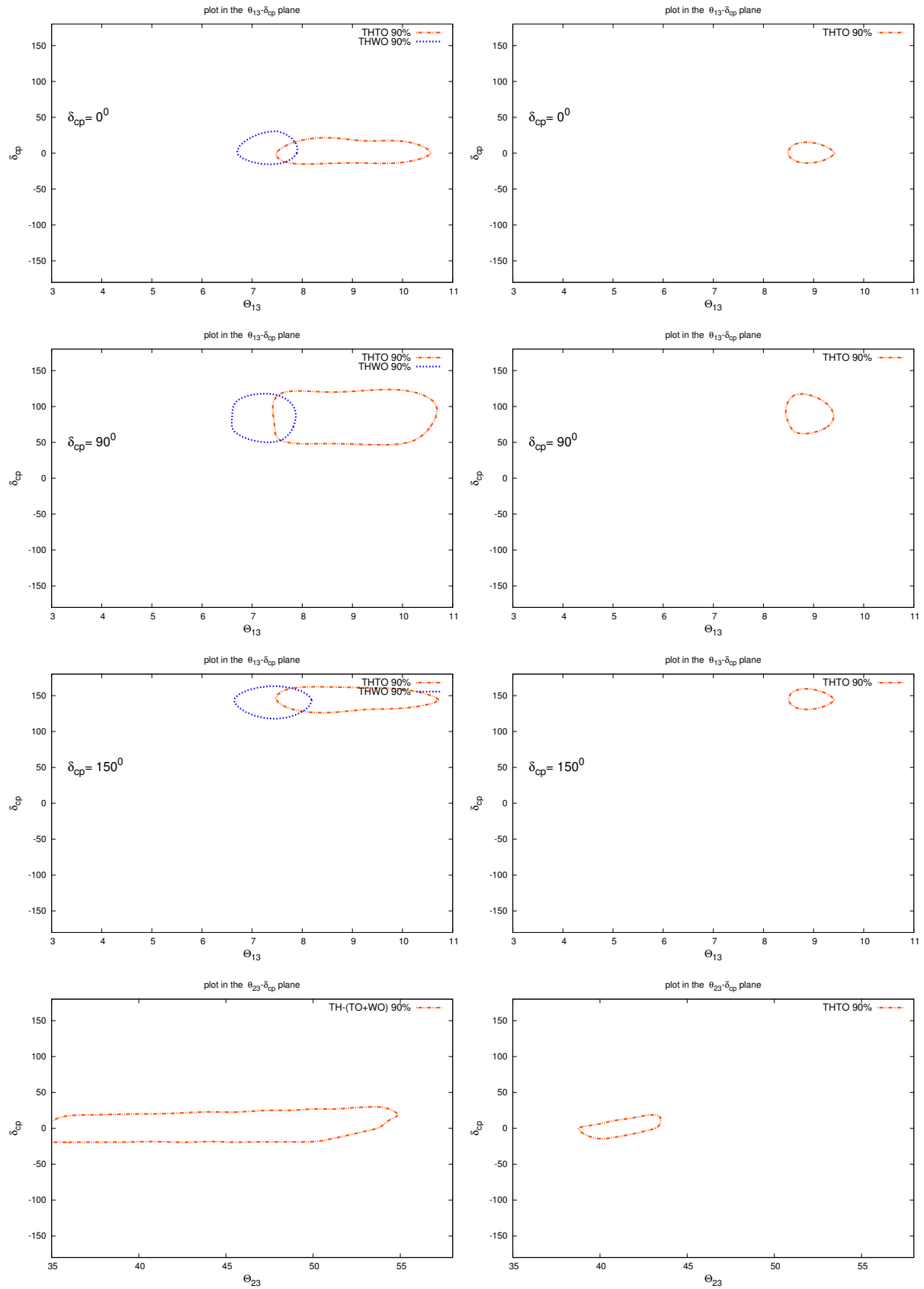


Figure 1. Contours in $\delta_{CP} - \theta_{13}$ plane (top six panels) for LBNE-like setup (1st column) and LBNE-like+Daya Bay setup (2nd column) at different δ_{CP} values and at 90% cl for normal hierarchy. Bottom two panels are for $\delta_{CP} - \theta_{23}$ at $\delta_{CP} = 0$.

- (iv) In Fig.1 (2nd column, top six panels), we see that THWO curves disappear, i.e. the Octant degeneracy has been resolved completely, after combining LBNE with Daya Bay experiment. Also we find that the size of the allowed regions decrease, i.e. the measurements of the neutrino oscillation parameters θ_{13} and δ_{CP} become more deterministic. In our opinion, this resolution of Octant degeneracy is because of the fact that, the difference in the values of θ_{13} , for the true and Octant degenerate curves, is more than the sensitivity of the Daya Bay reactor experiment. And therefore, the reactor data can pick up the true value of θ_{23} .
- (v) In Fig.1 (bottom two panels, 1st fig), the octant sensitivity is shown in $\delta_{CP} - \theta_{23}$ plane for LBNE like setup at $\delta_{CP} = 0$ degree. It is seen that the contour is spanning over both the octant (true and wrong). Hence from this contour, it is not possible to figure it out which one is the correct octant. But in 2nd fig (bottom panel), which is for the LBNE-like+Daya Bay setup, ambiguity of octant is resolved. It is clear that lower octant ($\theta_{23} < 45^\circ$) is the true octant as indicated by the disappearance of allowed region in the wrong octant or higher octant of θ_{23} . We have checked the results for different δ_{CP} and the results are consistent. Since, lower octant is also preferred by Global fit data, with the help of this proposal, we have been able to pinpoint the octant in LBNE which is the highlight of this work.

4. Discussion and conclusion

To conclude, in this work, we have presented interesting results on resolution of Octant degeneracy in LBNE-like setup. The Octant degeneracy is resolved after combining LBNE-like with Daya Bay reactor experiment. We can conclude that, in presence Daya Bay reactor setup can pinpoint the true octant of LBNE like setup. Since Octant degeneracy poses a major hurdle to precise measurement of neutrino oscillation parameter θ_{23} at long baseline neutrino experiments, results presented in this work are extremely important and relevant.

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