PROCEEDINGS OF SCIENCE

Parameter degeneracy and hierarchy sensitivity of NOνA in presence of sterile neutrino

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The first hint of neutrino mass hierarchy is expected to come from the NOνA experiment in Fermilab as the present best-fit parameter space i.e., normal hierarchy and $\delta_{CP} = -90^\circ$ is the favourable parameter space for NOνA where there is no degeneracy. But this situation may change if the standard three flavour framework is not complete and there is existence of new physics. In this work we consider the presence of an extra light sterile neutrino at the eV scale and study the new degeneracies which are absent in the standard three flavour framework. We also study the effect of these new degeneracies on the hierarchy measurement of NOνA.

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1. Introduction

In the standard three flavour framework, neutrino oscillation in which neutrinos change their flavour is described by six parameters: three mixing angles: θ_{12}, θ_{13}, θ_{23}, two mass squared differences: Δ_{21} ($m_2^2 - m_1^2$), and Δ_{31} ($m_3^2 - m_1^2$) and one phase δ_{13}. Among them one of the major unknown is the sign of Δ_{31} or the neutrino mass hierarchy. It can be either normal i.e., $\Delta_{31} > 0$ (NH) or inverted i.e., $\Delta_{31} < 0$ (IH). It is well known that for the favourable parameter space where there is no degeneracy, then NOνA [1] can determine neutrino mass hierarchy at more that 2σ C.L. The global analysis of the world neutrino data suggests that the best fit parameter space i.e., NH with $\delta_{13} = -90^\circ$ [2, 3, 4] is indeed the favourable parameter space for NOνA and thus it is expected that the first hint of neutrino mass hierarchy will come from the NOνA experiment. But the situation can be different if there exists new physics. In presence of new physics there can be additional degeneracies which can spoil the hierarchy sensitivity of NOνA even for the favourable parameter space. In this work we consider the existence of an extra light sterile neutrino at the eV scale [5] i.e. the 3+1 scenario. In this present work our aim is to identify the new degeneracies and study their effect in the determination of hierarchy in NOνA.

2. Oscillation parameters in 3+1 scheme

In presence of one extra light sterile neutrino, we parametrize the PMNS matrix as

4ν Parameters	True Value	Test Value Range
$\sin^2\theta_{12}$	0.304	N/A
$\sin^2 2\theta_{13}$	0.085	N/A
$\theta_{23}^{\rm LO}$	40°	$(40^\circ, 50^\circ)$
$\theta_{23}^{\rm HO}$	50°	$(40^\circ, 50^\circ)$
$\sin^2\theta_{14}$	0.025	N/A
$\sin^2\theta_{24}$	0.025	N/A
θ_{34}	0°	N/A
δ_{13}	-90°	$(-180^\circ, 180^\circ)$
δ_{14}	$-90^\circ, 0^\circ, 90^\circ$	$(-180^\circ, 180^\circ)$
δ_{34}	0°	N/A
Δ_{21}	$7.5 \times 10^{-5}{\rm eV}^2$	N/A
Δ_{31}	$2.475 \times 10^{-3}{\rm eV}^2$	$(2.2, 2.6) \times 10^{-3}{\rm eV}^2$
Δ_{41}	$1{\rm eV}^2$	N/A

Table 1: Expanded 4ν parameter true values and test marginalisation ranges, parameters with N/A are not marginalised over.

$$U_{\rm PMNS}^{4\nu} = U(\theta_{34}, \delta_{34}) U(\theta_{24}, 0) U(\theta_{14}, \delta_{14}) U_{\rm PMNS}^{3\nu} . \quad (2.1)$$

where

$$U_{\rm PMNS}^{3\nu} = U(\theta_{23}, 0) U(\theta_{13}, \delta_{13}) U(\theta_{12}, 0) . \quad (2.2)$$

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where $U(\theta_{ij}, \delta_{ij})$ contains a corresponding 2×2 mixing matrix:

$$U^{2\times 2}(\theta_{ij}, \delta_{ij}) = \begin{pmatrix} c_{ij} & s_{ij}e^{i\delta_{ij}} \\ -s_{ij}e^{i\delta_{ij}} & c_{ij} \end{pmatrix} \quad (2.3)$$

embedded in an $n \times n$ array in the i, j sub-block. Thus in this case the neutrino oscillation parameter space is increased by three more mixing angles: θ_{14}, θ_{24} and θ_{34}, two more Dirac type CP phases i.e., δ_{14} and δ_{34} and one more mass squared difference: Δ_{41} $(m_4^2 - m_1^2)$. In 3+1 case, the appearance channel expression in vacuum is given by [6]

$$P_{\mu e} \simeq 4s_{23}^2 s_{13}^2 \sin^2\Delta + 8s_{13}s_{12}c_{12}s_{23}c_{23}(\alpha\Delta)\sin\Delta\cos(\Delta \pm \delta_{13}) + 4s_{14}s_{24}s_{13}s_{23}\sin\Delta\sin(\Delta \pm \delta_{13} \mp \delta_{14})$$

where $\Delta \equiv \Delta_{31}L/4E$, $\alpha \equiv \Delta_{21}/\Delta_{31}$ with L being the baseline and E is the energy. For our present work we list our choice of parameters in Table 1 [7].

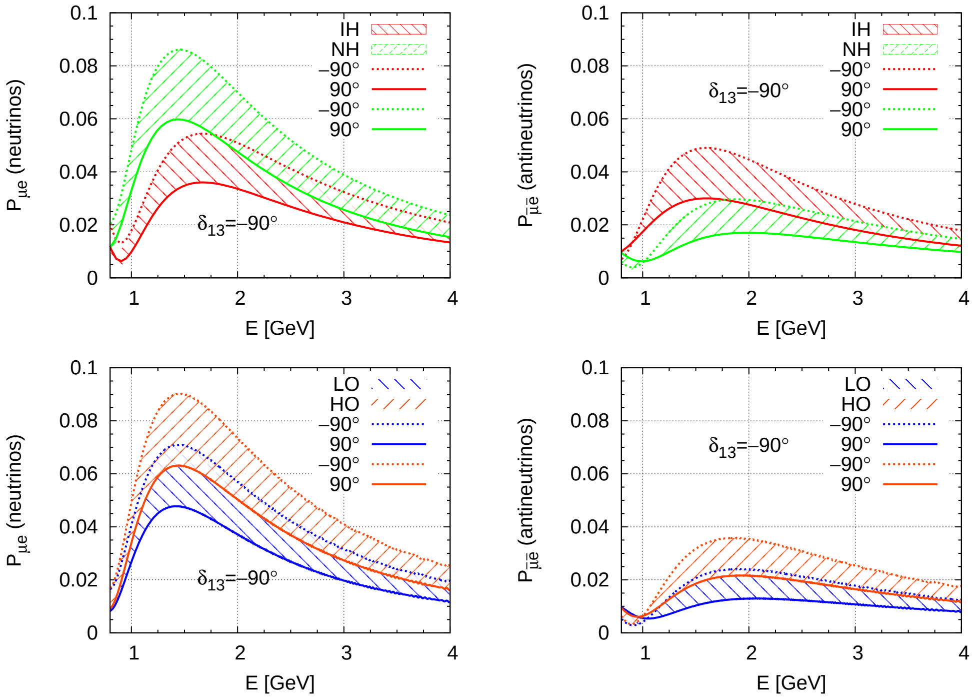

Figure 1: $\nu_\mu \to \nu_e$ oscillation probability bands for $\delta_{13} = -90^\circ$. Left panels are for neutrinos and right panels are for antineutrinos. The upper panel shows the hierarchy-δ_{14} degeneracy and the lower panels shows the octant-δ_{14} degeneracy.

In the table, LO implies the lower octant of θ_{23} and HO implies higher octant of θ_{23}. We have generated all our results with the GLoBES software [8].

3. Degeneracy at the probability level

In fig. 1, we have plotted the appearance probability vs energy for $\delta_{13} = -90^\circ$ and the bands are due to variation of δ_{14}. The upper panels show the hierarchy-δ_{14} degeneracy and the lower

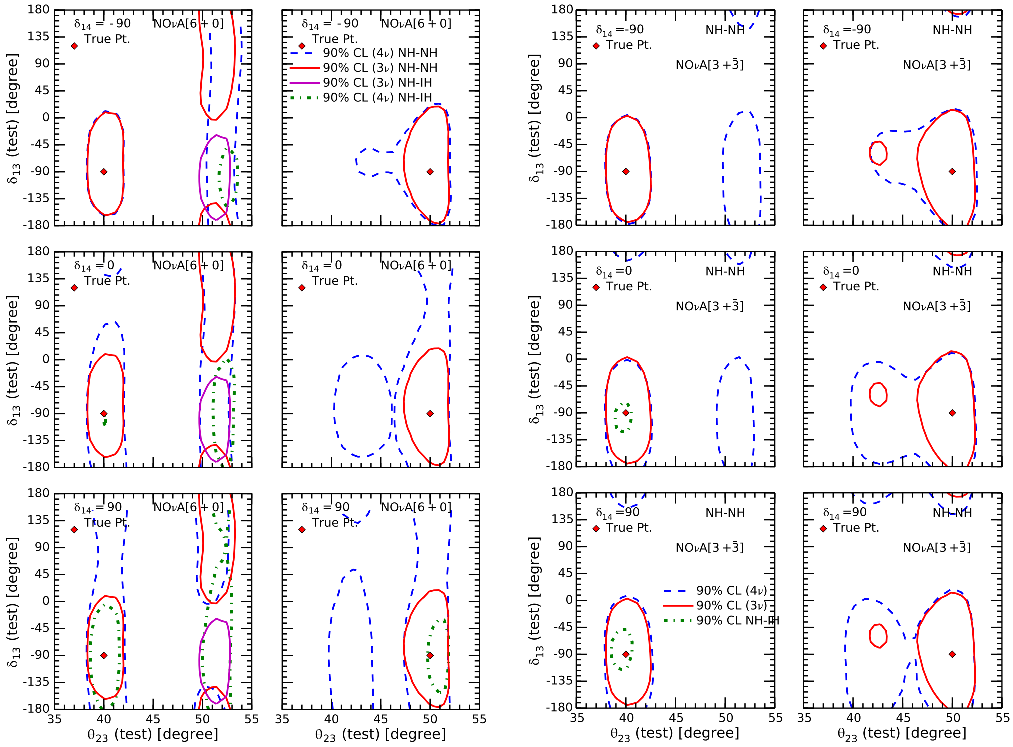

Figure 2: Contour plots in the θ_{23}(test) vs δ_{13}(test) plane for two different true values of $\theta_{23} = 40^\circ$ (first and third column) and 50° (second and fourth column) for NOνA $(6+\bar{0})$ (first and second column) and $(3+\bar{3})$ (third and fourth column). The first, second and third rows are for $\delta_{14} = -90^\circ$, 0° and 90° respectively. The true value for the δ_{13} is taken to be -90°. The true hierarchy is NH. We marginalize over the test values of δ_{14}. Also shown is the contours for the 3ν flavor scenario.

panels depict octant-δ_{14} degeneracy. From the upper panels we see that we have degeneracies in {NH, $\delta_{14} = 90^\circ$} with {IH, $\delta_{14} = -90^\circ$} for neutrinos and {NH, $\delta_{14} = -90^\circ$} with {IH, $\delta_{14} = 90^\circ$} for antineutrinos. Thus we understand that this degeneracy can be removed with a balanced run of neutrinos and antineutrinos. From the lower panels we see that there is degeneracies in {LO, $\delta_{14} = -90^\circ$ } with {HO, $\delta_{14} = 90^\circ$} for both neutrinos and antineutrinos. Thus it is clear that this degeneracy is unremovable. It was shown in Ref. [9] that due to this degeneracy, the octant determination of the long-baseline experiments is highly compromised.

4. Degeneracies at the event level

To Show the degeneracies at the event level, in Fig. 2 we have given the contour plots in the θ_{23} (test) - δ_{13} (test) plane. The true point is represented by the red diamond. In these panels, red and purple contours correspond to the right hierarchy and wrong hierarchy solutions respectively for the three generation case and the blue and green contours correspond to right hierarchy and wrong hierarchy solutions respectively for the 3+1 case. By comparing the pure neutrino results of NOνA labeled as NOνA (6+0) and mixed neutrino-antineutrino results labeled as NOνA (3+3) we notice that for three generation case, the all the degenerate solutions are almost gone when antineutrino

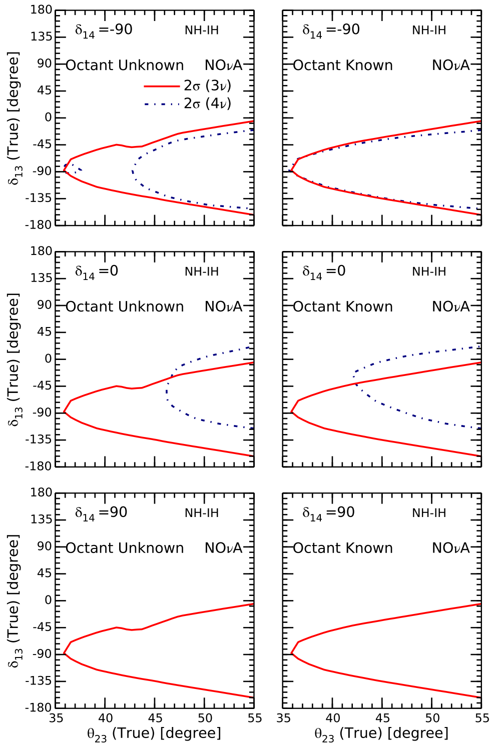

Figure 3: Contour plots at 2σ C.L. in the θ_{23}(true) vs δ_{13}(true) plane for Octant Unknown (left panel) and Octant Known (right panel) scenarios for NOνA ($3+\bar{3}$). The first, second and third rows are for $\delta_{14} = -90^\circ$, 0° and 90° respectively. The true and test hierarchies are chosen to be normal (NH) and inverted hierarchy (IH) respectively. Also shown contours for the 3ν flavor scenario.

data is considered. But for the 3+1 case, we notice that the wrong hierarchy solutions are almost gone but the wrong octant solutions does not get removed.

Thus from the above discussion we understand that even for NH and $\delta_{13} = -90^\circ$, where there is almost no degeneracy in the three generation case, there exists degenerate solutions when there is an extra light sterile neutrino.

5. Results for hierarchy sensitivity

To study the effect of these degeneracies on the hierarchy measurement in Fig. 3 we have plotted the hierarchy χ^2 in the true θ_{23} -true δ_{13} plane. From the figure we see that NOνA has good hierarchy sensitivity for $\delta_{13} = -90^\circ$ for the generation case. But for the 3+1 case, the sensitivity depends on the true value of δ_{14}. For $\delta_{14} = -90^\circ$ we see that the hierarchy sensitivity is lost for $\theta_{23} < 43^\circ$ if the octant is unknown. However if the octant is known then the sensitivity coincides with the three generation case. For $\delta_{14} = 0^\circ$, we note that the hierarchy sensitivity is lost if θ_{23} is less than 46° for both the cases. However the most remarkable result is obtained if δ_{14} is 90°. In this case we see that there is a complete loss of hierarchy sensitivity at 2σ for all true values of θ_{23}.

6. Summary

In this work we have studied the parameter degeneracy in neutrino oscillation in the presence of a light sterile neutrino in the eV scale for NOνA. In our work we have identified new degeneracies which are absent in the standard three generation case. Because of these there are unsolved degenerate region in the 3+1 case. We also showed that the hierarchy sensitivity depends on the true values of θ_{14}. If the observed hierarchy sensitivity of NOνA is less than the expected then this can be a hint of existence of sterile neutrinos. For more detail we refer to [10] on which this article is based upon.

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