Optimizing the $\theta_{23}$ octant search in long baseline neutrino experiments

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Abstract. Determination of the $\theta_{23}$ octant will be an important goal for the next generation of neutrino oscillation experiments, as it will show whether the true value of $\theta_{23}$ lies in the high octant, $\theta_{23} > 45^\circ$, or in the low octant, $\theta_{23} < 45^\circ$. In this work we investigate the prospects of studying the $\theta_{23}$ octant in future long baseline neutrino experiments. Using the GLoBES software, we study the sensitivity to $\theta_{23}$ octant in terms of baseline length and beam sharing and use the LBNO setup as our benchmark. We also show the interference on the octant determination that arises from the unconstrained CP violation angle $\delta_{CP}$. In our results, we show the impact of matter effects on the octant determination potential and establish a connection between the beam sharing and mass hierarchy.

1. Introduction

The history of science has seen a huge success unfold in the past few decades of neutrino physics. The 2015 Nobel Prize for physics was awarded for the discovery of neutrino oscillations, a phenomenon which proves that neutrinos have nonzero masses. A number of experiments set to study atmospheric, solar, accelerator, reactor and supernova neutrinos have allowed to determine the parameters related to neutrino masses and the mixing of neutrino flavors to a high precision (see Ref. [1] for a recent review). Yet the neutrino oscillation mechanism is all but solved. Among the unanswered questions are at present the exact ordering or neutrino masses and whether or not neutrinos violate the charge-parity (CP) symmetry. Future long baseline neutrino oscillation experiments such as DUNE and T2HK [2] will have an important role at finding answers to these questions and many others.

In this paper we address another unknown that is yet to be determined, the so called octant problem of the mixing angle $\theta_{23}$ [3]. It is known from experiments that the value of $\theta_{23}$ is close to $45^\circ$. However, it is not known whether it lies in the higher octant ($\theta_{23} > 45^\circ$) or in the lower octant ($\theta_{23} < 45^\circ$), as the present experiments are not sensitive enough to establish the correct octant. We follow our previous work [4] and derive the numerical limits where a potential next generation neutrino oscillation experiment with a wide-band beam and very long baseline could resolve the octant ambiguity at $5\sigma$ confidence level.
2. The problem of $\theta_{23}$ octancy

The atmospheric mixing angle $\theta_{23}$ has been historically determined from atmospheric neutrino oscillations and accelerator-based neutrino oscillations where $\nu_\mu$ and $\bar{\nu}_\mu$ particles oscillate into $\nu_e$ and $\bar{\nu}_e$, respectively. In disappearance experiments one studies the matter influenced survival probability $P^m_{\mu\mu}$, which is given by

\[
P^m_{\mu\mu} = 1 - \cos^2 \theta_{13}^m \sin^2 2\theta_{23} \sin^2 \left(1.27 \frac{L}{E} \left(\frac{\Delta m_{31}^2 + A + (\Delta m_{31}^2)_m}{2}\right)\right) - \sin^2 \theta_{13}^m \sin^2 2\theta_{23} \sin^2 \left(1.27 \frac{L}{E} \left(\frac{\Delta m_{31}^2 + A - (\Delta m_{31}^2)_m}{2}\right)\right) - \sin^4 \theta_{23} \sin^2 \theta_{13}^m \sin^2 \left(1.27 \frac{L}{E} (\Delta m_{31}^2)_m\right),
\]

(1)

where $L$ stands for baseline length, $A = 2\, E\, V$ is a product of neutrino energy $E$ and matter potential $V = 2\, G_F\, n_e$, and $G_F$ and $n_e$ are the Fermi coupling constant and the electron number density, respectively. We follow the one-mass scale dominant approximation [5], which is applicable to multi-GeV neutrino energies. Eq. (1) presents the survival probability of muon neutrinos up to the fourth order when the probability is expanded in powers of $\Delta m_{21}^2 / \Delta m_{31}^2 \sim 0.03$. The corresponding probability for antineutrinos is obtained through the transformation $V \rightarrow -V$.

The expression in Eq. (1) is given in terms of the matter enhanced versions of the parameters $\theta_{13}$ and $\Delta m_{21}^2$, which are defined as:

\[
(\Delta m_{31}^2)_m = \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - A)^2 + (\Delta m_{31}^2 (\sin 2\theta_{13}))^2} \\
\sin 2\theta_{13}^m = \frac{\Delta m_{31}^2}{(\Delta m_{31}^2)_m} \sin 2\theta_{13}.
\]

(2)

In the leading order, the expression in Eq. (1) is octant-degenerate, that is, two possible values of $\theta_{23}$ give the same probability:

\[
P^m_{\mu\mu}(\theta_{23}) = P^m_{\mu\mu}(\pi/2 - \theta_{23}).
\]

(3)

The octant degeneracy illustrated in Eq. (3) is the reason why the current bounds for $\theta_{23}$ are relatively loose; one cannot tell the difference between the lower octant, where $\theta_{23} < 45^\circ$, and the higher octant, where $\theta_{23} > 45^\circ$.

The expression derived for the survival probability, given in Eq. (1) and Eq. (2), does have a subleading term that is octant sensitive, however. This term is also subject to matter resonant effects, and therefore could also contribute to the determination of the $\theta_{23}$ octant.

3. Results

In this section we show the possible values of $\theta_{23}$ for which the lower octant could be ruled out at a 5 $\sigma$ confidence level or better in the benchmark setup which we define in Ref. [4]. We refrain to study the values in the higher octant, but it should be pointed out that the discovery limits in the lower octant are symmetric to the shapes we show for the higher octant. The full description of the simulation is given in Ref. [6].

The discovery limits for octant determination are shown for different baseline lengths and beam sharing options in Fig. 1 and Fig. 2, respectively. The neutrino beam is taken to be optimized to the first oscillation maximum at all times and the $\nu_\mu / (\nu_\mu + \bar{\nu}_\mu)$ ratio is defined as the fraction at which the benchmark experiment runs in neutrino mode.
Figure 1. The 5σ discovery reach of $\theta_{23}$ octant as a function of baseline length, as given in Ref. [6]. The discovery limits are shown for four different integrated luminosity values. The interference from $\delta_{\text{CP}}$ is shown for its all possible values, and the discovery limits are shown for both normal hierarchy (NH) and inverted hierarchy (IH).

Figure 2. The 5σ discovery reach of $\theta_{23}$ octant as a function of the beam sharing ratio, as given in Ref. [6]. The $\nu_\mu/\nu_\mu + \bar{\nu}_\mu$ ratio gives the fraction at which the benchmark setup runs in neutrino mode. The discovery limits are shown for four different integrated luminosity values, both normal hierarchy (NH) and inverted hierarchy (IH), and all possible $\delta_{\text{CP}}$ values.

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