Parameter degeneracies in FNAL-Homestake LBNE setup

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Abstract

LBNE (Longbaseline Neutrino Oscillation Experiments) provide a powerful experimental setup to study sensitivities and exclusion limits in neutrino oscillation parameter space. A longbaseline experiment is being planned, at USA, from FNAL (Fermilab National Accelerator Laboratory) to an underground laboratory at Homestake in South Dakota, at an angle of 5.84 degrees from FNAL (at a distance of 1289 km). The prospect of a new beamline towards this location from FNAL, and a 300 Kiloton water Cerenkov detector at the site is in planning stage, for the studies of the neutrino physics program. The long baseline provides sufficient matter effects for neutrino travel, and a large detector will help towards better statistics. In this work, we present, up to what extent, the parameter degeneracies, present in oscillation parameter space, can be resolved, using this FNAL-LBNE setup.

I. Introduction

There is now sufficient evidence that neutrinos have mass and hence they oscillate. The experiments with solar [1], atmospheric [2], reactor [3], and long baseline accelerator neutrinos [4], have provided compelling evidence for the existence of neutrino oscillations. Recently, MiniBooNE [5] and T2K [6] have also provided some data. MiniBooNE [5] suggest the evidence of oscillations in the $\nu_\mu \rightarrow \nu_e$ sector, at the value $\frac{L}{E} \sim 1 \text{ km/GeV}$, where $L$ is the baseline of the experiment and $E$ is the neutrino energy. This is almost similar to the result provided by LSND [7] about a decade ago. On the other hand, results from T2K suggests that $\sin^2 2\theta_{13} > 0.03$ [6]. This result from T2K boosts the expectation of discovery of CP violation by some future planned experiments [8]. A recent global analysis of available neutrino data can be found in [9].

Despite the results on values of $\theta_{12}, \theta_{23}, \Delta m^2_{21}, \Delta m^2_{23}$ and $\theta_{13}$, there are still some unknowns in neutrino sector – mass hierarchy, CP violation phase $\delta_{CP}$, precise value of $\theta_{13}$, absolute mass of neutrinos, whether neutrinos are majorana neutrinos, whether neutrinos constitute a part of Dark Matter and/or Dark Energy, etc. In this quest to find the unknowns, long baseline neutrino experiments (LBNE) have a very important role to play. Some of the ongoing and planned LBNEs are - MINOS [10], T2K [6], NOνA [11], FNAL-LBNE [12], etc. The LBNEs have an advantage that due to long baselines, the neutrinos travel long distances through matter, and hence matter effects become important. Due to this, they become capable of differentiating between normal mass hierarchy (NMH, $m^2_3 - m^2_2 > 0$) and inverted mass hierarchy (IMH, $m^2_3 - m^2_2 < 0$). This is because matter effects have opposite signs for these two hierarchies, in the formula for neutrino oscillation probabilities. Also, if the detector mass is very high (hundreds of kilotons), then the statistics become better, and precision physics become possible. They also become sensitive to measurement of the unknown mixing angle $\theta_{13}$, and CPV phase $\delta_{CP}$.

Along with these accelerator based neutrino physics issues, a very large detector could also be sensitive to some other studies [12]. These are – improved search for nucleon decay (see [39] for latest limits on proton life time), observation of natural sources of neutrino (such as the Sun, Earth’s atmosphere, Supernova explosion etc.). Also, there may be galactic sources of neutrinos, galactic neutrinos have a natural source in inelastic nuclear collisions through leptonic decays of charged secondary pions. Such neutrino sources, currently not detectable, could be seen by a large megaton neutrino detector that runs for several decades.

The LBNEs, although being very useful to study above discussed physics, suffer from a serious drawback – the presence of parameter degeneracies, see ref [13-19]. Due to the inherent structure of three flavor neutrino oscillation probabilities, for a given experiment, in general several disconnected regions in multi-dimensional space of oscillation parameters will be present. So, it becomes difficult to pin-point, which one is the exact (true) solution. There degeneracies can be classified as :

1. **The intrinsic or ($\delta_{CP}, \theta_{13}$)-degeneracy** [20,21] – As can be observed from the formula for oscillation probability for the appearance channel $\nu_\mu \rightarrow \nu_e$, for neutrinos and anti-neutrinos, for three flavor case, two disconnected
regions appear in the \((\delta_{CP}, \theta_{13})\) plane. But, for the experiments operating at first oscillation maximum, the second solution can be disfavored [13,15].

2. *The Hierarchy or sign \((\Delta m^2_{31})\)-degeneracy* [22]– The two degenerate solutions corresponding to two signs of \(\Delta m^2_{31}\) appear at different values of \(\delta_{CP}\) and \(\theta_{13}\).

3. The octant or \(\theta_{23}\)-degeneracy [23]– LBNEs are senesitive mainly to \(\sin^2\theta_{23}\), it is difficult to distinguish the two octants \(\theta_{23} < \frac{\pi}{4}\) and \(\theta_{23} > \frac{\pi}{4}\). The solutions corresponding to \(\theta_{23}\) and \(\frac{\pi}{2} - \theta_{23}\) appear at different values of \(\delta_{CP}\) and \(\theta_{13}\).

This leads to an eight-fold \((2 \times 2 \times 2)\) degeneracy, and hence ambiguity, in the determination of the oscillation parameters \(\delta_{CP}\) and \(\theta_{13}\). This in turn poses a serious problem, and somehow, we have to tackle this, to find out these parameters exactly. Several methods to resolve these degeneracies have been proposed:

1. Combination of experiments at various baselines and/or \(L\) values [13,22,24-27].
2. Use of spectral information [14, 28].
3. Combination of \(\nu_e \rightarrow \nu_{\mu}\) and \(\nu_e \rightarrow \nu_\tau\) oscillation channels [29].
4. Combination of LBNE and reactor experiments [30-34].
5. Combination of LBNE and atmospheric experiments [35, 36].

In this work, we present results on the presence of octant degeneracy, in FNAL-DUSEL setup (1300 km baseline), for a 120 GeV proton beam from NUMI. However, we have not attempted on, how to resolve them. But, we expect that, they could be resolved by combining this accelerator LBNE data, with the atmospheric neutrino oscillation experiment, if the same 300 kton water Cerenkov detector could in future, be used for the atmospheric experiment as well. This is because, the atmospheric neutrino data is sensitive to mass hierarchy (MH), \(\theta_{13}\) and octant of \(\theta_{23}\), while LBNEs are sensitive to \(\theta_{13}\), \(\delta_{CP}\) and \(|\Delta m^2_{31}|\). Hence, the two can be combined to break the degeneracies.

The paper has been organized as follows. Section II contains technical details of the planned FNAL-DUSEL LBNE and the detector, (as used in [12]), and the channels being used etc. Section III contains our results on parameter degeneracies in this experiment. This section is the highlight of this work. We have used the software GLoBES [37] in our work. Conclusions have been presented in Section IV. A more detailed analysis of this work will be presented elsewhere [38].

II. Details of the Experiment

In this section, we will present the technical details of the experiment and the detector, being used in this work, in general. They have been used from ref. [12], and we are mentioning them here, for the sake of brevity and completeness of this work. The FNAL-DUSEL beamline that we have considered here, is pointing from NuMI (Neutrino Main Injector) to Homestake mine in South Dakota, at an angle of 0.5°. The baseline from FNAL to Homestake is 1298 (1300) km. The 120 GeV proton beam is from Fermi-Lab accelerator only, which interacts with the target to produce muons. These muons then decay and produce muon-neutrinos.

The detector is a 300 kiloton water Cerenkov detector. Running time is 3 years for neutrinos and 3 years for anti-neutrinos. Base line is 1300 Kilometers (FNAL-DUSEL), the proton beam is 120 GeV, 0.5 degrees off-axis. Signals used are \(\nu_\mu\) and \(\bar{\nu}_\mu\) appearance channels, and the background used are NC and electron-beam events. The cross-sections used for both are as available with GLoBES software, i.e. those used with NOvA experiment. Energy window used for the analysis is \(0.5\) to \(12.0\) GeV. The pre- and post-smearing efficiencies, that have been used are taken from [12], which is also the spectral information. Here, the bin-wise efficiencies have been used, both for the signal and the background. The earth matter profile used is type 1 of GLoBES (constant density). Energy resolution used is 10 % for the electrons, and 5 % for the muons, 1% systematic error on the signal, and 10 % systematic error on the background has been used. The true values of the parameters used are as follows:

\[
\sin^2(2\theta_{12}) = 0.86
\]

\(^{1}\text{Prof. Mary Bishai has been kind enough to send me the 120 GeV proton beam flux files (back in 2010), (that have been used in ref [12] in figs 9-13), via e-mail.}\)
\[ \theta_{23} = \pi/4 \]
\[ \Delta m_{21}^2 = 0.86 \times 10^{-5} \]
\[ \Delta m_{31}^2 = 2.7 \times 10^{-3} \]

where \( \Delta m^2 \)'s are in eV\(^2\) and, 10% error on solar mass difference, 5% error on atomic mass difference, 5% error on atomic angle, 10% error on solar angle, 5% error on earth matter density has been used.

### III. Results and Analysis on Neutrino Mixing Parameter Degeneracies

Using the information given in Section II., we have generated the contours showing the parameter degeneracy in neutrino oscillation parameter space. Our results have been presented in figures [1-3]. In these figures, true \( \delta_{cp} = 153^\circ \), and systematics errors used are, 10% error in solar parameters and 5% error in atomic parameters.

Following observations are worth mentioning:

1. All these figures are drawn at 3\( \sigma \) (99.73 \%) CL for two parameters (i.e. at \( \chi^2 = 11.83 \)).
2. The true parameters used are:
   \[ \sin^2(2\theta_{12}) = 0.86, \sin^2 \theta_{23} = 0.6, \delta_{cp} = 153^\circ \]
3. Inclusion of systematics makes allowed regions bigger.
4. At \( \sin^2 2\theta_{13} = 0.007 \), 4-fold degeneracy can be seen, while at \( \sin^2 2\theta_{13} = 0.03 \) and 0.01, only 2-fold (Octant) degeneracy is seen to be present.
5. The allowed regions become bigger as \( \sin^2 2\theta_{13} \) becomes small. It means, it becomes difficult to pinpoint the actual value of the parameter, or we can say, as \( \sin^2 2\theta_{13} \) decreases, more difficult it becomes to resolve the degeneracy.

These results can be further analysed as follows:

- **Fig 1** - Here, only two degenerate solutions for TH-TO (green), TH-WO (blue) can be seen, but separation among them is not much. It means that mass hierarchy has been resolved at \( \sin^2 2\theta_{13} = 0.03 \), but Octant degeneracy is present. The green (TH-TO) and blue (TH-WO) occur at \( \sim \) same value of \( \delta_{cp} \), i.e. octant degeneracy affects measurement of \( \sin^2 2\theta_{13} \), while it does not affect measurement of \( \delta_{cp} \). In other words, we can pinpoint the value of \( \delta_{cp} \) even in the presence of octant degeneracy, while the value of \( \theta_{13} \) cannot be pinpointed. So, we definitely need another mechanism to break the Octant degeneracy.

- **Fig 2** - Here again, the situation is similar to \( \sin^2(2\theta_{13}) = 0.03 \) (fig 1 above), only allowed regions are bigger, i.e. it becomes little more difficult to pinpoint the exact value of the true parameters. Also, the TH-TO (green) and TH-WO (blue) curves are seen to be entangled, it means that it will be even more difficult to break the Octant degeneracy. Here also, we definitely need another mechanism to break the Octant degeneracy.

- **Fig 3** - The situation here is similar to fig 2 above, only the allowed region is even bigger, i.e. it is even more difficult to pinpoint the exact value of the parameters. Here, all the four degenerate solutions, i.e. TH-TO (green), TH-WO (blue), WH-TO (pink), WH-WO (cyan), are present. So, it will be most difficult here to pinpoint the true solution, as four-fold degeneracy is present.

So, we need information from another experiment, to break the Octant degeneracy present, even at \( \sin^2 2\theta_{13} = 0.03 \) and 0.01.
Figure 1: $3\sigma$ CL contours, showing allowed regions of true and degenerate solutions for $\sin^2 2\theta_{13}^{\text{true}} = 0.03$, and $\delta_{CP}^{\text{true}} = 0.85\pi$, for true NH. Blue (dark) curve is for TH-WO, and green (light) for TH-TO.

Figure 2: $3\sigma$ CL contours, showing allowed regions of true and degenerate solutions for $\sin^2 2\theta_{13}^{\text{true}} = 0.01$, and $\delta_{CP}^{\text{true}} = 0.85\pi$, for true NH. Blue (dark) curve is for TH-WO, and green (light) for TH-TO.
Figure 3: $3\sigma$ CL contours, showing allowed regions of true and degenerate solutions for $\sin^2 2\theta_{13}^{\text{true}} = 0.007$, and $\delta_{CP}^{\text{true}} = 0.85\pi$, for true NH. Blue (dark, small dots) curve is for TH-WO, green (light, small dots) for TH-TO, pink (continuous) for WH-TO, cyan (big dots) for WH-WO.

IV Conclusions

To conclude, in this work, we presented results on parameter degeneracies, of neutrino oscillation parameters, in a proposed FNAL-DUSEL (Homestake) Long Baseline Neutrino Experiment, for a 1300 km baseline, for a 300 kton water cerenkov detector. We find that, in this experiment, the mass hierarchy has been resolved at $\sin^2 2\theta_{13} = 0.01$ and $\sin^2 2\theta_{13} = 0.03$, so CL contours appear only for true hierarchy. Two contours appear, for TO and WO, but no WH contour is present. But at low values of $\sin^2 2\theta_{13} = 0.007$, four-fold degeneracy is present. In all the three figures, WO contours are present, so a mechanism is needed to resolve this octant degeneracy. As discussed in text, combination with atmospheric experiment with same detector, if such measurements could be performed in future, could help resolve octant degeneracy.

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