A comprehensive study of the discovery potential of NO\(\nu\)A, T2K and T2HK experiments and the effect of cross-section uncertainty

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Abstract

With the recent measurement of reactor mixing angle \(\theta_{13}\) the knowledge of neutrino oscillation parameters that describe PMNS matrix has improved significantly except the CP violating phase \(\delta_{CP}\). The other unknown parameters in neutrino oscillation studies are mass hierarchy and the octant of the atmospheric mixing angle \(\theta_{23}\). Many dedicated experiments are proposed to determine these parameters which may take at least 10 years from now to become operational. It is therefore very crucial to use the results from the existing experiments to see whether we can get even partial answer to these questions. In this paper we study the discovery potential of the ongoing NO\(\nu\)A and T2K experiments and as well as the forthcoming T2HK experiment in addressing these questions. In particular, we evaluate the sensitivity of NO\(\nu\)A to determine neutrino mass hierarchy, octant degeneracy and to obtain CP violation phase after running for its scheduled period of 3 years in neutrino mode and 3 years in anti-neutrino mode. We then extend the analysis to understand the discovery potential if the experiment will run for \((5\nu+5\bar{\nu})\) years and \((7\nu+3\bar{\nu})\) years. We also show how the sensitivity improves when we combine the data from \((3\nu+3\bar{\nu})\) years of NO\(\nu\)A run with \((3\nu+2\bar{\nu})\) years of T2K and \((3\nu+7\bar{\nu})\) years of T2HK experiments. We also study the quantitative connection between uncertainties in the \(\nu N\) and \(\bar{\nu} N\) cross-sections and the resulting induced error in the sensitivities of NO\(\nu\)A, T2K and T2HK experiments for their scheduled runs.

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I. INTRODUCTION

The discovery of neutrino oscillations has firmly established that neutrinos are massive. It has marked the beginning of many neutrino oscillation experiments. The mixing of three neutrino flavors can be described by Pontecorvo-Maki-Nakagawa-Sakata matrix $U_{PMNS}$ which is parameterized in terms of three rotation angles $\theta_{12}, \theta_{23}, \theta_{13}$ and three CP-violating phases, one Dirac type $\delta_{CP}$ and two Majorana types $\rho$ and $\sigma$. The neutrino oscillation data accumulated over many years allows us to determine the solar and atmospheric neutrino oscillation parameters with very high precision. Recently, the reactor mixing angle $\theta_{13}$ has been measured precisely [3–7] with a moderately large value, quite close to its previous upper bound.

The current results from recent neutrino oscillation experiments [8–11] and their global analysis [12–15] performed by several groups have implied that the minimal three neutrino framework is adequate to describe the observed oscillation phenomenology. The best-fit values and the $3\sigma$ ranges of the oscillation parameters from Ref. [15], are presented in Table-1.

Another important discovery in recent times is the precision measurement of $\sin^2 \theta_{23}$ by MINOS experiment [16] which is found to be non-maximal. Using the complete set of accelerator and atmospheric data they disfavored the maximal mixing by $-2\Delta \log(\mathcal{L}) = 1.54$. They obtained the best-fit value for the mixing angle $\theta_{23}$ as $\sin^2 \theta_{23} = 0.41$ (LO) and $\sin^2 \theta_{23} = 0.61$ (HO).

With these exciting discoveries of non-zero $\theta_{13}$ and non-maximal $\theta_{23}$ the focus of neutrino oscillation studies has now been shifted towards the determination of other unknown parameters. These include the determination of mass hierarchy, octant of the atmospheric mixing angle $\theta_{23}$, discovery of CP violation and the magnitude of the CP violating phase $\delta_{CP}$. In this paper we would like to investigate the prospects of addressing these issues with the off-axis long baseline experiments T2K, NO$\nu$A and T2HK.

The increasing number of long baseline neutrino oscillation experiments have intensified the quest for good theoretical models and precise experimental measurements of neutrino-nucleus cross-sections. These oscillation experiments aim at measuring various neutrino mixing angles and most importantly determining CP-violation. From Eq. (1) it can be seen that to obtain the oscillation probabilities it is crucial to precisely reconstruct the
neutrino energy $E_\nu$. This in turn demands the requirement of well motivated theory and accurate measurements on neutrino-nucleus cross-sections. So far many experiments have measured the total cross-sections for neutrino $\nu_\mu N \rightarrow \mu^- X$ and anti-neutrino $\bar{\nu}_\mu N \rightarrow \mu^+ X$ scattering off nucleons [17] covering a wide range of energies. The knowledge of cross-section values for energies between 0.5 GeV to 4 GeV, which covers the range for NO$\nu$A, T2K and T2HK experiments, is limited (with an error of about 10%). Without considering a specific theoretical model, the errors on cross-sections are in the range of 20-50% [18].

Thus, it is crucial to understand the role of this cross-section uncertainty in determination of CP violation for the above experiments. We do not emphasize on the actual size of these errors or the exact values of the resultant $\chi^2$, but on the relative effect of these errors on the determination of CP-violation in all these three experiments for various combinations of run periods.

NO$\nu$A [19] is an off-axis long baseline neutrino oscillation experiment designed to study $\nu_\mu \rightarrow \nu_e$ appearance measurements using Fermilab NuMI muon neutrino beam ($\nu_\mu$). Its

| Mixing Parameters | Best Fit value | 3$\sigma$ Range |
|-------------------|---------------|-----------------|
| $\sin^2 \theta_{12}$ | 0.323         | $0.278 \rightarrow 0.375$ |
| $\sin^2 \theta_{23}$ (NH) | 0.567         | $0.392 \rightarrow 0.643$ |
| $\sin^2 \theta_{23}$ (IH) | 0.573         | $0.403 \rightarrow 0.640$ |
| $\sin^2 \theta_{13}$ (NH) | 0.0234        | $0.0177 \rightarrow 0.0294$ |
| $\sin^2 \theta_{13}$ (IH) | 0.0240        | $0.0183 \rightarrow 0.0297$ |
| $\Delta m_{21}^2/10^{-5}$eV$^2$ | 7.6           | $7.11 \rightarrow 8.18$ |
| $|\Delta m_{31}|^2/10^{-3}$eV$^2$(NH) | 2.48          | $2.30 \rightarrow 2.65$ |
| $|\Delta m_{31}|^2/10^{-3}$eV$^2$(IH) | 2.38          | $2.20 \rightarrow 2.54$ |

TABLE I: The best-fit values and the 3$\sigma$ ranges of the neutrino oscillation parameters from Ref. [15].
secondary aim is to precisely measure $\nu_\mu$ disappearance parameters. It uses a high intensity proton beam with a beam power of 0.7 MW with $6 \times 10^{20}$ POT/year. Its detector is a 14 kt totally active liquid scintillator detector (TASD) located at Ash River, 810 km from Fermilab. The detector is located slightly off the centerline (14 mrad) to the neutrino beam where one can find a large flux of neutrinos of 2 GeV energy. The oscillation from $\nu_\mu \rightarrow \nu_e$ is expected to be maximum at this energy. It is scheduled to run 3 years in $\nu$ mode followed by 3 years in $\bar{\nu}$ mode. The detector properties of NO$\nu$A considered in our simulations are taken from Ref. [20] with the following characteristics:

|                | 45% for $\nu_e$ and $\bar{\nu}_e$ signal |
|----------------|------------------------------------------|
|                | 100% $\nu_\mu$ CC and $\bar{\nu}_\mu$ CC |
| Bkg efficiency | 0.83% $\nu_\mu$ CC, 0.22% $\bar{\nu}_\mu$ CC |
|                | 2% $\nu_\mu$ NC, 3% $\bar{\nu}_\mu$ NC |
|                | 26% (18% )$\nu_e$ ($\bar{\nu}_e$) beam contamination |
| NC bkg smearing | migration matrices |
| Systematics    | 5% signal norm error |
|                | 10% bkg norm error |

T2K (Tokai-to-Kamiokande) is a current long baseline experiment designed to study neutrino oscillations. An intense $\nu_\mu$ beam of 0.77 MW power is directed from J-PARC to Super-Kamiokande detector, 295 km away. It has a 22.5 kt water cherenkov detector. The details of T2K experiment can be found from [22]. We have considered input files for T2K from GLoBES package [21–23].

T2HK (Tokai-to-Hyper-Kamiokande) is a future long baseline experiment which is expected to be operational in 2023. It can be considered as a natural extension to the ongoing T2K experiment. It has same baseline and off-axis angle as T2K experiment. It uses J-PARC’s neutrino experimental facilities with an upgraded beam power (7.5 MW) and 1 Mt volume water Cherenkov detector, Hyper-Kamiokande (Hyper-K). We have considered a fiducial volume of 0.56 Mt and beam power of 7.5 MW in the input files for T2HK obtained from GloBES package [21–23]. The primary objective of this experiment is the discovery of CP asymmetry.
Since these experiments use $\nu_\mu$ beam and also will run in antineutrino mode their main focus is to study the appearance ($\nu_\mu \rightarrow \nu_e$) and the disappearance channels ($\nu_\mu \rightarrow \nu_\mu$) along with their antineutrino counterparts. Since the leading term in the appearance channels $\nu_\mu \rightarrow \nu_e (P_{\mu e})$ and the corresponding antineutrino mode $\bar{\nu}_\mu \rightarrow \bar{\nu}_e (P_{\bar{\mu} \bar{e}})$ is proportional to $\sin^2 2\theta_{13} \sin^2 \theta_{23}$ and with the observation of moderately large value of $\theta_{13}$, these experiments are well-suited for the determination of mass hierarchy and the octant of $\theta_{23}$. Although, these ongoing NO$\nu$A and T2K experiments are not planned to measure $\delta_{CP}$ or to explore CP violation in the neutrino sector, we would like to investigate whether it is possible to constrain the $\delta_{CP}$ phase using the data from these two experiments. In other words, how much of the $\delta_{CP}$ space can be ruled out by these experiments within the next 10 years. In particular, we would like to investigate

- whether the combination of T2K (3+2) and NO$\nu$A (3+3) provide more quantitative answer on the above posed questions than each one of these experiments.
- how the sensitivity on $\delta_{CP}$, mass hierarchy and $\theta_{23}$ octant will improve if NO$\nu$A runs for 10 years in the (5+5) and (7+3) combination of modes.
- the sensitivities of T2HK experiment for its scheduled run of 3 years in neutrino mode and 7 years in anti-neutrino beam.
- the effect of the uncertainty in $\nu_\mu N \rightarrow \mu^- X$ and $\bar{\nu}_\mu N \rightarrow \mu^+ X$ cross-sections on the sensitivities of all these three experiments individually.

The paper is organized as follows. In section II we briefly describe the physics reach of these experiments. The prospect of octant resolution and mass hierarchy determination along with the effect of 10% error on cross-section uncertainty on their sensitivities are discussed in section III and IV. Section V contains the CP violation discovery potential, the effect of 10% error on cross-section uncertainty on CP violation discovery potential and the correlations between the CP violating phase $\delta_{CP}$ and the mixing angles $\theta_{13}$ and $\theta_{23}$. We summarize our results in Section VI.

II. PHYSICS REACH

As discussed before, the determination of the mass hierarchy, octant of the atmospheric mixing angle $\theta_{23}$ and the search for CP violation in the neutrino sector are the important physics goals of the current and future oscillation experiments. A simple way to achieve the
above three goals is to measure the oscillation probabilities $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. This can be seen from the expression for probability of oscillation from $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$, where we have kept terms only first order in $\sin \theta_{13}$ and $\alpha = \Delta_{21}/\Delta_{31}$ from Refs. [24-26],

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\hat{A} - 1)\Delta}{(\hat{A} - 1)^2} + \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \frac{\sin \hat{A} \Delta \sin(\hat{A} - 1)\Delta}{\hat{A} (\hat{A} - 1)} \cos(\Delta + \delta_{CP}), \quad (1)$$

where $\Delta_{ij} = m_i^2 - m_j^2$, $\Delta = \Delta_{31}L/4E$ and $\hat{A} = 2\sqrt{2}G_F n_e E/\Delta_{31}$. $G_F$ is the Fermi coupling constant and $n_e$ is the electron number density. The transition probability can be enhanced or suppressed depending on the oscillation parameters $\theta_{13}$, $\theta_{23}$, mass hierarchy, i.e., the sign of $\Delta_{31}$ and CP violation phase $\delta_{CP}$. Parameters $\alpha$, $\Delta$ and $\hat{A}$ are sensitive to neutrino mass ordering. For neutrinos, $\hat{A}$ is positive for NH and negative for IH, while its sign changes when we go from neutrino to anti-neutrino mode. Moreover, sign of $\delta_{CP}$ is reversed for anti-neutrinos.

It should be noted from Eq. (1) that the leading term in the transition probability $P(\nu_\mu \rightarrow \nu_e)$ is proportional to $\sin^2 2\theta_{13} \sin^2 \theta_{23}$. Therefore, the observed moderately large value of $\theta_{13}$ makes it possible for the current generation long baseline experiments to address the problems of hierarchy and the octant of $\theta_{23}$ determination. The second term in Eq. (1) shows the prominence of matter effect on the oscillation probability. The dependency of all the terms on a moderately large reactor neutrino mixing angle $\theta_{13}$ suggests that NO$\nu$A detector will be able to collect a good number of $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$ events.

Here we will try to see if the energy spectrum information will help us in resolving the octant degeneracy and mass hierarchy. We have used GLoBES package [27, 28] for the simulation through out this paper. We consider the following true values for oscillation parameters as provided in Table-II, unless mentioned otherwise.

Fig. 1, shows the energy spectrum of the appearance probabilities $P(\nu_\mu \rightarrow \nu_e)$ for neutrino (left panel) and $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ for antineutrino (right panel) for NO$\nu$A experiment, where we vary $\delta_{CP}$ within the range $-\pi$ to $\pi$. In each panel the red (blue) band is for NH (IH). Furthermore, in each band the probability for $\delta_{CP} = 90^\circ$ and $\delta_{CP} = -90^\circ$ cases are shown explicitly by the solid and dashed lines. Due to matter effect the probability $P_{\mu e}$ increases for NH and decreases for IH and vice versa for $P_{\mu \bar{e}}$. Thus, for $\delta_{CP}$ lying in the lower half plane (LHP) i.e., $-180^\circ \leq \delta_{CP} \leq 0$, $P_{\mu e}$ is larger and for $\delta_{CP}$ in the upper half plane (UHP)
\[
\begin{array}{|c|c|}
\hline
\text{sin}^2 \theta_{12} & 0.32 \\
\text{sin}^2 2\theta_{13} & 0.1 \\
\text{sin}^2 \theta_{23} & 0.41 \text{ (LO), 0.59 \text{ (HO)}} \\
\Delta m^2_{\text{atm}} & 2.4 \times 10^{-3} \text{ eV}^2 \text{ for NH} \\
 & -2.4 \times 10^{-3} \text{ eV}^2 \text{ for IH} \\
\Delta m^2_{21} & 7.6 \times 10^{-5} \text{ eV}^2 \\
\delta_{CP} & 0^\circ \\
\hline
\end{array}
\]

**TABLE II:** The true values of oscillation parameters considered in the simulations.

\((0 \leq \delta_{CP} \leq 180^\circ), P_{\mu e}\) is much lower. The situations reverse for the antineutrino probability \(P_{\bar{\mu}e}\). Thus, LHP is the favorable half-plane for NH and UHP is for IH for neutrino mode. However, the most unfavorable condition is (NH, \(\delta_{CP} = 90^\circ\)) and (IH, \(\delta_{CP} = -90^\circ\)) as the bands almost overlap with each other for the entire energy range. In the lower panels of Fig. 1, we show the energy spectrum of \(P_{\mu e}\) and \(P_{\bar{\mu}e}\) for two different values of \(\theta_{23}\) assuming NH to be true hierarchy. The blue band in both the panels is for \(\theta_{23}\) in the LO and red band is for \(\theta_{23}\) in the HO. As can be seen from the figures that the two bands overlap with each other for some values of \(\delta_{CP}\) and distinct for others. The overlap regions are the unfavorable ones for the determination of the \(\theta_{23}\) octant.

**III. OCTANT RESOLUTION AS A FUNCTION OF \(\theta_{23}\)**

In this section we present the results of our analysis on octant sensitivity of \(\theta_{23}\) for T2K, NO\(\nu\)A and T2HK experiments. We also show the results when the data from all the experiments are combined. Although the octant sensitivity of various long baseline experiments has been discussed extensively by many authors \([29-31]\), here we would like to revisit the octant resolution potential of NO\(\nu\)A for its scheduled (3+3) years of run. Furthermore, we also investigate the situation if it runs for next 10 years what would be the potential for resolving octant degeneracy for (5+5) as well as (7+3) years of running. We also see the synergy between T2K, NO\(\nu\)A and T2HK experiments for their scheduled runs.

The indistinguishability of \(\theta_{23}\) and \((\pi/2 - \theta_{23})\) is known as octant degeneracy. The
FIG. 1: $P_{\mu e}$ energy spectrum for NO$\nu$A experiment. The left (right) panel is for neutrino (antineutrino). The red (blue) band in the top panel corresponds to NH (IH), where we have used $\sin^2 \theta_{23} = 0.5$, $\sin^2 2\theta_{13} = 0.1$, baseline $L = 810$ km and vary $\delta_{CP}$ between $(-\pi$ to $\pi)$. The red (blue) band in the bottom panel is for HO (LO), where we have used $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and keep the hierarchy as normal. The other parameters are same as for the previous case. Inside each band the probability for $\delta_{CP} = 90^{\circ}$ ($-90^{\circ}$) case is shown by solid (dashed) line.

relevant oscillation probability expressions for long baseline experiments NO$\nu$A, T2K and T2HK with negligible matter effects are given as

$$P_{\mu\mu}^\nu = 1 - \sin^2 2\theta_{23} \sin^2 \left[ 1.27 \frac{\Delta m^2_{31} L}{E} \right] + 4 \sin^2 \theta_{13} \sin^2 \theta_{23} \cos 2\theta_{23} \sin^2 \left[ 1.27 \frac{\Delta m^2_{31} L}{E} \right], \quad (2)$$

$$P_{\mu e}^\nu = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left[ 1.27 \frac{\Delta m^2_{31} L}{E} \right]. \quad (3)$$

The leading order term in the $\nu_\mu$ survival probability ($P_{\mu\mu}^\nu$) depends on $\sin^2 2\theta_{23}$ and one cannot distinguish between $P_{\mu\mu}^\nu(\theta_{23})$ and $P_{\mu\mu}^\nu(\pi/2 - \theta_{23})$. This kind of degeneracy that comes from the inherent structure of neutrino oscillation probability is called intrinsic octant degeneracy. Where as in the case of $P_{\mu e}^\nu$ the degeneracy of the octant with the parameter $\theta_{13}$
comes into play, since it depends on the parameter combination $\sin^2 \theta_{23} \sin^2 2\theta_{13}$. The values of $\theta_{23}$ in opposite octant for different values of $\theta_{13}$ and $\delta_{CP}$ can have the same probabilities, i.e., $P_{\mu e}(\theta_{23}, \theta_{13}, \delta_{CP}) = P_{\mu e}(\pi/2 - \theta_{23}, \theta_{13}, \delta_{CP})$. This also gives rise to octant degeneracy.

Before presenting the main results we would like to discuss what we can expect on the determination of mass hierarchy and octant of $\theta_{23}$ from the bi-probability plots i.e., neutrino-antineutrino appearance event rates. Fig. 2 shows $\nu$ versus $\bar{\nu}$ events for all octant-hierarchy combinations. The blue curves are obtained by considering inverted hierarchy mass ordering, LO (HO) $\sin^2 \theta_{23} = 0.41$ (0.59) and the red curves are obtained by considering normal...
hierarchy mass ordering, LO (HO) \( \sin^2 \theta_{23} = 0.41 \) (0.59). These ellipses are plotted by obtaining event spectra for (3+3) yrs, (5+5) yrs, (7+3) yrs in \( \nu \) and \( \bar{\nu} \) mode for all values of \( \delta_{CP} \) for NO\(\nu\)A, T2K and (3+7) yrs for T2HK. Each point on \( x \)-axis (\( y \)-axis) represents number of events measured by the respective experiments in neutrino (anti-neutrino) mode. The top panel represents the ellipses for (3+2), (5+5) and (7+3) years of running in neutrino and antineutrino modes for T2K, the second panel represents the NO\(\nu\)A event rates for (3+3), (5+5) and (7+3) years of run period and the bottom panel represents the T2HK event rates for (3+7) years of run period. For T2K and T2HK experiments the ellipses of both normal as well as inverted mass orderings overlap with each other for both the octants whereas for NO\(\nu\)A the overlap region is less (marginal) for LO (HO). Thus, it is very likely that the mass hierarchy and octant degeneracy could be probed better with the NO\(\nu\)A experiment.

Before doing the simulation, here we would like to emphasize that the relation between atmospheric parameters \( (\Delta m^2_{\text{atm}}) \) and \( \theta_{\mu\mu} \), measured in MINOS, and the standard oscillation parameters in nature are given as \[ 32, 33 \]

\[
\sin \theta_{23} = \frac{\sin \theta_{\mu\mu}}{\cos \theta_{13}}, \tag{4}
\]

\[
\Delta m^2_{31} = \Delta m^2_{\text{atm}} + (\cos^2 \theta_{12} - \cos \delta_{CP} \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23})\Delta m^2_{21}. \tag{5}
\]

It is clear from the above relations that the observed value of moderately large \( \theta_{13} \) significantly affects the oscillation parameters. So here we use corrected definitions of these parameters to analyze octant sensitivity. We allocate measured values \( \Delta m^2_{\text{atm}} \) and \( \theta_{\mu\mu} \) and calculate oscillation probabilities in terms of \( \Delta m^2_{31} \) and \( \theta_{23} \).

We have chosen the true values of oscillation parameters given in Table-II. We have varied the test values of \( \sin^2 \theta_{23} \) in LO for true higher octant and HO for true lower octant. We have marginalized over \( \sin^2 2\theta_{13} \) in the range \([0.07 : 0.13]\), \( \delta_{CP} \) in its full range, \( \Delta m^2_{\text{atm}} \) in the range \([2.05 : 2.75] \times 10^{-3} \text{ eV}^2 \) for NH. The parameters \( \theta_{12} \) and \( \Delta m^2_{21} \) have been kept fixed in the analysis. We have added priors for \( \sin^2 2\theta_{13} \) and \( \sin^2 \theta_{23} \) with \( \sigma(\sin^2 2\theta_{13}) = 0.01 \) and \( \sigma(\sin^2 \theta_{23}) = 0.05 \).

We simulate the long baseline experiments T2K, NO\(\nu\)A, T2HK using the GLoBES package. For T2K we assume 3 years of running in neutrino mode and 2 years in antineutrino mode. For NO\(\nu\)A, we consider 3 years of neutrino running followed by 3 years of antineutrino running. We consider 3 years of neutrino running followed by 7 years of antineutrino...
running for T2HK. Furthermore, we also consider the case if NOνA continues the data taking for ten years beyond its scheduled (3+3) years and perform the analysis for two possible combinations (5+5) and (7+3) years of running.

In Fig. 3, we illustrate the ability of NOνA experiment to determine the octant as a function of the true value of $\theta_{23}$. The values of $\chi^2$ are evaluated using the standard rules as described in GLoBES. The green, red and blue curves (in the bottom panel) represent the octant resolution of (3 + 3) yrs, (5 + 5) yrs and (7 + 3) yrs of runs in $\nu$ and $\bar{\nu}$ modes respectively. From Fig. 3, it can be seen that with only T2K data of (3+2) years of run, it is possible to resolve the octant degeneracy with 2$\sigma$ significance if the true $\sin^2 \theta_{23}$ will lie around 0.41 (LO) or 0.59 (HO) and one can have a better sensitivity for NOνA experiment with (3+3) yrs of run period. The significance increases significantly if we combine the data from both T2K and NOνA as seen from the top panels. For ten years of NOνA run although we get a better sensitivity than that of (3+3) yrs of run, there is no significant difference between (5+5) yrs and (7+3) years of running.
FIG. 4: Octant resolution significance with 10% on the individual cross-sections of $\nu_\mu$ and $\nu_e$ for scheduled runs of T2K and NO$\nu$A experiments for NH (IH) in the left (right) panel.

We have studied the effect of cross-section uncertainty in the octant discovery potential of T2K and NO$\nu$A experiments by considering an optimistic error of 10% on the individual cross-sections of $\nu_\mu$ and $\nu_e$. In Fig. 4 shows a narrow band around the values of $\sin^2 \theta_{23}$ due to uncertainty in cross-section for T2K and NO$\nu$A experiments.

IV. MASS HIERARCHY DETERMINATION

Determination of neutrino mass hierarchy is one of the outstanding issues in neutrino oscillation physics. The conventional method to achieve this is by using matter effects in very long baseline neutrino oscillation experiments as the matter effects enhance the separation between oscillation spectra, and therefore the event spectra between the normal and inverted hierarchy. In this section we describe the capabilities of T2K, NO$\nu$A and T2HK experiments for the determination of mass hierarchy.
To obtain the $\chi^2$ as a function of true value of $\delta_{CP}$, we have kept true parameters as in Table-II except for $\sin^2 \theta_{23} = 0.5$ and varying the true value of $\delta_{CP}$ in its full range ($-\pi, \pi$). We have obtained the test values by varying $\Delta m^2_{atm}$ in the IH (NH) range for true NH (IH). We have marginalized over $\Delta m^2_{31}$, $\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$ in their $3\sigma$ ranges and added prior to $\sin^2 2\theta_{13}$ with $\sigma(\sin^2 2\theta_{13}) = 0.01$.

![Diagram](image)

**FIG. 5:** Mass hierarchy significance as a function of true $\delta_{CP}$. In the left panel Normal hierarchy is considered as true hierarchy and inverted is taken as test hierarchy and in the right panel Inverted hierarchy is considered as true hierarchy and normal is taken as test hierarchy.

In Fig. 5, we present the hierarchy determination sensitivity of T2K, NO$\nu$A and T2HK as a function of true value of $\delta_{CP}$. We assume NH (IH) to be the true hierarchy in the left (right) panel. It can be seen that the wrong hierarchy can be ruled out quite effectively in the LHP (UHP) for NH (IH), which is basically the favorable half plane and in the other half plane the mass hierarchy can’t be determined effectively for T2K and NO$\nu$A experiments. However, the the combined data from these two experiments (T2K(3+2) and NO$\nu$A(3+3)) improves the situation significantly and the sensitivity increases to more than 1$\sigma$ for all values of $\delta_{CP}$. The mass hierarchy significance has a $\delta_{CP}$ coverage of 75% for T2HK experiment alone and
90% for combined data of T2K, NOνA and T2HK experiments above 3σ.

To study the effect of cross-section uncertainty in the determination of mass hierarchy for the above experiments, we have assumed an optimistic error of 10% on the individual cross-sections of νμ and νe for NOνA and T2HK experiments. Fig. 6 shows that the significance of mass hierarchy is affected by uncertainty in the cross-sections of νμ and νe for (3ν+3¯ν) years run NOνA and (3ν+7¯ν) years T2HK experiments. We have seen that the cross-section uncertainty does not play a significant role in determination of mass hierarchy of T2K experiment. For NOνA experiment the induced error in the values of δCP for which significance is above 3σ, when the true hierarchy is NH(IH), is ∼ 7%(∼ 8%), where as for T2HK experiment (from the bottom panel) it is observed to be ∼ 14% (∼ 10%) for significance above 5σ.
V. CP VIOLATION DISCOVERY POTENTIAL

Accelerator based long baseline neutrino oscillation experiments can address CPV problem through the appearance channels of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. From Eq. (1) we can see that the CP violating effects of $\delta_{CP}$ are modified by all the three mixing angles and their combinations thus resulting in an eight fold parameter degeneracy. In order to obtain the significance of CP violation sensitivity we simulated the true event spectrum by keeping the true values of oscillation parameters as in Table-II except for $\sin^2 \theta_{23} = 0.5$ and varying the true value of $\delta_{CP}$ in the range $(-\pi, \pi)$ and compared those with test event spectrum for $\delta_{CP}=0$ or $\pi$ and thus obtained the minimum $\chi^2$. We have considered the sign degeneracy of $\Delta m^2_{31}$ by marginalizing over it, in both NH and IH $3\sigma$ ranges, $\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$ in their $3\sigma$ and added prior to $\sin^2 2\theta_{13}$.

![Graphs showing CP violation sensitivity for different combinations of run time of T2K, NO$\nu$A and T2HK experiment for NH(IH) in the left(right) panel.](image)

**FIG. 7:** CP violation sensitivity for different combinations of run time of T2K, NO$\nu$A and T2HK experiment for NH(IH) in the left(right) panel.

In Fig. 7, we plot the sensitivity to rule out the CP conserving scenarios, as a function of true $\delta_{CP}$ assuming NH as the true hierarchy. From the figure one can notice that T2K by itself has no CP violation sensitivity at $2\sigma$ C.L.. For NO$\nu$A with $(3+3)$ years of running there
will be CP violation sensitivity above $1.5\sigma$ level for about one-third of the CP violating phase $\delta_{CP}$ space. Furthermore, the synergistic combination of NO$\nu$A and T2K leads to much better CP violation sensitivity compared to the individual capabilities. Even the combination of NO$\nu$A (3+3) and T2K (3+2) has comparable sensitivity as for 10 years running of NO$\nu$A. Owing to the fact that main goal of T2HK experiment is to determine CP violation, we can observe that it has a significance of above $5\sigma$ C.L for a fraction of two-fifth values of the CP violating phase $\delta_{CP}$ space. This in turn boosts up the sensitivity when its data is added to NO$\nu$A (3+3) yrs and T2K (3+2) yrs. In the lower panel one can observe that the sensitivity of NO$\nu$A increases slightly for 10 years of run time, with $(5\nu + 5\bar{\nu})$ combination has better sensitivity than that of $(7\nu + 3\bar{\nu})$ combination. The drop in the half planes of $\delta_{CP}$ i.e, in the region $[0,180]^\circ$ ($[-180,0]^\circ$) for NH (IH) is due to the fact that the hierarchy sensitivity is highly sensitive to $\delta_{CP}$. As a result, of marginalization over hierarchy causes the CPV sensitivity to drop for unfavorable values of $\delta_{CP}$.

To understand the role of the cross-section uncertainty in determination of CP violation for the above experiments. In this section we assume an optimistic error of 10% on the individual cross-sections of $\nu_\mu$ and $\nu_e$ for NO$\nu$A, T2K, T2HK experiments.

The top most panel of Fig. 8 shows a very thin band induced, when compared to that in the next two panels, due to a 10% error on the individual cross-sections of $\nu_\mu$ and $\nu_e$ for (3$\nu$+2$\bar{\nu}$) years run T2K experiment. Clearly, here the sensitivity to CP-violation is not effected much by this cross-section uncertainty. For NO$\nu$A experiment the induced error in the values of $\delta_{CP}$ for which significance is above $1.5\sigma$, when the true hierarchy is NH (IH), is $\sim 12\%$ ($\sim 10\%$), where as for T2HK experiment (from the last panel) it is observed to be $\sim 7\%$ (5%) for significance above $5\sigma$.

A. Correlation between $\delta_{CP}$ and $\theta_{13}$

The knowledge of reactor mixing angle $\theta_{13}$ plays a crucial role in the discovery potential of $\delta_{CP}$. The recent discovery of large value of $\theta_{13}$ has established the need to study and understand the dependency between $\delta_{CP}$ and $\theta_{13}$. In this subsection, we discuss the correlation between the oscillation parameters $\theta_{13}$ and $\delta_{CP}$. In obtaining the confidence region, we have kept true values as in Table-II and we consider true $\sin^2 \theta_{23} = 0.59$ for Higher Octant and true $\sin^2 \theta_{23} = 0.41$ for Lower Octant, since the octant of $\theta_{23}$ is not known. We have varied
FIG. 8: CP violation sensitivity with 10% on the individual cross-sections of $\nu_\mu$ and $\nu_e$ for scheduled runs of T2K, NO$\nu$A and T2HK experiments for NH (IH) in the left (right) panel.

the test value of $\sin^2 2\theta_{13}$ and $\delta_{CP}$ in their 3$\sigma$ ranges. We have marginalized over $\sin^2 \theta_{23}$ in the LO(HO) range for true value of LO(HO) and $\Delta m^2_{31}$ in NH (IH) for true NH (IH). In this analysis we have kept both true and test hierarchy as normal hierarchy. We also added prior to $\sin^2 2\theta_{13}$.

Fig. 9 shows the confidence regions in the $\sin^2 2\theta_{13}$ - $\delta_{CP}$ plane for different combinations of T2K and NO$\nu$A experiments. One can see from these figures that at the 3 $\sigma$ confidence level the uncertainty in the knowledge of $\theta_{23}$ octant has a noticeable effect on the correlation.
between $\delta_{CP}$ and $\theta_{13}$.

**B. Correlation between $\delta_{CP}$ and $\theta_{23}$**

From the previous subsection, we can see that the uncertainty in $\theta_{23}$ has a very large impact on determination of neutrino oscillation parameters. Thus, it is important to understand the exclusive correlation between $\delta_{CP}$ and $\theta_{23}$ while keeping the true values of rest of the oscillation parameters to be fixed. In this subsection, we discuss the correlation between the oscillation parameters $\theta_{23}$ and $\delta_{CP}$. For our analysis, we have kept true values of oscillation parameters as in table-II. We have varied test values of $\sin^2 \theta_{23}$ and $\delta_{CP}$ in their $3\sigma$ ranges. Marginalization is done over $\Delta m^2_{31}$ in their NH (IH) range for true NH (IH) and $\sin^2 2\theta_{13}$ in its $3\sigma$ range and added prior to $\sin^2 2\theta_{13}$ with $\sigma_{\sin^2 (2\theta_{13})} = 0.01$. The obtained results of the confidence regions in $\sin^2 (\theta_{23})$ - $\delta_{CP}$ plane are shown in Figs. 10 and 11 for all combinations of NO$\nu$A experiments.

**VI. SUMMARY AND CONCLUSION**

With the recent discovery of the last unknown reactor mixing angle $\theta_{13}$, the mechanism of three flavor neutrino mixing pattern is now well established. But still there are several issues related to neutrino oscillation parameters that remain open, namely the absolute mass scale of neutrinos, determination of the mass hierarchy, octant of the atmospheric mixing angle $\theta_{23}$, the magnitude of the CP violating phase $\delta_{CP}$ and the observation of CP violation in the neutrino sector. Therefore, the main focus of the current and future oscillation experiments is to provide answers to some of these unsolved questions.

In this paper we have investigated the prospects of the determination of mass hierarchy, the octant of $\theta_{23}$ and the observation of CP violation in the neutrino sector due to $\delta_{CP}$ with the currently running accelerator based neutrino experiments NO$\nu$A and T2K and the forthcoming T2HK experiment. As the reactor mixing angle $\theta_{13}$ is now known to be significantly large the oscillation probability $P(\nu_{\mu} \rightarrow \nu_{e})$ and its corresponding antineutrino counterpart are sensitive for the determination of mass hierarchy and $\theta_{23}$ octant. We found that T2K experiment with $(3\nu + 2\bar{\nu})$ years of running can resolve the octant degeneracy with nearly $2\sigma$ C.L. if the true value of $\theta_{23}$ to be around $\sin^2 \theta_{23} = 0.41$ (LO) or $\sin^2 \theta_{23} = 0.59$.
(HO). The sensitivity increases to nearly $3\sigma$ with $(3\nu + 3\bar{\nu})$ years running of NO\(\nu\)A. However, if we combine the data from these two experiments the sensitivity increases significantly than the sensitivities of individual experiments. Furthermore, if we assume that NO\(\nu\)A continues data taking for 10 years then octant degeneracy can be resolved with NO\(\nu\)A experiment alone with more than $3\sigma$ significance. For the determination of mass hierarchy also it is possible to rule out nearly one-third of the $\delta_{CP}$ space at $3\sigma$ C.L. if we use the synergy between NO\(\nu\)A and T2K experiments. In this case the sensitivity increases significantly for ten years of running of NO\(\nu\)A with $(5 + 5)$ combination is found to be more suitable than the combination of $(7+3)$ years.

Measuring CP violation in the lepton sector is another important challenging problems today. We have also performed a systematic study of the CP sensitivity of the current long-baseline experiments T2K and NO\(\nu\)A. Although these experiments are not planned to study leptonic CP violation, we analyze the synergies between these set-ups which may aid in CP violation discovery by constraining the value of $\delta_{CP}$. Although dedicated long baseline experiments like LBNE, LBNO are planned to study CP violation in neutrino sector, we may have the first hand information on $\delta_{CP}$ from these experiments much before those dedicated facilities are operational. We found that T2K by itself has marginal CP violation sensitivity at $1\sigma$ C.L.. For NO\(\nu\)A with $(3+3)$ years of running there will be CP violation sensitivity above $1.5\sigma$ level for about one-third of the CP violating phase $\delta_{CP}$ space. The sensitivity increases slightly for 10 years of run time, with $(5\nu + 5\bar{\nu})$ combination has better sensitivity than that of $(7\nu + 3\bar{\nu})$ combination. The data from T2HK experiment will improve the CPV sensitivity significantly. We have also obtained the Confidence regions in the $\delta_{CP} - \theta_{13}$ ($\theta_{23}$) plane for both T2K and NO\(\nu\)A experiments.

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FIG. 9: Confidence region in $\sin^2 2\theta_{13} - \delta_{CP}$ plane for $\delta_{CP} = 0$ and different run combinations of T2K and NOvA experiments.
FIG. 10: Confidence region in $\sin^2 \theta_{23} - \delta_{CP}$ plane for true $\delta_{CP} = 0$ and test hierarchy as IH.
FIG. 11: Confidence region in $\sin^2 \theta_{23} - \delta_{CP}$ plane for true $\delta_{CP} = 0$ and test hierarchy as NH.