Can we measure $\theta_{23}$ octant in 3+1 scheme?

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Abstract. Current 3$\nu$ global fits predict two degenerate solutions for $\theta_{23}$: one lies in lower octant ($\theta_{23} < \pi/4$), and the other belongs to higher octant ($\theta_{23} > \pi/4$). Here, we study how the measurement of $\theta_{23}$ octant would be affected in the upcoming Deep Underground Neutrino Experiment (DUNE) if there exist a light eV-scale sterile neutrino. We show that in 3+1 scheme, a new interference term in $\nu_{\mu} \rightarrow \nu_e$ oscillation probability can spoil the chances of measuring $\theta_{23}$ octant completely.

Keywords: Octant of $\theta_{23}$, sterile neutrino, Long-Baseline experiments

Introduction: The resolution of octant of $\theta_{23}$ is one of the fundamental problems in neutrino oscillation. Long-baseline (LBL) experiments can resolve this octant ambiguity of $\theta_{23}$ with the help of $\nu_{\mu} \rightarrow \nu_e$ appearance channel, and the vital information coming from $\nu_{\mu} \rightarrow \nu_{\mu}$ disappearance channel also play an important role. Interestingly, at present, there are short-baseline anomalies which hint towards the existence of light eV-scale sterile neutrino. Here, we expound in detail the capability of proposed LBL experiment DUNE to measure $\theta_{23}$ octant considering one light eV-scale sterile neutrino along with three active neutrinos.

Theoretical framework: In the 3+1 scheme, a new a mass eigenstate $\nu_4$ appears on top of 3$\nu$ framework whose mixing is parametrized as

$$U = R_{34} R_{24} R_{14} R_{23} R_{12},$$  \hspace{1cm} (1)

where $R_{ij}$ ($\tilde{R}_{ij}$) is a real (complex) rotation in the $(i,j)$ plane. The details of the parametrization of $U$ can be seen in [4].

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$^†$According to the present 3$\nu$ best-fit [5], $\theta_{23}$ can have two solutions: one < $\pi/4$, labelled as lower octant (LO), and other > $\pi/4$, known as higher octant (HO).
In [4], it was shown that the 4-flavor appearance probability can be approximately expressed as the sum of three terms
\[ P_{4\nu}^{\mu e} \simeq P_0 + P_1 + P_2, \]
which in vacuum appears as
\[ P_0 \simeq 4 s_{23}^2 s_{13}^2 \sin^2 \Delta, \]
\[ P_1 \simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} (\alpha \Delta) \sin \Delta \cos(\Delta \pm \delta_{13}), \]
\[ P_2 \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin \Delta \sin(\Delta \pm \delta_{13} \mp \delta_{14}). \]
where \( \Delta \equiv \Delta m_{31}^2 L/4E \) and \( \alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2 \). In the double sign, the upper (lower) sign corresponds to neutrinos (antineutrinos). The new interference term \( P_2 \) is governed by the interference between the atmospheric frequency and the large frequency related to the new mass eigenstate [4] which gets averaged out by the finite energy resolution of the detector. Recent global fits [5,6,7] suggests \( s_{13} \sim s_{14} \sim s_{24} \sim 0.15 (\sim \epsilon) \) and \( \alpha = 0.03 (\sim \epsilon^2) \) implying \( P_0 \sim \epsilon^2, P_1 \sim \epsilon^3, P_2 \sim \epsilon^3 \). An experiment can measure the octant of \( \theta_{23} \) even in the presence of unknown CP-phases, if there is a difference between the probabilities corresponding to the different octants, i.e.
\[ \Delta P \equiv P_{\mu e}^{\text{HO}}(\delta_{13}^{\text{HO}}, \delta_{14}^{\text{HO}}) - P_{\mu e}^{\text{LO}}(\delta_{13}^{\text{LO}}, \delta_{14}^{\text{LO}}) \neq 0, \]
where one of the two octants should be considered to generate data and the other octant should be used to simulate the theoretical model. From the expression of \( P_{4\nu}^{\mu e} \), \( \Delta P \) can be written as,
\[ \Delta P = \Delta P_0 + \Delta P_1 + \Delta P_2. \]
\( \Delta P_0 \) is positive-definite. \( \Delta P_1 \) and \( \Delta P_2 \) depends on the CP-phases and can be both positive or negative. These terms can be expressed as
\[ \Delta P_0 \simeq 8 \eta s_{13}^2 \sin^2 \Delta, \]
\[ \Delta P_1 = 4 s_{13} s_{12} c_{12} (\alpha \Delta) \sin \Delta \left[ \cos(\Delta \pm \phi^{\text{HO}}) - \cos(\Delta \pm \phi^{\text{LO}}) \right], \]
\[ \Delta P_2 = 2 \sqrt{2} s_{14} s_{24} s_{13} s_{23} \sin \Delta \left[ \sin(\Delta \pm \psi^{\text{HO}}) - \sin(\Delta \pm \psi^{\text{LO}}) \right]. \]
In above, \( \phi = \delta_{13} \) and \( \psi = \delta_{13} - \delta_{14} \) with the appropriate superscripts LO or HO. The term \( \eta \) is a positive definite angle and dictates the deviation from maximal mixing as \( \theta_{23} = \frac{\pi}{4} \pm \eta \), where +(-) corresponds to HO (LO). If we need to measure the octant of \( \theta_{23} \), the contribution coming from \( \Delta P_0 \) must not get cancelled completely in cases where the sum of \( \Delta P_1 \) and \( \Delta P_2 \) gives a negative contribution.

**Results and discussion:** Simulations for DUNE have been performed considering a total 248 kt.MW.yr of exposure, divided equally between \( \nu \) and \( \bar{\nu} \) mode. In fig[1] we show the bi-event plot. The ellipses (colored blobs) correspond to the 3\( \nu \) (3+1 scheme) where, \( \sin^2 \theta_{23} = 0.42 \) (0.58) has been assumed as a benchmark value for the LO (HO). Since mass hierarchy can be measured relatively easily in DUNE, we can only concentrate on one of the two hierarchies,

\[\text{In fig[1] we notice an small overlap between normal hierarchy (NH) and inverted hierarchy (IH) blobs which can be eliminated using the spectral information available in DUNE (see [8]).}\]
Fig. 1: Bi-event plot for DUNE. The ellipses (colored blobs) correspond to the $3\nu$ ($3+1$ scheme). $\sin^2 \theta_{23} = 0.42 (0.58)$ is taken as benchmark value for LO (HO). In cases of ellipses (colored blobs), the running parameter(s) is $\delta_{13}$ ($\delta_{13} & \delta_{14}$). In the $3+1$ case, $\theta_{34} = 0^0$ has been assumed. This figure has been taken from [10].

say normal hierarchy. While going from $3\nu$ to $3+1$ scheme, the ellipses becomes blobs because of the convolution of different combinations of $\delta_{13} & \delta_{14}$ (see [8,9]). In this figure, we see a substantial overlap between LO and HO blobs due to the presence of the term $\Delta P_2$, which depends on the new CP-phase $\delta_{14}$. For detailed discussion, see [10].

Fig 2 depicts the discovery reach of $\theta_{23}$ octant in $[\sin^2 \theta_{23}, \delta_{13}]$ (true) plane assuming NH as true choice. Left (right) panel shows the results for $3\nu$ ($3+1$) scheme. In $3\nu$ case, a minimum $2\sigma$ sensitivity can be achieved if $\sin^2 \theta_{23}$ (true) $<$ 0.47 and $\sin^2 \theta_{23}$ (true) $\gtrsim$ 0.55 irrespective of the choice of $\delta_{13}$ (true). But, in $3+1$ case we hardly have any octant sensitivity in the entire $[\sin^2 \theta_{23}, \delta_{13}]$ (true) plane.

**Conclusions:** In this work, we have studied the impact of a light eV-scale sterile neutrino in measuring the octant of $\theta_{23}$ at DUNE. The sensitivity towards $\theta_{23}$ octant can be completely lost if there is active-sterile oscillations.

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Fig. 2: Discovery potential for excluding the wrong octant in $[\sin^2 \theta_{23}, \delta_{13}]$ (true) plane assuming NH as true choice. The left (right) panel corresponds to the 3$\nu$ (3+1) case. In 3-flavor scenario, we marginalize over $(\theta_{23}, \delta_{13})$ (test). In 3+1 case, in addition, we marginalize over $\delta_{14}$ (true) and $\delta_{14}$ (test) fixing $\theta_{14} = \theta_{24} = 90$ and $\theta_{34} = 0$. This figure has been taken from [10].

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