Effect of sterile neutrino on degeneracy resolution capacities of NOvA and DUNE

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Introduction

- Precise measurement of neutrino oscillation parameters is important.
- Different sets of oscillation parameters may lead to the same value of oscillation probability
- Due to this true solutions can be mimicked by false solutions causing Parameter degeneracy.
- Octant of θ_{23} and Mass hierarchy (MH) are the 2 degeneracies that are yet to be resolved.
- The true value of the CP violation phase is also yet to be measured.
- Resolving these degeneracies is essential for NOvA and DUNE.

Introduction

- Sterile neutrino introduces new parameters to be measured.
- This increases the degrees of freedom and will affect degeneracy resolution capabilities of NOvA and DUNE.
- We have done a quantitative analysis of how sterile neutrino affects degeneracy resolution.

3+1 sterile neutrino model

- 3+1 flavor neutrino mixing is given by following 4X4 parameterization

$$U_{PMNS_{3+1}} = R_{34}(\theta_{34})\tilde{R_{24}}(\theta_{24}, \delta_{24})\tilde{R_{14}}(\theta_{14}, \delta_{14})U_{PMNS_3}. \quad (1)$$

- The addition of one sterile neutrino introduces 3 new mixing angles and 2 new CP-phases (properties of 4X4 Unitary matrix).
- Measuring the new parameters is important for the study of sterile neutrinos.
- Although Near Detector studies can give good bounds on sterile mixing angles ,they are not sensitive to new CP-phases introduced by ν_s as they need longer distances to become measurable.
- Long baseline(LBL) experiments explore CP phases. Combining both give us better measurements.

Oscillation Probability for 3+1 model

- $P_{\mu e}$ for LBL experiments in 3+1 model is expressed as sum of the four terms

$$P_{\mu e}^{4\nu} \simeq P_1 + P_2(\delta_{13}) + P_3(\delta_{14} - \delta_{24}) + P_4(\delta_{13} - (\delta_{14} - \delta_{24})). \quad (2)$$

- The second term gives ordinary CP violation
- The CP phases introduced due to sterile neutrinos persist in the $P_{\mu e}$ even after averaging out Δm^2_{41} lead oscillations.
- Last two terms of equation, give the sterile CP phase dependence terms.
- Thus, We see that LBL experiments are sensitive to sterile phases.

Oscillation Probability for 3+1 model

- Expanded form of $P_{\mu e}^{4\nu}$ is as follows:

$$P_1 = \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} + [a^2 \sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu}]\sin^2\Delta_{31}$$
$$+ [a^2 b^2 - \frac{1}{4}\sin^2 2\theta_{12}(\cos^4\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu} + a^2\sin^2 2\theta_{\mu e}^{3\nu})]\sin^2\Delta_{21},$$

$$P_2(\delta_{13}) = a^2 b \sin 2\theta_{\mu e}^{3\nu}(\cos 2\theta_{12}\cos\delta_{13}\sin^2\Delta_{21} - \frac{1}{2}\sin\delta_{13}\sin 2\Delta_{21}),$$

$$P_3(\delta_{14}-\delta_{24}) = ab\sin 2\theta_{\mu e}^{4\nu}\cos^2\theta_{13}\big[\cos 2\theta_{12}\cos(\delta_{14}-\delta_{24})\sin^2\Delta_{21}$$
$$-\frac{1}{2}\sin(\delta_{14}-\delta_{24})\sin 2\Delta_{21}\big],$$

$$P_4(\delta_{13}-(\delta_{14}-\delta_{24})) = a\sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\big[\cos 2\theta_{13}\cos(\delta_{13}-(\delta_{14}-\delta_{24}))\sin^2\Delta_{31}$$
$$+\frac{1}{2}\sin(\delta_{13}-(\delta_{14}-\delta_{24}))\sin 2\Delta_{31} - \frac{1}{4}\sin^2 2\theta_{12}\cos^2\theta_{13}\cos(\delta_{13}-(\delta_{14}-\delta_{24}))\sin^2\Delta_{21}\big],$$

Oscillation Probability for 3+1 model

- With the parameters defined as

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/4E, \text{ a function of baseline(L) and neutrino energy(E)}$$
$$a = \cos\theta_{14}\cos\theta_{24},$$
$$b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12},$$
$$\sin 2\theta^{3\nu}_{\mu e} = \sin 2\theta_{13}\sin\theta_{23},$$
$$\sin 2\theta^{4\nu}_{\mu e} = \sin 2\theta_{14}\sin\theta_{24}.$$

- We see that the amplitudes of atmospheric-sterile interference term and solar-atmospheric interference term, are of the same order.
- This new interference term reduces the sensitivity of experiments to the standard CP phase(δ_{13}). This will reduce degeneracy resolution capacities of LBL experiments.

Details of experiments

Table: Details of experiments

Name of Exp	NOνA [1]	DUNE [2]
Location	Minnesota	South Dakota
POT(yr^{-1})	6.0x10^{20}	1.1x10^{21}
Baseline(Far/Near)	812 km/1km	1300 km/500 m
Target mass(Far/Near)	14 kt/290 t	40 kt/8 t
Exposure(years)	6	6
Detector type	Tracking Calorimeters	LArTPCs

[1]. P.Adamson et al.[NOvA Collaboration], Phys.Rev.Lett.116,no.15

[2]. T.Alion et al.[DUNE Collaboration], arXiv:1606.09550

Oscillation Parameters

Parameters	True values	Test value Range
$\sin^2\theta_{12}$	0.304	NA
$\sin^2 2\theta_{13}$	0.085	NA
$\sin^2\theta_{23}$	0.5	$0.4 \longrightarrow 0.6$
	(LO 0.44)	$0.4 \longrightarrow 0.5$
	(HO 0.56)	$0.5 \longrightarrow 0.6$
δ_{CP}	$-90^\circ(LO), -143^\circ(HO)$	$-180^\circ \longrightarrow 180^\circ$
Δm^2_{12}	7.4×10^{-5} eV^2	NA
Δm^2_{31}	2.5×10^{-3} eV^2 (NH)	$(2.36 \longrightarrow 2.64) \times 10^{-3}$eV^2
	-2.5×10^{-3} eV^2 (IH)	$(-2.64 \longrightarrow -2.36) \times 10^{-3}$ eV^2
Δm^2_{14}	1 eV^2	NA
$\sin^2\theta_{14}$	0.025	θ_{14} $(0^\circ, 15^\circ)$
$\sin^2\theta_{24}$	0.025	θ_{24} $(0^\circ, 15^\circ)$
$\sin^2\theta_{34}$	0.025	θ_{34} $(0^\circ, 15^\circ)$
δ_{14}	-90°	$-180^\circ \longrightarrow 180^\circ$
δ_{24}	0°	$-180^\circ \longrightarrow 180^\circ$

Figure: The values of oscillation parameters, we considered in our analysis

Effect of δ_{13} on $P_{\mu e}$ in 3+1 model

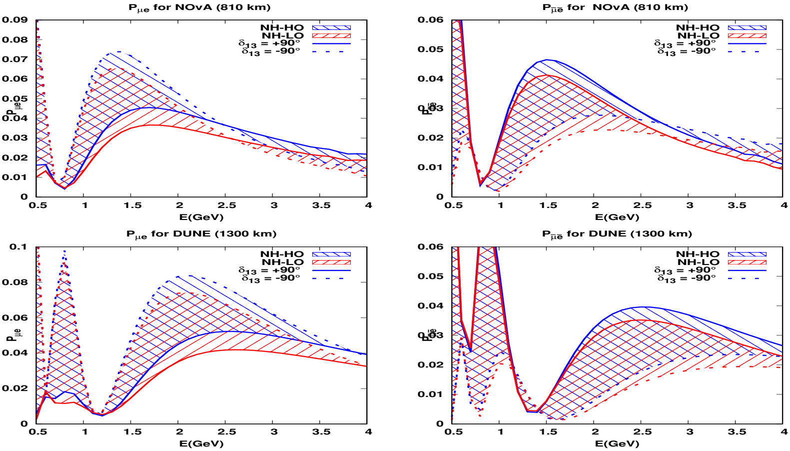


Figure: The oscillation probability $P_{\mu e}$ as a function of energy. The bands correspond to different values of δ_{13}, ranging from -180° to 180°.

Effect of δ_{14} and δ_{24} on $P_{\mu e}$ in 3+1 model

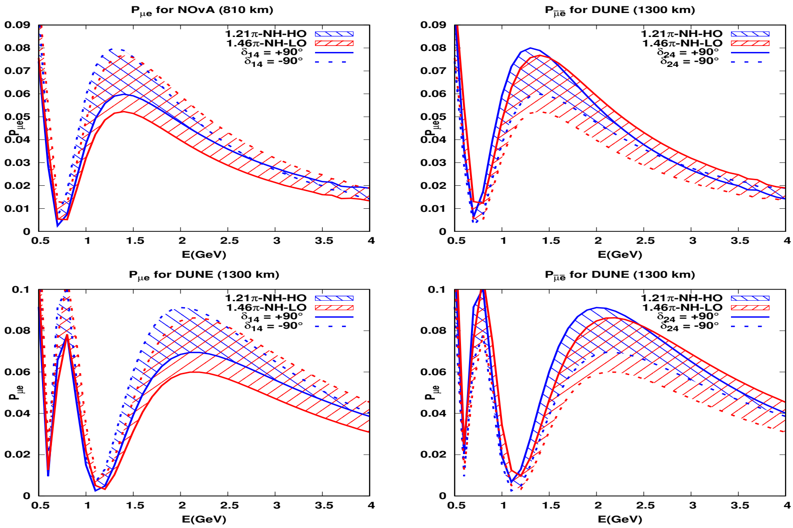


Figure: The oscillation probability $P_{\mu e}$ as a function of energy. The bands correspond to different values of δ_{14} and δ_{24}, ranging from -180° to 180°.

Problem Statement

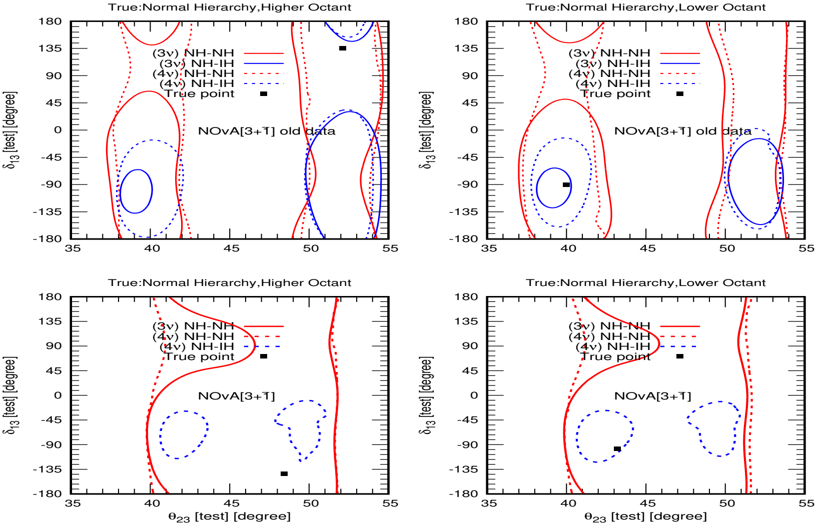
- Recent NOνA analysis, taking both appearance and disappearance channel data for 3 year of neutrino run,gave 2 best fit points for normal hierarchy(NH) and inverted hierarchy (IH) is disfavored at the 95% confidence level [3]
  - $\sin^2(\theta_{23}) = 0.47$ (Lower Octant(LO)) ,$\delta_{13} = 1.46\pi = 262.8^\circ$,NH
  - $\sin^2(\theta_{23}) = 0.56$ (Higher Octant(HO)),$\delta_{13} = 1.21\pi = 217.8^\circ$,NH
- Only one of them can be the true solutions,while other will correspond to degenerate solutions with wrong hierarchy(WH) and wrong octant(WO).
- We studied the extent to which future runs of NOνA and DUNE will resolve these degeneracies if the best fit values are the true values.

[3]. M.A.Acero et al.[NOvA Collaboration] Phys.Rev. D98 (2018) 032012

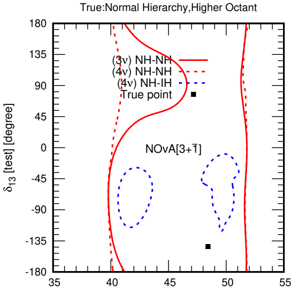
Results

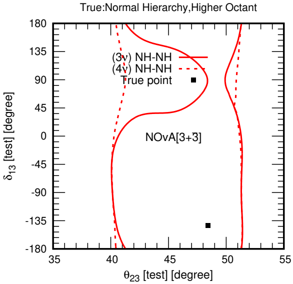
- We explore allowed regions in $\sin^2\theta_{23}$-δ_{cp} plane from NOνA and DUNE simulation data with different runtimes, considering latest NOνA results as true values.
- We plot test values for both NH and IH, of 3 and 3+1 neutrino models.
- The contour denotes the region where test hypothesis is not excluded at a given confidence interval(C.I).
- For example, contour titled NH-IH denotes, the region where IH(test hypothesis) could not be excluded at mentioned C.I when NH is the true hypothesis.
- Different test cases we used are : NH-NH(3ν),NH-IH(3ν),NH-NH(4ν),NH-IH(4ν)
- Absence of a contour in the plot implies that it's test hypothesis is excluded at mentioned C.I.

Results (New vs Old)



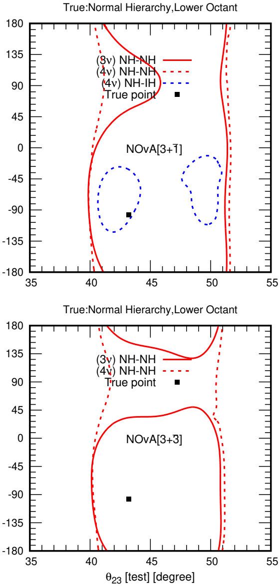
Results





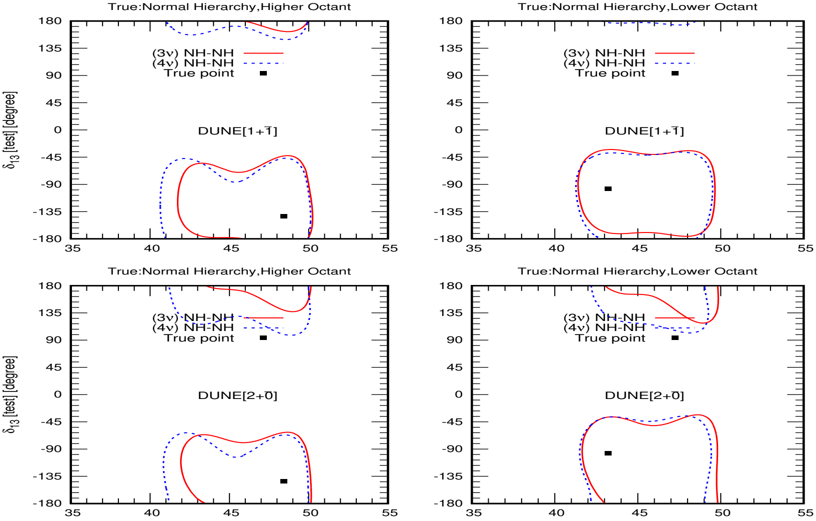
- The contours of this figure are plotted for 2σ C.I regions. We take NH-HO as true values for this case.
- NOvA[3+1] has WH(NH-IH)(Blue) contour for 4ν case which was absent in 3ν case.
- For NOvA[3+1], WH (NH-IH) is excluded even for for 4ν.
- We observe that the allowed contour sizes reduce for NOvA[3+3] due to increased statistics.

Results



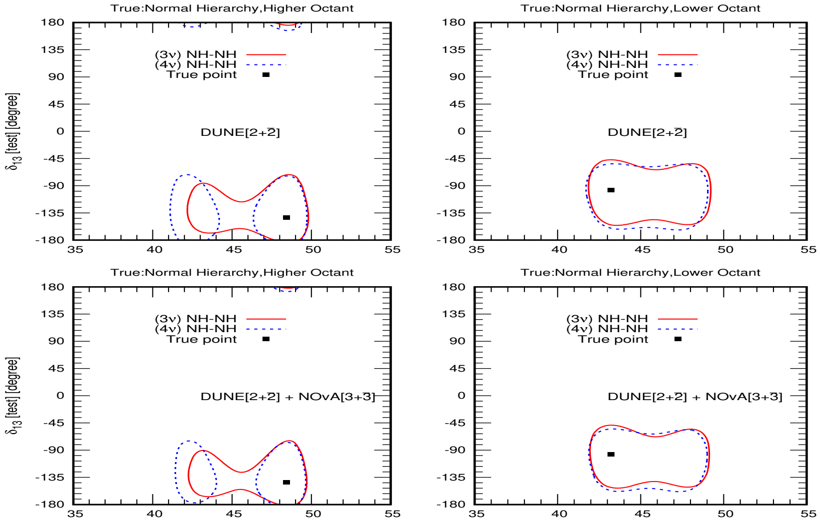
- The contours of this figure are plotted for 2σ C.I regions. We take NH-LO as true values for this case.
- NOvA[3+1] has WH (NH-IH)(Blue) contour for 4ν case which was absent in 3ν case.
- For NOvA[3+1], WH(NH-IH) is excluded even for for 4ν.
- We observe that whole range of δ_{13} is allowed for 4ν case while [45:120] is excluded for 3ν.

Results



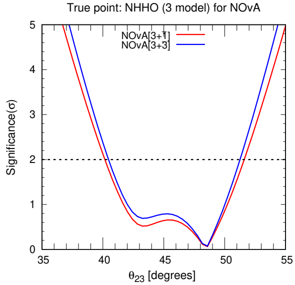
- The contours of this figure are plotted for 2σ C.I regions for all NOvA best fit values.

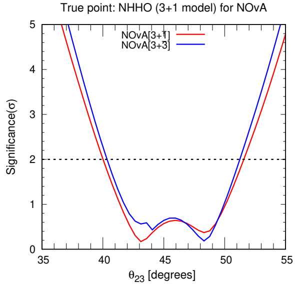
Results



- The contours of this figure are plotted for 2σ C.I regions for all NOvA best fit values.

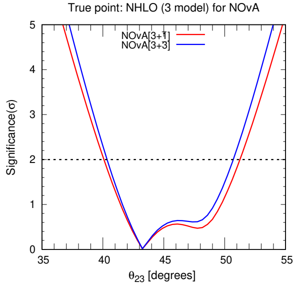
Octant resolution sensitivity

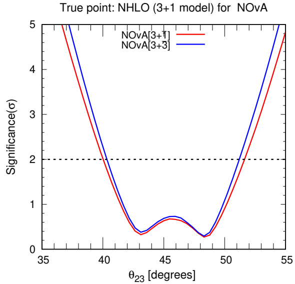




- In this figure we project the above contours onto θ_{23} axis, to see the C.I with which test value is excluded when true values is given.
- We take NH-HO as true values for this case.
- We see that LO test value is not excluded for both 4ν and 3ν cases.
- A slight increase in sensitivity is observed with increasing run-time.
- Since, the true value is close to maximal mixing(MM) angle, we need more data to exclude MM angle as seen.

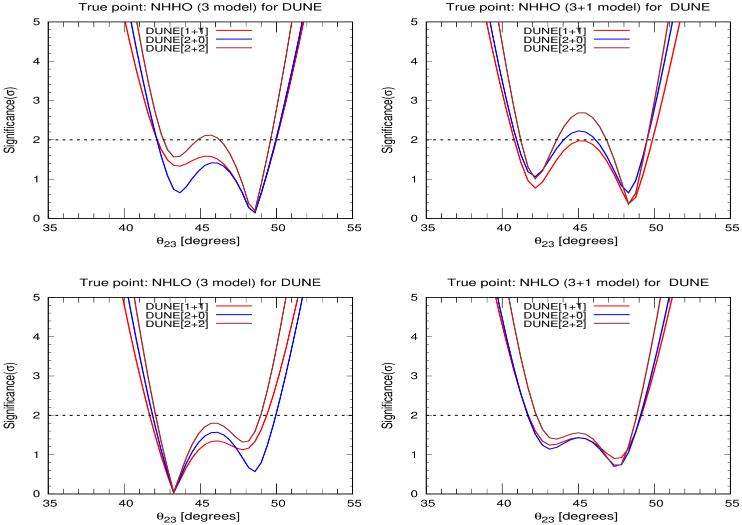
Octant resolution sensitivity



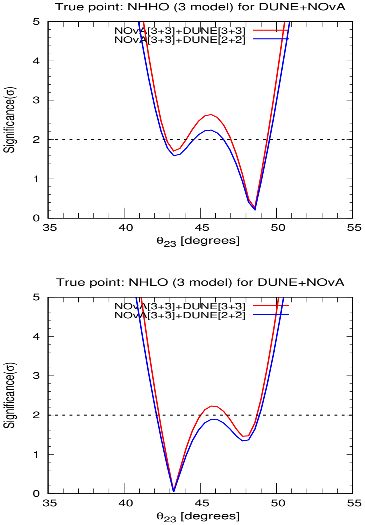


- We take NH-LO as true values for this case.
- We see that LO test value is not excluded for both 4ν and 3ν cases.
- A slight increase in sensitivity is observed with increasing run-time.
- Since, the true value is close to maximal mixing(MM) angle, we need more data to exclude MM angle as seen.

Octant resolution sensitivity



Octant resolution sensitivity



Summary

- We have discussed how the presence of a sterile neutrino will affect, the physics potential of the proposed experiment DUNE and future runs of NOνA.
- We see that for the current best-fit values of NOvA, small IH degeneracy introduced by 3+1 model gets resolved at 2σ level with increased run-time of experiment.
- Since the best-fit values are close to MM angle, more data is required to exclude MM angle.
- Dune clearly has better precision over NOvA as it is designed to be.

Thank You