Implications of the latest NOνA results

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We discuss the implications of the latest NOνA results on the measurement of νe - νx conversions. From a combined analysis of the disappearance and appearance data, the preferred solutions reported by NOνA are normal hierarchy (NH) with two degenerate best-fit points one in the lower octant (LO) and another in the higher octant (HO) with δCP = 0.74π. There is also another solution with inverted hierarchy (IH) which is 0.46σ away from the best-fit. We discuss and quantify the possibility of resolving these degeneracies by inclusion of NOνA antineutrino runs. We show that if the true solution corresponds to (NH, LO, δCP ≈ 0) then future data from NOνA comprising of 3 years of neutrino and 3 years of antineutrino run will be able to resolve the degenerate solutions at 95.45% C.L. However, if the true solution corresponds to (NH, HO, δCP ≈ 0.74π), a wrong hierarchy-wrong δCP solution remains unresolved even at 68% C.L. with the full 3ν + 3ν̄ projected run of NOνA. Same is the case if the IH solution turns out to be the true solution. We further show that DUNE (10 kton) will be able to resolve these degenerate solutions at 99.73% C.L. with only 1 year of neutrino and one year of antineutrino run [1+1] while 5+5 years of DUNE data can resolve the degeneracies at 99.99% C.L.

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I. INTRODUCTION

Neutrino oscillation physics is standing at a very interesting juncture, awaiting the determination of the three remaining unknown parameters – the neutrino mass hierarchy, octant of the 2-3 mixing angle and the CP phase δCP. Neutrino oscillation implies that the flavour states (νe, νμ, ντ) of the neutrinos are not the same as the mass states (ν1, ν2, ν3). Depending on the relative ordering of the third mass eigenstate there can be two possible mass orderings or hierarchies. If m3 > m2 > m1 we call it normal hierarchy (NH) whereas m3 < m1 ≈ m2 is termed as inverted hierarchy (IH). If the mixing angle θ23 is not exactly π/4 then there can be two options: θ23 < π/4 known as the lower octant (LO) or it is > π/4 called the higher octant (HO). For the CP phase δCP the best-fit comes close to 270o while at 3σ the whole range from 0 – 2π remains allowed from global oscillation analysis [1, 2]. These analyses have not yet included the recent NOνA results reported in [3]. The other oscillation parameters, namely, the two mass squared differences (∆m21 = m2 − m12, |∆m23| = |m3 − m2|), the two leptonic mixing angles (θ12, θ13) have been determined with a good precision by the global analysis of data from oscillation experiments [1, 2]. At present the focus is on the currently running beam based, off-axis, experiments T2K and NOνA which have declared their initial results on measurement of δCP [3–6]. These experiments, in conjunction with the reactor measurement of the 1-3 mixing angle θ13 [7–9], are expected to shed light on the above unknown parameters and provide the direction for future experiments.

The major problem, in the accurate determination of the above unknowns, in long-baseline experiments is the parameter degeneracies [10–16]. For recent studies see e.g. [17–30]. Recently, it was shown that if we classify the solutions in terms of the three unknown parameters hierarchy, octant and δCP then there can be a total of eight degenerate solutions involving wrong hierarchy and/or wrong octant and/or wrong δCP [31]1. This can be best studied in terms of a generalized hierarchy-θ23 – δCP degeneracy, presented as contours in θ23 – δCP plane [31]. Which of these degeneracies actually exists depends on the baseline of the experiment and the true parameter values.

The most recent NOνA analysis, incorporating both appearance and disappearance channel data in neutrino mode, shows that there are two best-fit points occurring for normal hierarchy [3]. These are (i) sin2 θ23 = 0.404, δCP = 1.48π = 266.4o and (ii) sin2 θ23 = 0.623, δCP = 0.74π = 133.2o. The two solutions correspond to the degeneracy in neutrino probability between opposite octants due to different values of δCP. One of them could be the true solution whereas the other corresponds to a degenerate solution with wrong-octant and wrong-δCP. NOνA also reports a solution with IH, HO and δCP = 270o which is only 0.46σ away from the best-fit. This corresponds to the wrong-hierarchy solution with wrong octant and right δCP for (i) and wrong-hierarchy right-octant and wrong δCP solution with respect to (ii). Inverted hierarchy with θ23 belonging to lower octant is disfavoured at greater than 90% C.L. irrespective of the value of δCP. The

1 Note that these solutions are somewhat different from the original eightfold degeneracy discussed in [10]. Specifically the intrinsic θ13 – δCP degeneracy [12] which is a part of the eightfold degeneracy is now resolved.
T2K results on the measurement of $\delta_{CP}$ on the other hand gave a hint of $\delta_{CP} \sim 270^\circ$ from neutrino data [4]. Recently T2K has published their results for search of CP violation using both neutrino and antineutrino runs and including appearance and disappearance channel data [6]. The best-fit obtained is for NH at $\delta_{CP} = 1.43\pi = 258^\circ$. It has been argued in [31], based on the degeneracies in the probabilities and a simulation of T2K data with its projected full power, that a hint of $\delta_{CP} \sim 270^\circ$ in neutrino channel will imply the hierarchy to be NH and octant to be HO while such an indication for the antineutrino channel will imply the octant to be LO. Thus an unambiguous hint for $\delta_{CP} = 270^\circ$ in both neutrino and antineutrino channel will signify the mixing angle $\theta_{23}$ to be maximal. T2K has indicated that $\delta_{CP} \sim 270^\circ$ in both neutrino and antineutrino mode and the $\theta_{23}$ from analysis of T2K data indeed comes out to be $45^\circ$ [2]. Thus there is some mismatch between the T2K and NO\text{\tiny{ν}}A results and more data may be able to resolve these issues.

In this paper, we study the implications of the latest NO\text{\tiny{ν}}A results and to what extent the different degenerate solutions can be resolved by future runs of NO\text{\tiny{ν}}A. The projected runtime of NO\text{\tiny{ν}}A is 3 years in neutrinos and 3 years in antineutrinos. After declaring the results with one year neutrino run NO\text{\tiny{ν}}A is currently running in the antineutrino mode. It is well studied that the addition of antineutrino runs can resolve the wrong octant solutions [31–34] and can give rise to an improved precision in $\delta_{CP}$. In view of this we discuss if it is profitable for NO\text{\tiny{ν}}A to continue with the antineutrino runs for three years or they should switch over to neutrino run after one year of antineutrino run. We also investigate how the next generation experiment DUNE at Fermilab can further improve the prospect of resolution of these degeneracies.

The plan of the paper is as follows – in section (II) we present the experimental specifications that have been used in our numerical simulation. In the next section (III), we demonstrate the probabilities for the NO\text{\tiny{ν}}A and the DUNE baselines and show the occurrence of degeneracies at the probability level. We also show the fate of the degenerate solutions for different run times of NO\text{\tiny{ν}}A assuming each of the three solutions – NH-LO, NH-HO and IH-HO as the true solutions, in section (IV). Finally, in section (V) we present the results combining DUNE with NO\text{\tiny{ν}}A and estimate at what significance the degeneracies can be removed. We summarize our findings in section (VI).

### II. SPECIFICATIONS OF THE EXPERIMENT

In the numerical simulations of the NO\text{\tiny{ν}}A (NuMI Off-Axis $\nu_e$-Appearance, Fermilab) and DUNE (Deep Underground Neutrino Experiment) data, we use the GLoBES package [35, 36] along with the required auxiliary files [37, 38]. The NO\text{\tiny{ν}}A experiment sends muon neutrino beams through two detectors – one the near detector (at Fermilab) and the far detector (northern Minnesota). The far detector is placed 810 km away from the source by making an off-axis angle of $0.8^\circ$. The detector is a totally active scintillator detector (T ASD) with a volume of 14 kton. NO\text{\tiny{ν}}A has planned to reach 700 kW beam power which corresponds to $6 \times 10^{20}$ POT (proton on target) per year. The current reach is 560 kW. The experiment will run for ($3 + 3$) years ($\nu + \bar{\nu}$). In our simulation of NO\text{\tiny{ν}}A data, we consider the reoptimized NO\text{\tiny{ν}}A setup up from Refs.[39, 40]. For the numerical analysis of DUNE data, we consider 10 kton far detector mass which will be 1300 km away on-axis from the neutrino source and is planned to be placed at the Sanford Lab in South Dakota. The source of this project is also based on the NuMI beam at Fermilab. The beam flux will be peaked at 2.5 GeV. The current plan of DUNE collaboration is to have an initial beam of 1.2 MW which will be upgraded to 2.3 MW [41]. In this analysis, we use neutrino flux from [42] corresponding to 1.2 MW beam power and 120 GeV proton energy which will produce $10^{21}$ POT per year. Systematic errors are taken into account using the method of pulls [43, 44] as outlined in Ref.[45]. We have added a 5% prior on sin$^22\theta_{13}$.

The values of the oscillation parameters used in our numerical simulation are given in tab. I.

### III. PROBABILITY LEVEL DISCUSSION

The relevant expressions for the oscillation and survival probabilities in matter of constant density (a good approximation for the baselines concerned) are as follows [46–48]:

\[
P_{\mu e} = \alpha^2 \sin^2 2\theta_{12}^c \sin^2 \frac{\Delta}{2} + 4s_{13}^2 s_{23}^2 \sin^2 \left(\frac{\hat{A} - 1}{2}\right) A
\]

\[
+ 2\alpha s_{13} \sin \theta_{12} \sin \theta_{23} \times \cos (\Delta + \delta_{CP}) \sin \frac{\hat{A}}{2} \sin \left(\frac{\hat{A} - 1}{2}\right) A
\]

\[
\times \sin \left(\Delta + \delta_{CP}\right) \sin \left(\frac{\hat{A} - 1}{2}\right) A
\]

\[
P_{\mu \mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + O(\alpha, s_{13})
\]

\[
\text{Osc. param.} & \quad \text{True Values} & \quad \text{Test Values} \\
\hline
\sin^2 2\theta_{13} & 0.085 & 0.075 - 0.095 \\
\sin^2 \theta_{12} & 0.306 & \text{Fixed} \\
\sin^2 \theta_{23} & \text{LO=0.40, HO=0.62} & 0.22 - 0.70 \\
\Delta_{21} (\text{eV}^2) & 7.50 \times 10^{-5} & \text{Fixed} \\
\Delta m^2_{31} (\text{eV}^2) & 2.40 \times 10^{-3} & (2.30 - 2.70) \times 10^{-3} \\
\delta_{CP} & 135^\circ, 270^\circ & 0^\circ - 360^\circ
\]
where, $s_{ij}(c_{ij}) = \sin \theta_{ij} (\cos \theta_{ij})$ for $j > i$ ($i,j = 1,2,3$), 
$\Delta = \Delta m_{31}^2 L/4E$ , and $\hat{A} = A/\Delta m_{31}^2$, with $A = 2EV = 0.76 \times 10^{-4} \mu (\frac{q}{\text{GeV}}) \times E(\text{GeV})$, being the Wolfenstein matter term. 
The antineutrino oscillation probability can be obtained by replacing $\delta_{\text{CP}} \rightarrow -\delta_{\text{CP}}$ and $V \rightarrow -V$. As we have discussed earlier, $\Delta m_{31}^2 > 0$ for NH and $\Delta m_{31}^2 < 0$ for IH. The matter term $\hat{A}$ is positive for the neutrinos and negative for the antineutrinos. Therefore, in the case of the neutrino, $\hat{A} > 0$ for NH and $\hat{A} < 0$ for IH whereas reverse is true for the antineutrinos.

In figure 1 we discuss the oscillation probability $P_{\mu e}$ vs energy for the three different sets of hierarchy, octant and $\delta_{\text{CP}}$. The top (bottom) panels are for NOvA (DUNE) baseline whereas the left (right) panel represents the neutrino (antineutrino) probability. The pink-solid, blue-dotted and orange-dash dotted curves are for $270^\circ$-NH-LO, $135^\circ$-NH-HO and $270^\circ$-IH-HO respectively. The values of $\sin^2 \theta_{23}$ for LO and HO correspond to 0.40 and 0.62 respectively. We consider these values because the current combined analysis of NOvA $\nu_{e}$-appearance and $\nu_{\mu}$-disappearance data favors these values of $\theta_{23}$ and $\delta_{\text{CP}}$ close to these points [3]. We notice from the left panel that for the neutrinos, at energy around $E \sim 2$ GeV, for which the flux peaks for NOvA, all the three curves exhibit a degeneracy. However, whereas the two NH probabilities are almost the same over the whole energy range, the IH probability differs from these, specially for energies $< 2$ GeV. On the other hand, as can be seen from the right panel, for the antineutrinos, the LO curve is well separated from the two HO curves over most of the energy range. This signifies that if the true point is $270^\circ$-NH-LO then addition of antineutrino information can differentiate between the degenerates points with opposite octants clearly.

In the bottom panels, we present the probabilities for DUNE. For this case, due to enhanced matter effect the neutrino probabilities are higher, but still there exists degeneracy between $270^\circ$-NH-LO and $135^\circ$-NH-HO whereas $270^\circ$-IH-HO differs from these over a larger energy range. However, for the antineutrinos, all the three cases are seen to be well separated. Thus, addition of DUNE antineutrino run is expected to resolve the wrong octant and wrong hierarchy solutions efficiently.

**IV. RESULTS FOR NOvA**

In this section we present the allowed areas in the test $\sin^2 \theta_{23} - \delta_{\text{CP}}$ plane from simulation of NOvA data with different run times and identify the wrong solutions $^3$

In figure 2, in the first row we present the allowed areas with NOvA $[1+0]$ which corresponds to running in neutrino mode for one year with a total pot of $6 \times 10^{20}$. The first plot

$^3$ In this section and throughout the paper we have used the following abbreviations — WH(RH) $\equiv$ wrong(right) hierarchy , WO(RO) $\equiv$ wrong(right) octant $W\delta_{\text{CP}}(R\delta_{\text{CP}}) \equiv$ wrong(right) $\delta_{\text{CP}}$. 

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**FIG. 1:** The oscillation probability $P_{\mu e}$ as a function of energy. Here, we consider $\sin^2 \theta_{23} = 0.4(0.62)$ for LO (HO). The top (bottom) panel is for NOvA (DUNE). The left panel is for neutrinos, while the right panel is for antineutrinos.
is assuming the true values to be $\delta_{CP} = 270^\circ$, $\sin^2 \theta_{23} = 0.4$ and NH as both true and test hierarchy. In this case, the WO solution is present even at 68% C.L. However, the maximal mixing solution is seen to be disfavoured at 90% C.L. It also shows that at 90% C.L. the full range of $\delta_{CP}$ remains allowed. The second plot inconstellation the first row is for the true value $\delta_{CP} = 135^\circ$, $\sin^2 \theta_{23} = 0.62$ around the best-fit point reported by NO$\nu$A [3] and for NH. This plot also shows the presence of wrong octant solutions even at 68% C.L. The $\theta_{23}$ precision is also worse as compared to the earlier case and even maximal mixing is seen to be allowed for some of the values of $\delta_{CP}$. The CP precision is also worse and even at 68% C.L. the full range of $\delta_{CP}$ remains allowed for the true solution. In the third plot, we consider true and test hierarchy as IH and the true values as $\delta_{CP} = 270^\circ$, $\sin^2 \theta_{23} = 0.62$ for which NO$\nu$A reported a local minima [3]. We consider this case as well in our study since it’s within $1\sigma$ of the best-fit solutions. We see that in this case the LO solutions with $0 < \delta_{CP} < 180^\circ$ gets disfavoured at 90% C.L. Note that to obtain these plots we have not fitted the NO$\nu$A data, but assumed that the parameters for which NO$\nu$A gets global or local minimum are the true values and have performed our analysis with the simulated data of one year of neutrino run.

In the bottom row of figure 2 we show the allowed areas corresponding to 1 year neutrino and 1 year antineutrino run of NO$\nu$A. For this analysis also we take the true values as the best-fit points obtained by NO$\nu$A as above. The first plot shows that the WO solution is resolved at 68% C.L. with addition of one year of antineutrino data. At 90% C.L. the WO solutions with CP values near 90$^\circ$ are largely resolved but wrong octant solutions close to $\delta_{CP} = 270^\circ$ remain allowed. The range of $\delta_{CP}$ for the true solution also gets restricted. The wrong octant solution is also seen to be almost resolved at 68% C.L. for the middle plot in the 2nd row. But at 90% C.L. WO solutions can still be there. However, the maximal mixing solution gets disfavoured. For the true solution, at 90% C.L., the full range of $\delta_{CP}$ remains allowed. But the range of $\delta_{CP}$ in the wrong octant gets more restricted. The third plot is for IH and for this case also the wrong octant solution gets resolved at 68% C.L. and only a small region with WO-$\delta_{CP}$ remains allowed at 90% C.L. The range of both $\theta_{23}$ and $\delta_{CP}$ gets more constricted around the true value, though the full range $0 - 360^\circ$ still remains allowed for $\delta_{CP}$.

We next ask the question, given the scenario described above after one year of neutrino run and one year of antineutrino run, should NO$\nu$A continue running in the antineutrino mode or switch to neutrino mode again.

To assess this, in the first row of figure 3 we show the plots for 3+1 (i.e 3 years of neutrino and 1 year of antineutrino run) case whereas in the 2nd row we demonstrate the allowed area for the 1+3 (i.e 1 year of neutrinos and 3 years of antineutrino run) case. In these figures (and all subsequent figures) we also explore the occurrence of the wrong hierarchy solutions by giving the contours for wrong hierarchy in the same plot unlike the figure 2. The first plot in the top row is for the true value in the LO and $\delta_{CP} = 270^\circ$. It shows that for 3+1 years of NO$\nu$A run the WO solution gets largely reduced at 90% C.L. The precision of the true solution is also increased. For this case, no wrong hierarchy solution appears at 90% C.L. However, if the runtime is 1+3 years then the wrong octant solution is resolved at 90% C.L. though the precision around the true solution is better for the previous case due to more statistics.

The middle column is for $\delta_{CP} \sim 135^\circ$ and HO with true hierarchy as NH. The first row (3+1 case) shows the presence of WH-RO-$\delta_{CP}$ solutions (magenta contours) even at 68%
C.L. A small region corresponding to RH-WO solution is also seen to be present at 90% C.L. The 2nd row shows the contours for the 1+3 case. In this case, a small RH-WO region as well as a small WH-WO region is seen to be present at 90% C.L.

The last column is for true hierarchy IH, $\delta_{CP} = 270^\circ$ and $\sin^2 \theta_{23} = 0.62$. In this case also, for 3+1 scenario the WH-RO-$\delta_{CP}$ solutions are visible even at 68% C.L. A very small region with wrong octant also remains allowed at 90% C.L. For the 1+3 case (2nd row) the WO solutions are resolved at 90% C.L. The last column is for true hierarchy IH, $\delta_{CP} = 270^\circ$ and $\sin^2 \theta_{23} = 0.62$. In this case also, for 3+1 scenario the WH-RO-$\delta_{CP}$ solutions are visible even at 68% C.L. A very small region with wrong octant also remains allowed at 90% C.L. For the 1+3 case (2nd row) the WO solutions are resolved at 90% C.L. The last row is for the 3+3 case which is the projected run plan of NO$\nu$A. For this case we present the contours at 90% and 99.73% C.L. From the first plot in the last row we see that the WO-RH solution is resolved at 90% C.L. but appears at 99.73% C.L. In addition a WH-RO-$\delta_{CP}$ solution (magenta dash-dotted contour) is also seen at 99.73% C.L. In the middle panel of the last row the WH-W-$\delta_{CP}$-RO solutions can be seen at 90% C.L. In addition, WH-WO-W-$\delta_{CP}$ as well as WO-RH solution is seen at 99.73% C.L. Similar results can also be found for the third column for which true hierarchy is IH.

Thus we can conclude that 1+3 case will do relatively better for removing the WO solutions at 90% C.L. for all the three cases. However, for the solutions with true value in the HO, the WH-RO solutions remain unresolved. Even with 3+3 runtime also, the WH-RO-W-$\delta_{CP}$ solutions are not resolved for the two scenarios where the true value of $\theta_{23}$ is considered to be in the higher octant.

In view of this it is instructive to see to what extent the DUNE experiment will be able to resolve the degeneracies. This is addressed in the next section.

In figure (4), we plot the CP sensitivity for NO$\nu$A[3+3] as a function of test $\delta_{CP}$. The left most column is for true NH-LO. We notice from this plot that that if the true solution is NH-LO then NO$\nu$A[3+3] can rule out the NH-HO solution at 95.45% C.L. ($\chi^2 = 4$) whereas the range $156^\circ < \delta_{CP} < 315^\circ$ remains allowed at 99.73% C.L. If this is the true solution then the degeneracies are more prominent for the right value of
\(\delta_{CP}\). It is also seen that the IH-HO solution gets disfavoured at 99.73\% C.L. (\(\chi^2 = 9\)). The middle panel is for true NH-HO. In this case the IH-HO solution gives a degenerate minima near \(\delta_{CP} \sim 270^\circ\) but is disfavoured at 99.73\% C.L. for most of the \(\delta_{CP}\) values in the same half plane as the true \(\delta_{CP}\). The NH-LO solution is disfavoured at 99.73\% C.L. excepting for \(\delta_{CP}\) near the CP conserving values of 0 and \(\pi\). The third panel is for true IH-HO. In this case NH-HO gives degenerate minima with wrong \(\delta_{CP}\) values. The NH-LO solution, on the other hand, is disfavoured at 99.73\% C.L. for most of the \(\delta_{CP}\) values. Although the information content of figure (4) is similar to the panel 3 of figure 3, the former shows precisely with what C.L. the wrong solutions are disfavoured for all values of \(\delta_{CP}\).

V. RESULTS FOR NOVA+DUNE

In this section we discuss to what extent the DUNE experiment can resolve the degeneracies existing after NO\(\nu\)A 3+3 run. The first row of figure 5 demonstrates the results after 1 year of neutrino run of DUNE while the second row is for 1+1 years of (\(\nu + \bar{\nu}\)) run. The last row presents the results for 5+5 years (\(\nu + \bar{\nu}\)) run of DUNE. DUNE, being a high statistics experiment, we present the contours at 99.73\% (3\(\sigma\)) and 99.99\% (4\(\sigma\)) C.L. for all the panels.

The first plot shows the presence of RH-WO solution at 99.99\% C.L. with no wrong hierarchy solution as expected. The full range of \(\delta_{CP}\) remains allowed at this C.L. There is also a small WO-RH solution at 99.73\% C.L. The 1st plot in the middle row shows the same results with 1+1 year run of DUNE. For this case the WO-RH solution appears at 99.99\% C.L. around right \(\delta_{CP}\).

The middle column in this plot is for \(\delta_{CP} = 135^\circ\) and HO. In this case with the addition of 1 year of neutrino data from DUNE to NO\(\nu\)A [3+3], the WH-RO-W\(\delta_{CP}\) solution is seen to be resolved at 99.99\% C.L. However, a small WO solution remains at this C.L. around \(\delta_{CP} = 360^\circ\). The middle plot in the 2nd row shows that with 1+1 run of DUNE there are no WO and WH solutions at 99.73\% C.L. However, WH-RO-W\(\delta_{CP}\) and RH-WO solutions appear at 99.99\% C.L.

The last column represents true IH, HO and \(\delta_{CP} = 270^\circ\). For this case WH-RO and RH-WO solutions are seen at 99.73\% C.L. in the first row i.e for 1+0 run of DUNE. But with 1+1 these solutions appear at 99.99\% C.L. only.

The last row is for DUNE (5+5). One can see that for this case all the degenerate solutions are resolved by DUNE at 99.99\% C.L.

In figure 6 we show the allowed areas in the test \(\delta_{CP} - \sin^2 \theta_{23}\) plane for the second phase of DUNE with a volume of 40 kton. We can see that the precision improves considerably with enhanced statistics. Specially the demarcation between the CP conserving and CP violating values are seen to be much improved. The precision of \(\theta_{23}\) also shows significant improvement. In table (II) we compare the precision of \(\sin^2 \theta_{23}\) and \(\delta_{CP}\) around the best-fit values, for the two cases. The precision of these two parameters can be defined as:

\[
\text{Precision} = \frac{Max - Min}{(true \ value) \times 6} \times 100\%
\]  

(3)

It is seen that below 1\% precision in \(\sin^2 \theta_{23}\) and \(\lesssim 10\%\) precision in \(\delta_{CP}\) can be achieved by DUNE 40 kton volume for the true values considered.

| True pt. | \(\sin^2 \theta_{23}\) | \(\delta_{CP}\) |
|----------|-----------------|-----------------|
| 0.40-270-NH | 1.6 | 9 | 0.6 | 6 |
| 0.62-135-NH | 1 | 22 | 0.5 | 11 |
| 0.62-270-IH | 0.8 | 10 | 0.4 | 6 |

TABLE II: Precision table on \(\sin^2 \theta_{23}\) and \(\delta_{CP}\) for NO\(\nu\)A[3+3]+DUNE[5+5] with 10 kton and 40 kton detector mass of DUNE respectively.
FIG. 5: Same as figure 3 but top, middle and bottom row are for 1+0, 1+1 and 5+5 years of $(\nu + \bar{\nu})$ runs of DUNE respectively, combined with NOνA [3+3].

FIG. 6: The allowed areas in test $\Delta_{CP} - \sin^2 \theta_{23}$ plane for NOνA[3+3]+DUNE[5+5], using DUNE detector volume as 40 kton.

VI. CONCLUSIONS

We discuss the implications of the recent NOνA results for future runs of NOνA as well as for DUNE. The best-fit parameters reported in [3] point towards degenerate solutions. We explore to what extent these degeneracies can be resolved by tuning the neutrino and antineutrino run times of NOνA.

We consider the latest NOνA best-fit values as our true values. First we describe the effect of 1 year of antineutrino run of NOνA and find that the wrong octant solutions can be resolved at 68% C.L. for all the three choices of true values. Next we present the comparison of NOνA 1+3 ($\nu + \bar{\nu}$) and 3+1 case and find that 1+3 provides a better option for the removal of wrong-octant solutions. However, the wrong
hierarchy-wrong $\delta_{CP}$ solution remains present at 90% C.L. even after 3+3 year running of NO$\nu$A. DUNE[1+1] can resolve the degeneracies at 99.73% C.L. whereas DUNE[5+5] can resolve all the degeneracies at 99.99% C.L. In conclusion, if one of the current NO$\nu$A best-fit values in reference [3] is the true value, then the FERMILAB experiments NO$\nu$A and DUNE together will be able to solve all the degeneracies at 99.73% C.L. The second phase of DUNE with a volume of 40 kton can further improve the precision of the allowed regions.

VII. ACKNOWLEDGEMENT

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