Degeneracy resolution capabilities of NOνA and DUNE in the presence of light sterile neutrino

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Abstract

We investigate the implications of a sterile neutrino on the physics potential of the proposed experiment DUNE and future runs of NOνA using latest NOνA results. Using combined analysis of the disappearance and appearance data, NOνA reported preferred solutions at normal hierarchy (NH) with two degenerate best-fit points one in the lower octant (LO) and δ13 = 1.48π and other in higher octant (HO) and δ13 = 0.74π. Another solution of inverted hierarchy (IH) which is 0.46σ away from best fit was also reported. We discuss chances of resolving these degeneracies in the presence of sterile neutrino(3+1 model).

1 Introduction

Sterile neutrinos are hypothetical particles that do not interact via any of the fundamental interactions other than gravity. The term sterile is used to distinguish them from active neutrinos, which are charged under weak interaction. The theoretical motivation for sterile neutrino explains the active neutrino mass after spontaneous symmetry breaking, by adding a gauge singlet term (sterile neutrino) to the Lagrangian under $SU(3)_c \otimes SU(2)_L \otimes U(1)_r$.

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where the Dirac term appears through the Higgs mechanism, and Majorana mass term is a gauge singlet, and hence appears as a bare mass term [1]. The diagonalization of the mass matrix gives masses to all neutrinos due to the See-Saw mechanism.

Some experimental anomalies also point towards the existence of sterile neutrinos. Liquid Scintillator Neutrino Detector (LSND) detected $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions indicating $\Delta m^2 \approx 1 eV^2$ which is inconsistent with $\Delta m_{32}^2, \Delta m_{21}^2$ (LSND anomaly) [2]. Measurement of the width of Z boson by LEP gave number of active neutrinos to be $2.984\pm0.008$ [3]. Thus the new neutrino introduced to explain the anomaly has to be a sterile neutrino. MiniBooNE, designed to verify the LSND anomaly, observed an unexplained excess of events in low-energy region of $\bar{\nu}_e, \nu_e$ spectra, consistent with LSND [4]. SAGE and GALLEX observed lower event rate than expected, explained by the oscillations of $\nu_e$ due to $\Delta m^2 \geq 1eV^2$ (Gallium anomaly) [5–7]. Recent precise predictions of reactor anti-neutrino flux has increased the expected flux by 3% over old predictions. With the new flux evaluation, the ratio of observed and predicted flux deviates at 98.6% C.L (Confidence level) from unity, this is called “Reactor anti-neutrino Anomaly” [8]. This anomaly can also be explained using sterile neutrino model.

Short-baseline (SBL) experiments are running to search for sterile neutrinos. SBL experiments are the best place to look for sterile neutrino, as they are sensitive to new expected mass-squared splitting $\Delta m^2 \sim 1eV^2$. However, SBL experiments cannot study all the properties of sterile neutrinos, mainly new CP phases introduced by sterile neutrino models. These new CP phases need long distances to become measurable [9,10], thus can be measured using Long baseline (LBL) experiments. With the discovery of relatively large value for $\theta_{13}$ by Daya Bay [11], the sensitivity of LBL experiments towards neutrino mass hierarchy and CP phases increased significantly. Using recent global fits of oscillation parameters in the 3+1 scenario [12], current LBL experiments can extract two out of three CP phases (one of them being standard $\delta_{13}$) [10]. Now, the sensitivity of LBL experiments towards their original goals decreases due to sterile neutrinos. It is seen in case of the CPV measurement; new CP-phases will decrease the sensitivity towards standard CP phase ($\delta_{13}$). This will reduce degeneracy resolution capacities of LBL experiments. In this paper, we study hierarchy-$\theta_{23}$-$\delta_{13}$ degeneracies using contours in $\theta_{23}$-$\delta_{13}$ plane and how they are affected by the introduction of sterile neutrinos. We attempt to find the extent to which these degeneracies can be resolved in future runs of NO$\nu$A and DUNE.

The outline of the paper is as follows. In section 2, we present the experimental specifications of NO$\nu$A and DUNE used in our simulation. We introduce the effect of sterile neutrino on parameter degeneracies resolution in section 3. Section 4 contains the discussion.
about the degeneracy resolving capacities of future runs of NO\(\nu\)A and DUNE assuming latest NO\(\nu\)A results - NH(Normal hierarchy)-LO(Lower octant), NH-HO(Higher octant), and IH(Inverted hierarchy)-HO as true solutions for both 3 and 3+1 models. Finally, Section 5 contains concluding comments on our results.

2 Experiment specifications

We used GLoBES (General Long Baseline Experiment simulator) \[13, 14\] to simulate the data for different LBL experiments including NO\(\nu\)A and DUNE. The neutrino oscillation probabilities for the 3+1 model are calculated using the new physics engine available from Ref. \[15\].

NO\(\nu\)A \[16, 17\] is an LBL experiment which started its full operation from October 2014. NO\(\nu\)A has two detectors, the near detector is located at Fermilab (300 ton, 1 km from NuMI beam target) while the far detector(14 Kt) is located at Northern Minnesota 14.6 mrad off the NuMI beam axis at 810 km from NuMI beam target, justifying “Off-Axis” in the name. This off-axis orientation gives us a narrow beam of flux, peak at 2 GeV \[18\]. For simulations, we used NO\(\nu\)A setup from Ref. \[19\]. We used the full projected exposure of \(3.6 \times 10^{21}\) p.o.t (protons on target) expected after six years of runtime at 700kW beam power. Assuming the same runtime for neutrino and anti-neutrino modes, we get \(1.8 \times 10^{21}\) p.o.t for each mode. Following \[20\] we considered 5% normalization error for the signal, 10% error for the background for appearance and disappearance channels.

DUNE (Deep Underground Neutrino Experiment) \[21, 22\] is the next generation LBL experiment. Long Base Neutrino Facility(LBNF) of Fermilab is the source for DUNE. Near detector of DUNE will be at Fermilab. Liquid Argon detector of 40 kt to be constructed at Sanford Underground Research Facility situated 1300 km from the beam target, will act as the far detector. DUNE uses the same source as of NO\(\nu\)A; we will observe beam flux peak at 2.5GeV. We used DUNE setup give in Ref. \[23\] for our simulations. Since DUNE is still in its early stages, we used simplified systematic treatment, i.e., 5% normalization error on signal, 10% error on the background for both appearance and disappearance spectra. Oscillation parameters are estimated from the data by comparing observed and predicted \(\nu_e\) and \(\nu_\mu\) interaction rates and energy spectra. Oscillation parameters are estimated from the data by comparing observed and predicted \(\nu_e\) and \(\nu_\mu\) interaction rates and energy spectra.

GLoBES calculates event rates of neutrinos for energy bins taking systematic errors, detector resolutions, MSW effect due to earth’s crust etc into account. The event rates
generated for true and test values are used to plot $\chi^2$ contours. GLoBES uses its inbuilt algorithm to calculate $\chi^2$ values numerically considering parameter correlations as well as systematic errors. In our calculations we used $\chi^2$ as:

$$\chi^2 = \sum_{i=1}^{\text{#ofbins}} \sum_{E_n=E_1,E_2,..} \frac{(O_{E_n,i} - (1 + a_F + a_{E_n})T_{E_n,i})^2}{O_{E_n,i} + a_F^2/\sigma_F^2 + a_{E_n}^2/\sigma_{E_n}^2}$$

where $O_{E_1,i}, O_{E_2,i,..}$ are the event rates for the $i^{th}$ bin in the detectors of different experiments, calculated for true values of oscillation parameters; $T_{E_n,i}$ are the expected event rates for the $i^{th}$ bin in the detectors of different experiments for the test parameter values; $a_F, a_{E_n}$ are the uncertainties associated with the flux and detector mass; and $\sigma_F, \sigma_{E_n}$ are the respective associated standard deviations. The calculated $\chi^2$ function gives the confidence level in which tested oscillation parameter values can be ruled out with referenced data. It provides an excellent preliminary evaluation model to estimate the experiment performance.

Table 1: Details of experiments

| Name of Exp      | NO\nu A      | DUNE          |
|------------------|--------------|---------------|
| 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            | 10            |
| Detector type    | Tracking Calorimeters | LArTPCs     |

3 Theory

In a 3+1 sterile neutrino model, the flavour and mass eigenstates are connected through a $4 \times 4$ mixing matrix. A convenient parametrization of the mixing matrix is [25]

$$U = R_{34} \bar{R}_{24} \bar{R}_{14} R_{23} \bar{R}_{13} R_{12}. \quad (2)$$

where $R_{ij}$ and $\bar{R}_{ij}$ represent real and complex $4 \times 4$ rotation in the plane containing the $2 \times 2$ sub-block in (i,j) sub-block
Table 2: Systematic errors associated with NOνA and DUNE

| Name Of Exp | Rule       | Normalization error |
|-------------|------------|---------------------|
|             | signal(%) | background(%)       |
| NOνA        | $\nu_e$ appearance | 5                  | 10               |
|             | $\nu_\mu$ disappearance | 2                  | 10               |
|             | $\bar{\nu}_e$ appearance | 5                  | 10               |
|             | $\bar{\nu}_\mu$ disappearance | 2                 | 10               |
| DUNE        | $\nu_e$ appearance | 5                  | 10               |
|             | $\nu_\mu$ disappearance | 5                  | 10               |
|             | $\bar{\nu}_e$ appearance | 5                  | 10               |
|             | $\bar{\nu}_\mu$ disappearance | 5                 | 10               |

Table 3: Oscillation parameters considered in numerical analysis. The $\sin^2 \theta_{23}$ and $\delta_{13}$ are taken from latest NOνA results [24].

| Parameter   | True value     | Marginalization Range |
|-------------|----------------|------------------------|
| $\sin^2 \theta_{12}$ | 0.304          | Not Marginalized       |
| $\sin^2 \theta_{13}$ | 0.085          | [0.075,0.095]          |
| $\sin^2 \theta_{23}$ | 0.623(HO),0.404(LO) | [0.32,0.67]          |
| $\sin^2 \theta_{14}$ | 0.025          | Not Marginalized       |
| $\sin^2 \theta_{24}$ | 0.025          | Not Marginalized       |
| $\sin^2 \theta_{34}$ | 0.025          | Not Marginalized       |
| $\delta_{13}$    | 135(NH-LO),-90(NH-HO,IH) | [-180,180]       |
| $\delta_{14}$    | [-180,180]     | [-180,180]             |
| $\delta_{24}$    | [-180,180]     | [-180,180]             |
| $\Delta m^2_{21}$ | $7.50 \times 10^{-5} \text{ eV}^2$ | Not Marginalized |
| $\Delta m^2_{31}(\text{NH})$ | $2.40 \times 10^{-3} \text{ eV}^2$ | Not Marginalized |
| $\Delta m^2_{31}(\text{IH})$ | $-2.33 \times 10^{-3} \text{ eV}^2$ | Not Marginalized |
| $\Delta m^2_{41}$ | $1 \text{ eV}^2$ | Not Marginalized       |

\[
R_{ij}^{2 \times 2} = \begin{pmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{pmatrix} \quad \tilde{R}_{ij}^{2 \times 2} = \begin{pmatrix} c_{ij} & s_{ij}^* \\ -s_{ij}^* & c_{ij} \end{pmatrix}
\] (3)
Where, \(c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}, \tilde{s}_{ij} = s_{ij} e^{-i\delta_{ij}}\) and \(\delta_{ij}\) are the CP phases.

There are three mass squared difference terms in 3+1 model- \(\Delta m^2_{21}\) (solar) \(\simeq 7.5 \times 10^{-5}\) eV\(^2\), \(\Delta m^2_{31}\) (atmospheric) \(\simeq 2.4 \times 10^{-3}\) eV\(^2\) and \(\Delta m^2_{41}\) (sterile) \(\simeq 1\) eV\(^2\). The mass-squared difference term towards which the experiment is sensitive depends on L/E of the experiment. Since SBL experiments have small a very small L/E, \(\sin^2(\Delta m^2_{ij} L/4 E) \simeq 0\) for \(\Delta m^2_{21}\) and \(\Delta m^2_{31}\). \(\Delta m^2_{41}\) term survives. Hence, SBL experiments depend only on sterile mixing angles and are insensitive to the CP phases. The oscillation probability, \(P_{\mu e}\) for LBL experiments in 3+1 model, after averaging \(\Delta m^2_{41}\) oscillations and neglecting MSW effects, [26] is expressed as sum of the four terms

\[
P^{4\nu}_{\mu e} \simeq P_1 + P_2(\delta_{13}) + P_3(\delta_{14} - \delta_{24}) + P_4(\delta_{13} - (\delta_{14} - \delta_{24})).
\]

These terms can be approximately expressed as follows:

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

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

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

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

With the parameters defined as

\[
\Delta_{ij} \equiv \Delta m^2_{ij} L/4 E, \text{ a function of baseline(L) and neutrino energy(E)}
\]

\[
a = \cos \theta_{14} \cos \theta_{24},
\]

\[
b = \cos \theta_{13} \cos \theta_{23} \sin 2\theta_{12},
\]

\[
\sin 2\theta^3_{\mu e} = \sin 2\theta_{13} \sin \theta_{23},
\]

\[
\sin 2\theta^4_{\mu e} = \sin 2\theta_{14} \sin \theta_{24}.
\]
The CP phases introduced due to sterile neutrinos persist in the $P_{\mu e}$ even after averaging out $\Delta m^2_{41}$ lead oscillations. Last two terms of equation 4, give the sterile CP phase dependence terms. $P_3(\delta_{14} - \delta_{24})$ depends on the sterile CP phases $\delta_{14}$ and $\delta_{24}$, while $P_4$ depends on a combination of $\delta_{13}$ and $\delta_{14} - \delta_{24}$. Thus, we expect LBL experiments to be sensitive to sterile phases. We note that the probability $P_{\mu e}$ is independent of $\theta_{34}$. One can see that $\theta_{34}$ will affect $P_{\mu e}$ if we consider earth mass effects. Since matter effects are relatively small for NO$\nu$A and DUNE, their sensitivity towards $\theta_{34}$ is negligible. The amplitudes of atmospheric-sterile interference term (eq.8) and solar-atmospheric interference term(eq.6), are of the same order. This new interference term reduces the sensitivity of experiments to the standard CP phase($\delta_{13}$).

In figure 1, we plot the oscillation probability($P_{\mu e}$) as a function of energy for the three best fit values of latest NO$\nu$A results [24] i.e; NH-LO-1.48$\pi$[$\delta_{13}$], NH-HO-0.74$\pi$ and IH-HO-1.48$\pi$. Where, HO implies $\sin^2\theta_{23} = 0.62$ and LO implies $\sin^2\theta_{23} = 0.40$. For the flux peak of NO$\nu$A, $E \approx 2$GeV, We observe a degeneracy between NH and IH best-fit values due to the presence of $\delta_{14}$ band for both neutrinos and anti-neutrinos. This implies that addition of sterile neutrino decreases hierarchy resolution capacity of NO$\nu$A. The second row plots $P_{\mu e}$ for DUNE at baseline 1300 km. We observe smaller overlap between bands compared to NO$\nu$A. We see that $\delta_{14}$ phase mainly effects mass hierarchy resolution capacity. Similarly we plot $P_{\mu e}$ while varying $\delta_{24}$ in figure 2. We see that unlike $\delta_{14}$ case, $\delta_{24}$ band also causes degeneracy between HO and LO fit values for neutrino case. Thus we observe that the addition of new CP phases decrease both octant and mass hierarchy resolution capacities.

In the next section, we explore how parameter degeneracies are affected in the 3+1 model and the extent to which these degeneracies can be resolved in future runs of NO$\nu$A and DUNE.

4 Results for NO$\nu$A and DUNE

We explore allowed regions in $\sin^2\theta_{23}$-$\delta_{cp}$ plane from NO$\nu$A and DUNE simulation data with different runtimes, considering latest NO$\nu$A results as true values. Using combined analysis of the disappearance and appearance data, NO$\nu$A reported preferred solutions [24] at normal hierarchy (NH) with two degenerate best-fit points, one in the lower octant (LO) and $\delta_{cp} = 1.48\pi$, the other in higher octant (HO) and $\delta_{cp} = 0.74\pi$. Another solution of inverted hierarchy (IH), 0.46$\sigma$ away from best fit is also reported. By studying the allowed regions, we understand the extent to which future runs of NO$\nu$A and DUNE will resolve
Figure 1: The oscillation probability \( P_{\mu e} \) as a function of energy. The Top(bottom) panel is NO\( \nu A \) (DUNE). The bands correspond to different values of \( \delta_{14} \), ranging from \(-180^\circ\) to \(180^\circ\). Inside each band, the probability for \( \delta_{14} = 90^\circ \) (\( \delta_{14} = -90^\circ \)) case is shown as the solid (dashed) line. The left(right) panel corresponds to neutrinos(antineutrinos).

these degeneracies, if the best fit values are true values.

In the first row of figure 3, we show allowed areas for NO\( \nu A[3+\bar{0}] \). In first plot of first row, we show 90% C.L allowed regions for true values of \( \delta_{13} = 135^\circ \) and \( \theta_{23} = 52^\circ \) and normal hierarchy. We plot test values for both NH and IH, of 3 and 3+1 neutrino models. We observe that introducing sterile neutrino largely decreases the precision of \( \theta_{23} \). The WO-RH region, for 3\( \nu \) case confined between \(45^\circ\) to \(-180^\circ\) of \( \delta_{13} \), confines the whole \( \delta_{13} \) region for 4\( \nu \)
Figure 2: The oscillation probability $P_{\mu e}$ as a function of energy. The Top(bottom) panel is NO$\nu$A(DUNE). The bands correspond to different values of $\delta_{24}$, ranging from $-180^\circ$ to $180^\circ$. Inside each band, the probability for $\delta_{24} = 90^\circ$ ($\delta_{24} = -90^\circ$) case is shown as solid (dashed) line. The left(right) panel is for neutrinos(antineutrinos).

case. The WH-RO region of 3$\nu$ case doubles, covering the entire region of $\delta_{13}$ for 4$\nu$ case. The 3+1 model also introduces a small WH-WO region, that was absent in 3$\nu$ model. In the second plot of first row(true value $\delta_{13} = -90^\circ$, $\theta_{23} = 40^\circ$ and normal hierarchy), for the 3$\nu$ case, we see RH-RO region excluding $45^\circ$ to $150^\circ$ of $\delta_{13}$, while RH-WO region covers whole of the $\delta_{13}$ region. In 3+1 model, both RH-RO, RH-WO regions cover whole of the $\delta_{13}$ region. WH-RO solution occupies a small region for 3$\nu$ case, covering half of $\delta_{13}$ region for 4$\nu$ case.
Figure 3: Contour plots of allowed regions in the test plane, $\theta_{23}$ vs $\delta_{13}$, at 90% C.I with top, middle and bottom rows for NOνA runs of $3+\bar{0}, 3+\bar{1}$ and $3+\bar{3}$ years respectively.

WH-WO region covers whole of the $\delta_{13}$ region for $4\nu$ case. In the third plot of first row, true values are taken as, $\delta_{13} = -90^\circ$, $\theta_{23} = 52^\circ$ and inverted hierarchy. The RH-RO region covers the entire range of $\delta_{13}$ for both $3\nu$ and $4\nu$ case, where as, RH-WO region almost doubles from $3\nu$ case to $4\nu$ case. A small range of $\delta_{13}$ excluded from WH-RO for $3\nu$ case are covered in $4\nu$ case. WH-WO region of $3\nu$ case excludes $60^\circ$ to $150^\circ$ of $\delta_{13}$ while full $\delta_{13}$ range is covered for $4\nu$ case.
In the second row of the figure, we plot allowed regions for NO\(\nu A[3+1]\). We take true values as best fit points obtained by NO\(\nu A\). We observe an increase in precision of parameter measurement, due to an increase in statistics, from added 1 yr of anti-neutrino run. In the first plot of the second row, the RH-RO octant region covers entire \(\delta_{13}\) range for both 3\(\nu\) and 4\(\nu\) case. RH-WO region includes \(-180^\circ\) to \(45^\circ\) of \(\delta_{13}\) for 3\(\nu\) case, while whole range of \(\delta_{13}\) is covered in 4\(\nu\) case. A slight increase in the area of WH-RO is observed form 3\(\nu\) to 4\(\nu\) case. 4\(\nu\) introduces WH-WO region which was resolved for 3\(\nu\) case. In the second plot, RH-RO region covers full range of \(\delta_{13}\) for 4\(\nu\) case, while it was restricted to lower half of CP range in 3\(\nu\) case. We see WH-RO solution which was resolved in 3\(\nu\) case, is reintroduced in 4\(\nu\) case. We also see a slight increase in the size of WH-WO solution from 3\(\nu\) to 4\(\nu\). In third plot, RH-RO region covers whole CP range for 4\(\nu\) while 35\(^\circ\) to 125\(^\circ\) of \(\delta_{13}\) are excluded in 3\(\nu\) case. The almost resolved RH-WO solution for 3\(\nu\) doubles for 4\(\nu\) case. WH-RO, WH-WO cover entire region of \(\delta_{13}\) for 4\(\nu\) case.

In the third row, we show allowed regions for NO\(\nu A[3+\bar{3}]\). In the first plot, it can be seen that small area of RH-WO in case of 3\(\nu\) case now covers the whole of \(\delta_{13}\) region for 4\(\nu\) case. While the 3\(\nu\) case has WH-W\(\delta_{13}\) degeneracy, 4\(\nu\) case introduces equal sized WH-WO-W\(\delta_{13}\) degeneracy. In second plot, for 3\(\nu\) case: most of \(\delta_{13}\) values above \(0^\circ\) are excluded, but for 4\(\nu\) case we see contour covers whole of \(\delta_{13}\) range. Already present small area of RH-WO of 3\(\nu\) is also increased for 4\(\nu\) case. 4\(\nu\) case also introduces a small region of WH solutions which were not present in 3\(\nu\) case. In the third plot, we see that 4\(\nu\) introduces RH-WO region of the almost equal size of RH-RO region of 3\(\nu\) case. We observed a slight increase in WH-RO region for 4\(\nu\) over 3\(\nu\) case, while the WH-WO region almost triples for 4\(\nu\) case.

In the figure 4, we show allowed parameter regions for DUNE experiment for different run-times. DUNE being the next generation LBL experiment it is expected to have excellent statistics. Hence, We plot 99% C.L regions for DUNE. In the first row of figure 4, We show 99% C.L for DUNE[1+0]. In the first plot, RH-RO region covers entire of \(\delta_{13}\) range for both 3\(\nu\) and 4\(\nu\) case. The RH-WO region which covers only lower half of \(\delta_{13}\) region for 3\(\nu\) case covers the whole range for 4\(\nu\) case. A small region of WH is also observed. The second plot we see that all WH solutions are resolved. RH-WO covers the whole range of \(\delta_{13}\) for both 3\(\nu\) and 4\(\nu\) case. RH-RO solutions exclude \(0^\circ\) to \(155^\circ\) of \(\delta_{13}\) for 3\(\nu\) case, while \(20^\circ\) to \(100^\circ\) of \(\delta_{13}\) is excluded for 4\(\nu\) case. In third plot, we see that 4\(\nu\) case extends RH-RO to whole range of \(\delta_{13}\) while 30\(^\circ\) to 140\(^\circ\) of \(\delta_{13}\) were excluded for 3\(\nu\) case. We can see that DUNE clearly has better precision than NO\(\nu A\) experiment. In the second row, we show allowed regions for DUNE[1+1]. We see the WH solutions are resolved for both 3\(\nu\) and 4\(\nu\) cases.
Figure 4: Contour plots of allowed regions in the test plane $\theta_{23}$ vs $\delta_{13}$ at 99% C.L with top, middle and bottom rows for DUNE runs of $1 + \bar{0}$, $1 + \bar{1}$ years and DUNE[$1 + \bar{1}$]+NOvA[$3 + \bar{3}$] respectively.

for all the best-fit values. In the first plot, $4\nu$ case introduces RH-WO solution of similar size as RH-RO region of $3\nu$ case. In the second plot, there is no considerable change in $4\nu$, compared to $3\nu$ case for RH-RO region, while RH-WO octant is approximately doubled for $4\nu$ case compared to $3\nu$ case. In the third plot, $4\nu$ case introduces small region of RH-WO which covers $-45^\circ$ to $-170^\circ$ of $\delta_{13}$. In third row, we combine statistics of DUNE[$1+\bar{1}$] and
NOνA[3+3]. There is a small improvement in precision from the combined result over the result from DUNE[1+1] alone. In the first plot, we see a small RH-WO region is introduced by 4ν case. In the second plot, there is no considerable change between 3ν and 4ν case for RH-RO region, while RH-WO octant almost doubles over 3ν case for 4ν case. In the third plot, 4ν case introduces small region of RH-WO which covers $-35^\circ$ to $-160^\circ$ of $\delta_{13}$.

Figure 5: Contour plots of allowed regions in the test plane $\theta_{23}$ vs $\delta_{13}$ at 99% C.L with top and bottom rows for DUNE[5+5] and NOνA[3+3] + DUNE[5+5] respectively.

In the next figure 5, we show allowed parameter regions for DUNE experiment, at 99% C.L for DUNE[5+5]. We see that WH regions completely disappear for all the true value assumptions. In the first plot, RH-RO region covers a small $\delta_{13}$ range for both 3ν and 4ν case indicating high precision measurement capacity of DUNE. We see that $\delta_{13}$ range for 4ν case is approximately doubled as compared to the 3ν case. A small region of RH-WO is observed for 4ν case. In the second plot, RH-RO region covers small $\delta_{13}$ range of equal area for both 3ν and 4ν case. A small region of RH-WO is observed for 4ν case. In the third plot, the RH-WO solution is resolved. There is an increase in precision due to an increase in statistics. DUNE[5+5] clearly has a better precision compared to the NOνA[3+3] experiment. In the
second row, we combine full run of NO\textsubscript{\(\nu\)A} and DUNE to check their degeneracy resolution capacity. The WH solutions are resolved for both 3\(\nu\) and 4\(\nu\) cases for all the best-fit values. In the first plot, RH-WO solution is almost resolved for 4\(\nu\) case. In the second plot, RH-RO region covers small \(\delta_{13}\) range of equal area for both 3\(\nu\) and 4\(\nu\) case. A small region of RH-WO is observed for 4\(\nu\) case. We observe a slight improvement in degeneracy resolution, on consideration of combined statistics of full run DUNE and NO\textsubscript{\(\nu\)A}, over DUNE[5+\,\bar{5}].

5 Conclusions

We have discussed how the presence of a sterile neutrino will affect, the physics potential of the proposed experiment DUNE and future runs of NO\textsubscript{\(\nu\)A}, in the light of latest NO\textsubscript{\(\nu\)A} results [24]. The best-fit parameters reported by NO\textsubscript{\(\nu\)A} still contain degenerate solutions. We attempt to see the extent to which these degeneracies could be resolved in future runs for the 3+1 model. Latest NO\textsubscript{\(\nu\)A} best-fit values are taken as our true values. First, we show the degeneracy resolution capacity, for future runs of NO\textsubscript{\(\nu\)A}. We conclude that NO\textsubscript{\(\nu\)A}[3+\,\bar{3}] could resolve WH-WO solutions for first two true value cases, at 90% C.L for 3\(\nu\) case, but not for 4\(\nu\) case. DUNE[1+\,\bar{1}] could resolve WH and RH-W\(\delta_{cp}\) solutions for both 3\(\nu\) and 4\(\nu\) case. WO degeneracy is resolved for 3\(\nu\) case at 99% C.L except for small RH-WO region for the second case of true values. DUNE[1+\,\bar{1}] combined with NO\textsubscript{\(\nu\)A}[3+\,\bar{3}] shows increased sensitivity towards degeneracy resolution. Finally, for the full planned run of DUNE[5+\,\bar{5}], all the degeneracies are resolved at 99% C.L for 3\(\nu\) case while a tiny region of WO linger on for 4\(\nu\) case. For combined statistics of DUNE[5+\,\bar{5}] and NO\textsubscript{\(\nu\)A}[3+\,\bar{3}], we observe that all the degeneracies are resolved at 99% C.L for both 3\(\nu\) and 4\(\nu\) case except for the NH-LO case. Thus, we conclude that NO\textsubscript{\(\nu\)A} and DUNE experiments together can resolve all the degeneracies at 99% C.L even in the presence of sterile neutrino, if one of the current best-fit values of NO\textsubscript{\(\nu\)A}, is the true value.

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