Mass hierarchy determination using current and upcoming neutrino experiments

Suprabh Prakash\textsuperscript{a}, Sushant Raut\textsuperscript{a} and S Uma Sankar\textsuperscript{a,b}

\textsuperscript{a} Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India
\textsuperscript{b} Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400005, India
E-mail: suprabh@iitb.ac.in

Abstract. Determination of mass hierarchy is a crucial open ended question in neutrino physics today. In the wake of recent T2K \cite{1}, MINOS \cite{2} and DChooz \cite{3} results which support a high best-fit to $\theta_{13}$, it is worthwhile to explore the potential of the upcoming and already running neutrino experiments for determining mass hierarchy. We consider the long baseline experiments NO$\nu$A and T2K and the reactor neutrino experiments Daya Bay, DChooz and RENO. In our analysis we find out that NO$\nu$A by itself is insufficient and would require another long baseline experiment such as T2K. This work assumes that by the time reactor neutrino experiments are over, we will have a precise $\theta_{13}$ information. Final results are presented as hierarchy exclusion plots in $\sin^{2} 2\theta_{13} - \delta_{CP}$ plane.

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1. Introduction

The electron appearance probability is the best bet to find out the unknowns in neutrino physics as it is sensitive to all the neutrino parameters.

\[ P(\nu_{\mu} \rightarrow \nu_{e}) = \sin^{2} 2\theta_{13} \sin^{2} \theta_{23} \frac{\sin^{2} \hat{\Delta} (1 - \hat{A})}{(1 - \hat{A})^{2}} + \alpha^{2} \sin^{2} 2\theta_{12} \cos^{2} \theta_{13} \cos^{2} \theta_{23} \frac{\sin^{2} \hat{\Delta} \hat{A}}{\hat{A}^{2}} + \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos (\hat{\Delta} + \delta_{CP}) \frac{\sin \hat{\Delta} \sin (1 - \hat{A})}{\hat{A}} \frac{1 - \hat{A}}{1 - \hat{A}} \]

where $\hat{\Delta} = \Delta_{31} L/4E$, $\hat{A} = A / \Delta_{31}$, $\alpha = \Delta_{21} / \Delta_{31}$. Here $A = 2EV_{CC}$: where $V_{CC}$ is the matter dependent potential. In this work, we address the question of finding out the sign of $\Delta_{31}$. This is termed as neutrino mass hierarchy: Normal ($\Delta_{31} > 0$) or Inverted ($\Delta_{31} < 0$).

2. Problem of degeneracy

The problem with the electron appearance channel is that it is plagued with degeneracies. That is one can have a situation where

- $P(\text{NH, } \theta_{13}^{1}) = P(\text{IH, } \theta_{13}^{2})$ for the same $\delta_{CP}$: hierarchy-$\theta_{13}$ degeneracy
- $P(\text{NH, } \delta_{CP}^{1}) = P(\text{IH, } \delta_{CP}^{2})$ for the same $\theta_{13}$: hierarchy-$\delta_{CP}$ degeneracy
3. Reactor neutrino experiments: Daya Bay, DChooz and RENO
The reactor neutrino experiments intend to measure a non-zero value of $\theta_{13}$. They will use the electron disappearance channel which is independent of CP violating phase $\delta_{CP}$. These experiments are built for very short baselines (very small matter effects) and therefore are insensitive to hierarchy-$\delta_{CP}$ degeneracy. This makes an independent $\theta_{13}$ measurement possible. The proposed reactor neutrino experiments are Daya Bay, DChooz and RENO.

4. Long baseline experiments: NO\nu A and T2K
The long baseline experiments considered are the ones which are sure to be installed as of now viz. NO\nu A and T2K. A brief description of the two experiments follow. Greater details can be found from their websites [4][5]. NO\nu A will use the NuMI beam from Fermilab which peaks around 1.6 GeV. The detector for NO\nu A is a Totally Active Scintillator Detector (TASD) of 15 kton fiducial volume, placed 810 km away from the beam source. The beam consists primarily of muon neutrinos and NO\nu A will look for electron events in the detector. The NuMI beam power has been assumed to be 0.7 MW. For T2K, a beam peaking at 0.6 GeV will come from the J-PARC accelerator at Tokai. A 22.5 kton fiducial volume Water Cerenkov detector is placed 295 km away at Kamioka. T2K will also look for electron neutrinos in a beam which was initially muon neutrinos. The beam power for T2K has been assumed to be 750 MW.

5. Simulation details
We use the software GLoBES [6][7] for our analysis. The runtime for NO\nu A is $(6\nu+3\bar{\nu})$ for all the plots shown. The runtime for T2K is $(3\nu+4\bar{\nu})$ for all the plots shown. Only electron appearance events have been considered as signal events. The backgrounds for this channel is formed by misidentified muons, NC events and intrinsic beam $\nu_e$. We have done marginalization wherever required. Priors were added for $\theta_{13}$, $\theta_{23}$ and $\Delta_{31}$ with $\sigma (\sin^2 2\theta_{13}) = 0.01$, $\sigma (\sin^2 2\theta_{23}) = 0.02$ and $\sigma (\Delta_{31}) = 0.03 \times (\Delta_{31})$. A prior of $\sigma (\sin^2 2\theta_{13}) = 0.01$ effectively takes into account the data due to reactor neutrinos experiments. We have taken care in defining $\Delta_{atmos}^{NH}$ and $\Delta_{atmos}^{IH}$ in terms of the measured quantity $\Delta_{atmos}$:[8]

$$\Delta_{31} = \Delta_{atmos} + \left( \cos^2 \theta_{12} - \cos \delta \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23} \right) \Delta_{21}$$

where $\Delta_{atmos} = \pm 2.4 \times 10^{-3} \text{eV}^2$ : + for NH, - for IH. We have assumed a 5% systematics uncertainty on both signal and background.
6. Hierarchy exclusion plots
The following plots show the hierarchy excluding capabilities.

![Hierarchy exclusion plots](image1)

**Figure 2.** Hierarchy exclusion plots (without systematics) for NOνA only.

![Hierarchy exclusion plots](image2)

**Figure 3.** Hierarchy exclusion plots (with systematics) for the combined setup of NOνA and T2K.

The plots show different confidence level regions and for all \((\delta_{CP} - \sin^2 2\theta_{13})\) points on the right of a line, the wrong hierarchy can be excluded from the right hierarchy with that confidence level. It can be seen from this plot that NOνA performs very well only for a particular range of true \(\delta_{CP}\) depending on the true mass hierarchy. For NH, this range is \(-120^\circ\) to \(-60^\circ\) and for IH, this range is \(60^\circ\) to \(120^\circ\). In \(\delta_{CP}\) ranges other than these, NOνA does not perform well because of the hierarchy-\(\delta_{CP}\) degeneracy. Similar studies were also done in [9].

7. How and why does T2K data help?
It can be seen from figure 3 that at 90% C.L., T2K data boosts significantly NOνA’s ability for determining mass hierarchy for NH as the true hierarchy in the upper half plane (UHP) of \([0,180^\circ]\) and for IH in the lower half plane (LHP) of \([-180^\circ,0]\). This can be understood by analysing the error plots (figures 4 and 5) due to individual runs of NOνA and T2K with NH as the true hierarchy and IH as the test hierarchy for the following true points: \(\sin^2 2\theta_{13} = 0.05\), \(\delta_{CP} = -90^\circ\) and \(\sin^2 2\theta_{13} = 0.15\), \(\delta_{CP} = 90^\circ\). For NH as the true hierarchy, the favorable plane for NOνA is LHP.

![Error plots: NOνA.](image3)

**Figure 4.** Error plots: NOνA.

![Error plots: NOνA and T2K; individually.](image4)

**Figure 5.** Error plots: NOνA and T2K; individually.

In LHP, NOνA by itself performs very well and T2K data does not have significant effects.
This is evident from the error plots. For the true point \( \sin^2 2\theta_{13} = 0.05, \delta_{CP} = -90^\circ \) (\( \delta_{CP} \) in the LHP), there is no error in the NO\( \nu \)A measurements (no contours at 90% and 95% C.L.). However when the true point is \( \sin^2 2\theta_{13} = 0.15, \delta_{CP} = 90^\circ \) (\( \delta_{CP} \) in the UHP), NO\( \nu \)A gives totally wrong results. True point lies out of 90% and 95% C.L. contours. A wrong hierarchy and wrong \( \delta_{CP} \)-plane fakes the true point. This is hierarchy-\( \delta_{CP} \) degeneracy. However the error plots for T2K correctly predicts the true point. This is because it experiences less hierarchy-\( \delta_{CP} \) degeneracy as it is a shorter baseline and appreciable matter effects do not develop. Thus T2K data provide the additional \( \Delta \chi^2 \) at the wrong hierarchy-wrong \( \delta_{CP} \) point thereby increasing the sensitivity to hierarchy exclusion. This point can be elaborated more by figures 6 and 7 (for an updated analysis, see [10]).

**Figure 6.** \( \Delta \chi^2 \) vs. \( \delta_{CP} \) for \( \sin^2 2\theta_{13} = 0.05, \delta_{CP} = -90^\circ \): Moving along \( \sin^2 2\theta_{13} = 0.05 \) in the error plot plane.

**Figure 7.** \( \Delta \chi^2 \) vs. \( \delta_{CP} \) for \( \sin^2 2\theta_{13} = 0.15, \delta_{CP} = 90^\circ \): Moving along \( \sin^2 2\theta_{13} = 0.15 \) in the error plot plane.

### 8. Results

The exclusion plots show that the combined setup of the LBL experiments - NO\( \nu \)A and T2K and the reactor neutrino experiments will be able to exclude the wrong hierarchy from the right one @ 90% C.L. for all \( \delta_{CP} \) provided \( \sin^2 2\theta_{13} > 0.115 \). This is the best that we can achieve with the present statistics.

### References

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