PROCEEDINGS OF SCIENCE

Optimizing the θ_{23} octant search in long baseline neutrino experiments

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We investigate the potential of future long baseline neutrino experiments at the task of resolving the θ_{23} octancy, that is, whether the atmospheric mixing angle lies in the high octant, where $\theta_{23} > 45^\circ$, or the low octant, where $\theta_{23} < 45^\circ$. We demonstrate the importance of the matter effects in the determination of the θ_{23} octant, and show with the GLoBES software how operating in neutrino and antineutrino modes contribute to the octant determination.

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1. Introduction

Long baseline neutrino experiments are accelerator-driven facilities where neutrino oscillations are studied by sending intense muon neutrino and antineutrino beams to travel thousands of kilometers underground. These experiments make use of the matter effects to maximize the muon neutrino oscillation to the electron neutrino state. The next generation of such experiments will address the long-standing questions of the neutrino mass ordering and the potential violation of the CP symmetry, but there are also other unknowns that have yet to be determined.

In this work we will address the question of θ_{23} octant, which was first introduced in Ref. [1]. It is known from experiments that the value of θ_{23} is close to 45°, but it is not known whether it lies in the high octant, where $\theta_{23} > 45^\circ$, or in the low one, where $\theta_{23} < 45^\circ$, as the present experiments are not sensitive enough to trace the difference on a reliable level. Though the emphasis of future experiments will be on the mass hierarchy and CP violation questions, resolving the octant ambiguity remains a well motivated issue to be investigated in the process. In this work we study the prospects of octant determination in future long baseline neutrino experiments and demonstrate how running in neutrino and antineutrino modes contribute to the determination of the θ_{23} octant.

2. Octant determination long baseline experiments

In long baseline neutrino experiments intense muon neutrino and antineutrino beams are sent to travel long distances through matter. As the neutrinos propagate in the matter medium, they experience coherent charged current forward scattering with the electrons and nucleons in the Earth, which gives rise to the so called Mikheyev-Smirnov-Wolfenstein (MSW) effect. The MSW effect influences the survival probability as follows:

$$\begin{aligned} P^m_{\mu\mu} \approx 1 &- \cos^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2\left(1.27\,\frac{L}{E}\left(\frac{\Delta m^2_{31}+A+(\Delta m^2_{31})_m}{2}\right)\right) \\ &- \sin^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2\left(1.27\,\frac{L}{E}\left(\frac{\Delta m^2_{31}+A-(\Delta m^2_{31})_m}{2}\right)\right) \\ &- \sin^4\theta_{23}\sin^2 2\theta^m_{13}\sin^2\left(1.27\,\frac{L}{E}(\Delta m^2_{31})_m\right), \end{aligned} \tag{2.1}$$

where L and E stand for the experiment's baseline length and neutrino energy, A is the charged current matter potential, θ_{23} is the atmospheric mixing angle, and θ^m_{13} and $(\Delta m^2_{31})_m$ are matter-enhanced versions of the standard oscillation parameters θ_{13} and Δm^2_{31}. In the vicinity of the MSW resonance, the subleading octant-sensitive term $\sin^4\theta_{23}\sin^2 2\theta^m_{13}\sin^2[1.27\,(L/E)\,(\Delta m^2_{31})_m]$ dominates over the previous two terms and makes $P^m_{\mu\mu}$ sensitive to the θ_{23} octant. See Ref. [2] for more details.

In the leading order the survival probability shown in Eq. (2.1) is degenerate with respect to the so called maximal mixing, which corresponds to $\theta_{23} = 45^\circ$. In this order the same probability is obtained with two different θ_{23} values, that is,

$$P^m_{\mu\mu}(90^\circ - \theta_{23}) \approx P^m_{\mu\mu}(\theta_{23}). \tag{2.2}$$

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The ambiguity in Eq. (2.2) is commonly known as the octant degeneracy problem. In accelerator-based experiments where the baseline is very long, a solution to this discrepancy could be sought in the octant-sensitive fourth term in Eq. (2.1) which is subject to the MSW resonance.

The MSW resonance arises from the matter potential $A = \pm 2\sqrt{2}G_F N_e$, which depends on the Fermi coupling constant G_F and the electron number density N_e of the medium through which the neutrinos and antineutrinos traverse. Since A is positive for neutrinos and negative for antineutrinos, the MSW resonance occurs only for neutrinos when the neutrino masses follow the normal hierarchy (NH), and for antineutrinos when it follows the inverted hierarchy (IH). This means that neutrino and antineutrino runs have different impact onto octant determination in long baseline experiments.

3. Numerical simulations

In the following we show the sensitivity to the θ_{23} octant at future experiments. We used the General Long Baseline Experiment Simulator (GLoBES) and simulated a hypothetical future long baseline neutrino oscillation experiment that utilizes the liquid argon time projection chamber technology and a very long baseline. For this purpose we define the beam sharing ratio $\nu_\mu/(\nu_\mu + \bar{\nu}_\mu)$ as the fraction at which the simulated experiment runs in neutrino mode, whilst the rest of the total running time is dedicated to antineutrino mode. This means that at $\nu_\mu/(\nu_\mu + \bar{\nu}_\mu) = 0$ the experiment runs entirely in antineutrino mode, whereas $\nu_\mu/(\nu_\mu + \bar{\nu}_\mu) = 1$ indicates that only neutrino mode is used.

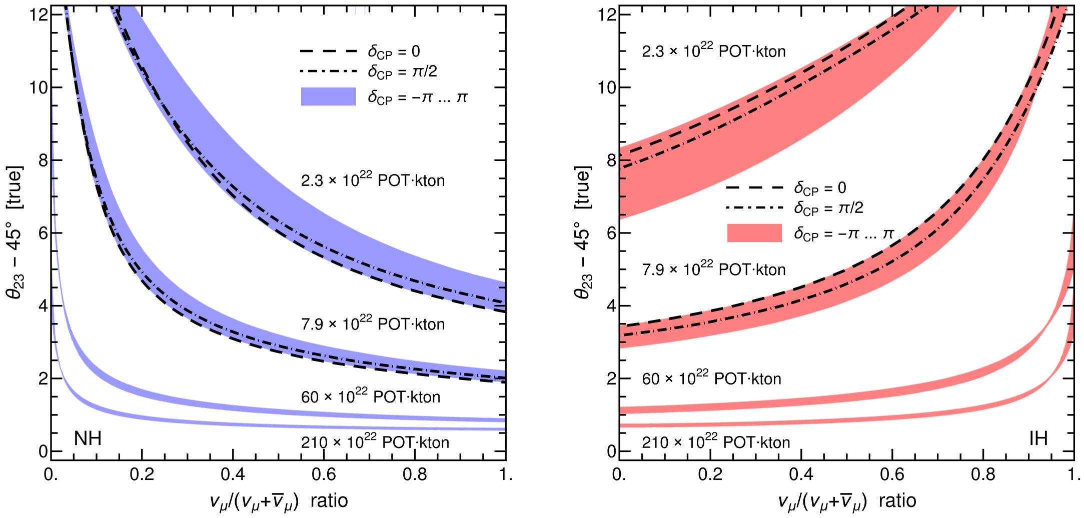

Figure 1: The 5σ discovery reach of θ_{23} octant as a function of the beam sharing ratio (see Ref. [2] for more details). The discovery limits are shown for four different integrated luminosity values, using the LBNO setup as benchmark. The interference from δ_{CP} is shown for its all possible values, and the discovery limits are shown for both normal hierarchy (NH) and inverted hierarchy (IH).

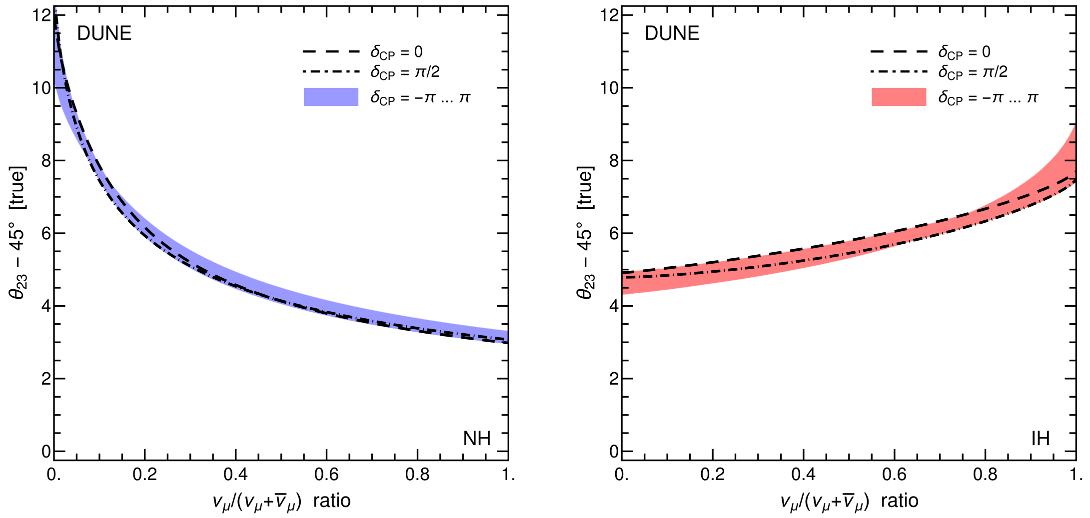

Figure 2: The 5σ discovery reach of θ_{23} octant as a function of the beam sharing ratio. The sensitivities are displayed for the Deep Undeground Neutrino Experiment (DUNE) and are shown for both normal hierarchy (NH) and inverted hierarchy (IH). The $\nu_\mu/(\nu_\mu+\bar{\nu}_\mu)$ ratio gives the fraction at which the benchmark setup runs in neutrino mode, whereas the rest of the run is dedicated to antineutrinos. The width of the curves comes from the interference from δ_{CP}.

In Fig. 1, we show the values of θ_{23} for which the octant could be discriminated at a 5σ confidence level or better. We took the LBNO setup [3] as our benchmark and varied the beam sharing ratio whilst keeping the total running time normalized to 10 years. For comparison, the sensitivity curves are provided for four different integrated luminosity values. The sensitivities are only shown for θ_{23} values in the high octant, as the curves in the low octant were found to be symmetrical in shape.

We also computed the sensitivities for the DUNE setup [4], for which the results are presented in Fig. 2. The results are again symmetrical in the low octant, and hence it is not shown.

Altogether, we find that future long baseline neutrino oscillation experiments such as DUNE offer a strong improvement in the still large octant ambiguity, and emphasize the role of $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ oscillations in the process of octant determination.

References

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