PROCEEDINGS OF SCIENCE

What antineutrinos can tell about octant and δ_{CP} in DUNE?

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We study the efficiency of DUNE, a next generation long baseline oscillation experiment to resolve two major unknowns in neutrino oscillation physics. These are, octant of θ_{23} (i.e. if θ_{23} is $< 45^\circ$ or $> 45^\circ$) and Dirac CP phase δ_{CP}. We mainly focus on the role of antineutrinos when they travel 1300 km baseline of DUNE. We observe that for DUNE, the antineutrino runs help to remove parameter degeneracies even in the parameter space where the antineutrino probability suffers from various degeneracies. We study these points in detail and find that, due to enhanced matter effect longer baseline experiments create an increased tension between the neutrino and the antineutrino probabilities which helps to increase total sensitivity in case of combined runs. We also find that, antineutrino run increases overall CP sensitivity due to its ability to abolish octant-δ_{CP} degeneracy.

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1. Introduction

The standard three flavor neutrino oscillation scenario consists of two mass squared differences ($\Delta m^2_{i1}, i = 2,3$) , three mixing angles ($\theta_{ij}, j > i = 1,2,3$) and the Dirac CP phase δ_{CP}. Various neutrino oscillation experiments have measured or given a hints about these parameters. The CP phase δ_{CP} remains one of the least known parameters among all these. Other than this, what we do not know in neutrino oscillation physics are (i) the sign of $|\Delta m^2_{31}|(\Delta m^2_{31} > 0$ is known as the normal hierarchy (NH) or $\Delta m^2_{31} < 0$ is known as the inverted hierarchy (IH)), (ii) the octant of θ_{23}($\theta_{23} < 45^\circ$ is known as the lower octant (LO) or $\theta_{23} > 45^\circ$ is known as the higher octant (HO)). The current best fit values and their 3σ ranges are given in [1, 2] by performing global analysis of neutrino oscillation data. Ongoing long baseline oscillation experiments like, T2K [3] and NOνA [4] can give information on these unknown parameters. The main difficulties which these experiments have to overcome are the problem of parameter degeneracies i.e. different parameter sets giving equally good fit to the experimental data.

In this work, we focus on the determination of octant degeneracy and the Dirac CP phase δ_{CP}. The primary channel to determine octant of θ_{23} is the disappearance channel $P_{\mu\mu}$, but for shorter baseline experiments, it suffers from intrinsic octant degeneracy i.e. for θ_{23} and $90^\circ - \theta_{23}$ one gets the same probability value. Whereas appearance channel $P_{\mu e}$ does not suffer from intrinsic degeneracy because of the $\sin^2\theta_{23}\sin^2 2\theta_{13}$ dependency, but suffer from generalized degeneracies as pointed out in [5, 6, 7, 8, 9]. Therefore, we focus on the combined run of both the channels which can be helpful to determine octant of θ_{23} because of their different functional dependency on θ_{23}. We also explore the non-trivial contribution of antineutrino run in enhancing CP sensitivity by considering hierarchy and octant as known, as well as unknown. In our analysis, we consider 10 kt liquid argon detector and 1.2 MW beam for DUNE [10] and the remaining details that we have considered in this work are given in [11] and the references there in.

2. Results

In this section, we present the octant sensitivity and CP violation (CPV) discovery potential of DUNE. We have four possible combinations of (hierarchy$-$octant) depending on true hierarchy and true octant, namely: NH-LO, NH-HO, IH-LO and IH-HO. Here, we only discuss the cases NH-LO and NH-HO. The detailed descriptions of all the four cases are described in [11].

In figure [1], we present the octant sensitivity of DUNE. In both the columns, dark-blue (magenta) curves represents True:NH - Test:NH (True:NH - Test:IH). The horizontal yellow line represents the octant sensitivity at 3σ C.L. True values of θ_{23} for the two columns are considered as, 39° (left) and 51° (right) respectively. From the left column, we can see that DUNE can reach 3σ octant sensitivity with pure neutrino run i.e. [10+0] year for known hierarchy (see solid blue curve). However, for unknown hierarchy we see that only neutrino run is not able to resolve the octant degeneracy even at 3σ due to the wrong hierarchy(WH)-wrong octant(WO) solutions appearing in the region $9^\circ < \delta_{CP} < 90^\circ$(see solid magenta curve). We find that once antineutrino run is added with neutrino, considering the case with (7+3) years of $(\nu + \overline{\nu})$ run, octant degeneracy can be resolved with more than 4σ C.L. without any information of the true hierarchy for any value of δ_{CP}. The right column describes the case for true (NH-HO). We see that there is 3σ octant sensitivity in

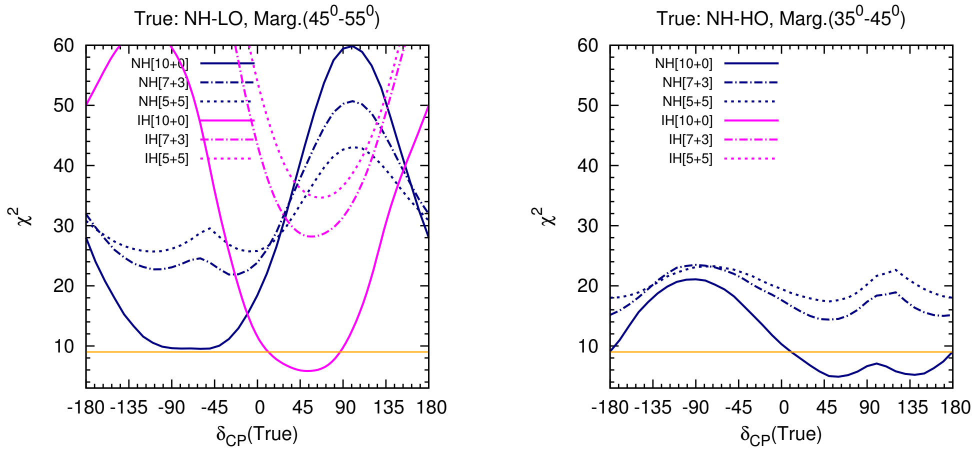

Figure 1: Octant discovery χ^2 for DUNE, considering true hierarchy as NH. Here, left (right) column is for true $\theta_{23} = 39^\circ(51^\circ)$ and test(θ_{23}) is marginalized over opposite octant.

the lower half plane (LHP) i.e. $-180^\circ < \delta_{CP} < 0^\circ$ even with only neutrino run whereas upper half plane (UHP) i.e. $0^\circ < \delta_{CP} < 180^\circ$ suffers from octant degeneracy in neutrino mode. But with the (5+5) years of $(\nu + \overline{\nu})$ run more than 4σ octant sensitivity can be attained[1].

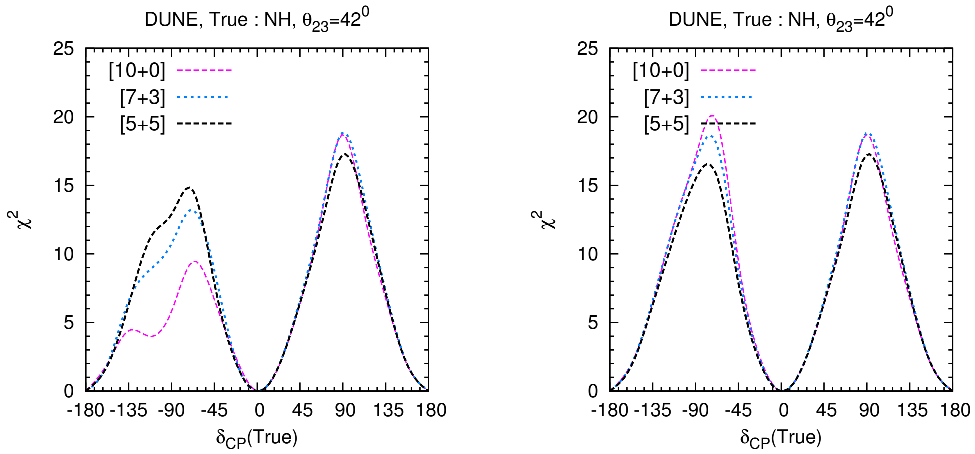

Figure 2: Both the columns represent CPV χ^2 for unknown(known) hierarchy and octant respectively.

In left (right) column of figure [2], we present the CP discovery χ^2 as a function of true δ_{CP} for unknown(known) hierarchy and octant. The CPV discovery potential of an experiment is defined as to distinguish between CP ($\delta_{CP} \neq 0^\circ, 180^\circ$) violating values from CP conserving values. This figures show the role of antineutrinos in discovering CP phase and the dependency with the octant of θ_{23}. Comparing left column with right column we see that the CP sensitivity for -90°-LO improves for known hierarchy and octant, infact 10+0 case provides the best sensitivity. We observe that this enhancement for known hierarchy and octant is also true for IH. This indeed proves the fact that, antineutrino run is an instrumental for the removal of the wrong octant solutions.

[1]Note that in the rhs of fig.(1) does not have any magenta curve because of the absence of WH-WO solution for NH-HO.

In figure [3], we plot the CPV discovery potential at 3σ C.L. in (percentage of $\overline{\nu}$ run - percentage of δ_{CP}) plane. We consider all the four combinations of hierarchy-octant. We observe from both the columns that a lesser CP fraction is achieved with the dominant neutrino or antineutrino run. Comparing both the plots, we find that maximum CPV fraction can be attained for IH-HO and minimum for NH-HO. Also, 40% antineutrino run seems to be optimum to achieve maximum CPV fraction in all the cases.

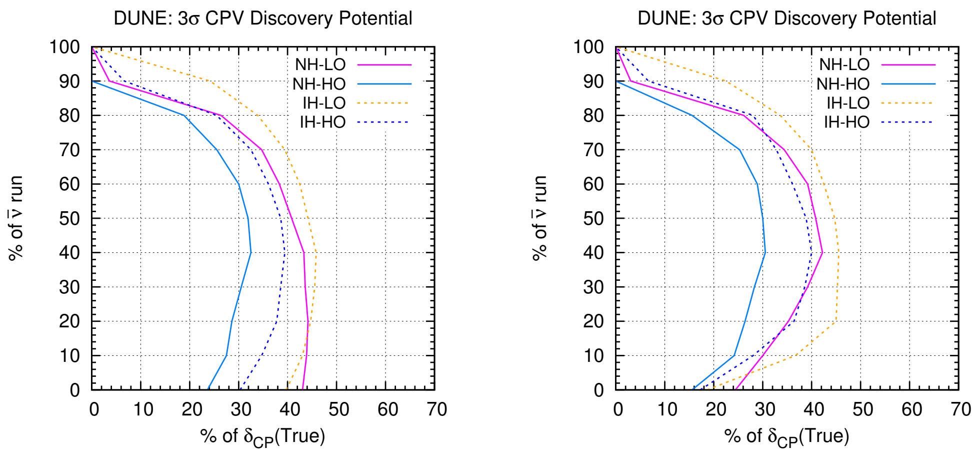

Figure 3: CPV discovery plot in (% of $\delta_{CP}(True)$, % of antineutrino run) plane at 3σ C.L. First (second) column are for known (unknown) hierarchy and octant.

In conclusion, we have examined the significant role of antineutrinos in providing an enhanced octant and CP sensitivity in the next generation superbeam experiment like DUNE. In our study, we observe that combined $(\nu + \overline{\nu})$ run gives better sensitivity. In the case of CPV discovery, antineutrino run plays a leading role due to the synergistic behaviours between neutrinos and antineutrinos even under the assumption of known octant.

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