Research Article

A Comprehensive Study of the Discovery Potential of NOνA, T2K, and T2HK Experiments

C. Soumya, K. N. Deepthi, and R. Mohanta

School of Physics, University of Hyderabad, Hyderabad 500 046, India

Correspondence should be addressed to R. Mohanta; rukmani98@gmail.com

With the recent measurement of reactor mixing angle θ_{13} the knowledge of neutrino oscillation parameters has improved significantly except the CP violating phase δ_{CP}, mass hierarchy, and the octant of the atmospheric mixing angle θ_{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 answers to these questions. In this paper we study the discovery potential of the ongoing NOνA and T2K experiments as well as the forthcoming T2HK experiment in addressing these questions. In particular, we evaluate the sensitivity of NOνA to determine neutrino mass hierarchy, octant degeneracy, and δ_{CP} after running for its scheduled period of 3 years in neutrino mode and 3 years in antineutrino mode. We then extend the analysis to understand the discovery potential if the experiments will run for $(5\nu + 5\overline{\nu})$ years and $(7\nu + 3\overline{\nu})$ years. We also show how the sensitivity improves when we combine the data from NOνA, T2K, and T2HK experiments with different combinations of run period. The CP violation sensitivity is marginal for T2K and NOνA experiments even for ten-year data taking of NOνA. T2HK has a significance above 5σ for a fraction of two-fifths values of the δ_{CP} space. We also find that δ_{CP} can be determined to be better than 35°, 21°, and 9° for all values of δ_{CP} for T2K, NOνA, and T2HK respectively.

1. 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} [1, 2], which is parameterized in terms of three rotation angles θ_{12}, θ_{23}, and θ_{13} and three CP violating phases, one Dirac type (δ_{CP}) and two Majorana types (ρ and σ). 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 θ_{13} has been measured precisely [3–7] with a moderately large value, quite close to its previous upper bound. The observation of the largish value of θ_{13} has attracted a lot of attention in recent times to understand the mixing pattern in the lepton sector. Furthermore, it also opens up promising prospects for the observation of leptonic CP violation [8, 9]. As θ_{13} is nonzero,

there could be CP violation in the lepton sector, analogous to the quark sector, provided the CP violating phase δ_{CP} is not vanishingly small.

The current results from recent neutrino oscillation experiments [10–13] and their global analysis [14–17] 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 3σ ranges of the oscillation parameters from [17] are presented in Table 1.

Another important discovery in recent times is the precision measurement of $\sin^2\theta_{23}$ by MINOS experiment [18], which is found to be nonmaximal. Using the complete set of accelerator and atmospheric data they disfavored the maximal mixing by $-2\Delta\log(\mathscr{L}) = 1.54$. They obtained the best-fit value for the mixing angle θ_{23} as $\sin^2\theta_{23} = 0.41$, known as lower octant (LO) and $\sin^2\theta_{23} = 0.61$, the so-called higher octant (HO) values.

TABLE 1: The best-fit values and the 3σ ranges of the neutrino oscillation parameters from [17].

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

With these exciting discoveries of nonzero θ_{13} and nonmaximal θ_{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 θ_{23}, discovery of CP violation, and the magnitude of the CP violating phase δ_{CP}. In this paper we would like to investigate the prospects of addressing these issues with the off-axis long-baseline experiments T2K, NOνA, and T2HK with updated experimental specifications. The experimental specifications of these experiments are briefly described below.

(i) NOνA [19, 20] is an off-axis long-baseline neutrino oscillation experiment designed to study $\nu_\mu \to \nu_e$ appearance measurements using Fermilab NuMI muon neutrino beam (ν_μ). Its secondary aim is to precisely measure ν_μ disappearance parameters. It uses a high intensity proton beam with a beam power of 0.7 MW with 6×10^{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 $\nu_\mu \to \nu_e$ is expected to be maximum at this energy. It is scheduled to run 3 years in ν mode followed by 3 years in $\bar\nu$ mode. The detector properties of NOνA considered in our simulations are taken from [21] with the following characteristics as given in Table 2.

(ii) T2K (Tokai-to-Kamiokande) is a currently running long-baseline experiment designed to study neutrino oscillations. An intense ν_μ 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 in [22]. We have considered input files for T2K from the General Long-Baseline Experiment Simulator (GLoBES) package [22–24] and the updated experimental description of T2K is taken from [25]. We have matched our results with the ones presented in [25]. In this analysis, we have used $(3\nu + 2\bar\nu)$ running modes for T2K.

(iii) T2HK (Tokai-to-Hyper-Kamiokande) is a future long-baseline experiment which is expected to be operational around 2023. It can be considered a natural advancement to the ongoing T2K experiment. It has the same baseline and off-axis angle as T2K experiment. It uses J-PARC's neutrino experimental facilities with an improved 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 and other specifications are taken from [26]. Hence, T2HK will have high statistics of neutrino events compared to T2K. These features of T2HK make it one of the most sensitive experiment to probe neutrino CP violation. The input files for T2HK are obtained from GLoBES package [22–24]. The primary objective of this experiment is the discovery of CP asymmetry.

Since these experiments use ν_μ beam and also will run in antineutrino mode their main focus is to study the appearance ($\nu_\mu \to \nu_e$) and the disappearance channels ($\nu_\mu \to \nu_\mu$) along with their antineutrino counterparts. Since the leading term in the appearance channels $\nu_\mu \to \nu_e$ ($P_{\mu e}$) and the corresponding antineutrino mode $\bar\nu_\mu \to \bar\nu_e$ ($P_{\bar\mu\bar e}$) is proportional to $\sin^2 2\theta_{13}\sin^2\theta_{23}$ and with the observation of moderately large value of θ_{13}, these experiments are well-suited for the determination of mass hierarchy and the octant of θ_{23}. Although the ongoing NOνA and T2K experiments are not planned to measure δ_{CP} or to explore CP violation in the neutrino sector, we would like to investigate whether it is possible to constrain the δ_{CP} phase using the data from these two experiments. In other words, how much of the δ_{CP} space can be ruled out by these experiments within the next 10 years? In particular, we would like to investigate

(i) whether the combination of T2K (3 + 2) and NOνA (3 + 3) provide more quantitative answer on the above posed questions than each one of these experiments,

(ii) how the sensitivity on δ_{CP}, mass hierarchy, and θ_{23} octant will improve if NOνA runs for 10 years in the (5 + 5) and (7 + 3) combination of modes,

(iii) the sensitivities of T2HK experiment for its scheduled run of 3 years in neutrino and 7 years in antineutrino mode.

The paper is organized as follows. In Section 2 we briefly describe the physics reach of these experiments. The prospect of octant resolution and mass hierarchy determination are discussed in Sections 3 and 4. Section 5 contains the CP violation discovery potential and the correlations between the CP violating phase δ_{CP} and the mixing angles θ_{13} and θ_{23}. We summarize our results in Section 6.

2. Physics Reach

As discussed before, the determination of the mass hierarchy, octant of the atmospheric mixing angle θ_{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 $P(\nu_\mu \to \nu_e)$ and $P(\bar\nu_\mu \to \bar\nu_e)$. This can

TABLE 2: Details of NOνA detector characteristics considered in this analysis.

Signal efficiency	45% for ν_e and $\overline{\nu}_e$ signal
	100% ν_μ CC and $\overline{\nu}_\mu$ CC
Background efficiency	0.83% ν_μ CC, 0.22% $\overline{\nu}_\mu$ CC
	2% ν_μ NC, 3% $\overline{\nu}_\mu$ NC
	26% (18%) ν_e ($\overline{\nu}_e$) beam contamination
NC background smearing	Migration matrices
Systematics	5% signal normalization error
	10% background normalization error

TABLE 3: The true values of oscillation parameters considered in the simulations.

$\sin^2\theta_{12}$	0.32
$\sin^2 2\theta_{13}$	0.1
$\sin^2\theta_{23}$	0.41 (LO), 0.59 (HO)
Δm^2_{atm}	2.4×10^{-3} eV^2 for NH
	-2.4×10^{-3} eV^2 for IH
Δm^2_{21}	7.6×10^{-5} eV^2
δ_{CP}	$0°$

be seen from the expression for probability of oscillation from $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$ [27–29], where we have kept terms only first order in $\sin\theta_{13}$ and $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$:

$$
\begin{aligned}
P\left(\nu_\mu \longrightarrow \nu_e\right) &\approx \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2\left(\widehat{A}-1\right)\Delta}{\left(\widehat{A}-1\right)^2} + \alpha \\
&\quad \cdot \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \\
&\quad \cdot \frac{\sin\widehat{A}\Delta}{\widehat{A}}\frac{\sin\left(\widehat{A}-1\right)\Delta}{\left(\widehat{A}-1\right)} \\
&\quad \cdot \cos\left(\Delta+\delta_{\text{CP}}\right),
\end{aligned}
\tag{1}
$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$, $\Delta = \Delta m^2_{31}L/4E$, and $\widehat{A} = 2\sqrt{2}G_F n_e E/\Delta m^2_{31}$. 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 θ_{13}, θ_{23}, mass hierarchy, that is, the sign of Δm^2_{31} and CP violation phase δ_{CP}. Parameters α, Δ, and $\widehat{A}$ are sensitive to neutrino mass ordering. For neutrinos, $\widehat{A}$ is positive for normal hierarchy (NH) and negative for inverted hierarchy (IH), while its sign changes when we go from neutrino to antineutrino mode. Moreover, sign of δ_{CP} is reversed for antineutrinos.

It should be noted from (1) that the leading term in the transition probability $P(\nu_\mu \to \nu_e)$ is proportional to $\sin^2 2\theta_{13}\sin^2\theta_{23}$. Therefore, the observed moderately large value of θ_{13} makes it possible for the current generation long-baseline experiments to address the problems of hierarchy and the octant of θ_{23} determination. The second term in (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 θ_{13} suggests that NOνA detector will be able to collect a good number of $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$ events.

First, we will try to see whether the energy spectrum information will help us in resolving the octant degeneracy and mass hierarchy. We use GLoBES package [30, 31] for the simulation to obtain the energy spectra. In our analysis, we consider the true values of oscillation parameters as provided in Table 3, unless mentioned otherwise.

Figure 1 shows the energy spectrum of the appearance probabilities $P(\nu_\mu \to \nu_e)$ for neutrino (left panel) and $P(\overline{\nu}_\mu \to$

$\overline{\nu}_e$) for antineutrino (right panel) for NOνA experiment, where we have varied δ_{CP} within the range $-\pi$ to π. In the upper panel the red (blue) band is for NH (IH). Furthermore, in each band the probability for $\delta_{\text{CP}} = 90°$ and $\delta_{\text{CP}} = -90°$ cases are shown explicitly by the magenta and green lines. Due to matter effect the probability $P_{\mu e}$ increases for NH and decreases for IH and vice versa for $P_{\overline{\mu}\overline{e}}$. Thus, for δ_{CP} lying in the lower half plane (LHP), that is, $-180° \leq \delta_{\text{CP}} \leq 0$, $P_{\mu e}$ is larger and, for δ_{CP} in the upper half plane (UHP) ($0 \leq \delta_{\text{CP}} \leq 180°$), $P_{\mu e}$ is much lower. The situations reverse for the antineutrino probability $P_{\overline{\mu}\overline{e}}$. Thus, LHP is the favorable half plane for NH and UHP is for IH for neutrino mode. However, the most unfavorable condition is (NH, $\delta_{\text{CP}} = 90°$) and (IH, $\delta_{\text{CP}} = -90°$) as the bands almost overlap with each other for the entire energy range. In the lower panels of Figure 1, we show the energy spectrum of $P_{\mu e}$ and $P_{\overline{\mu}\overline{e}}$ for two different values of θ_{23} assuming NH to be true hierarchy. The blue band in both of the panels is for θ_{23} in the LO and red band is for θ_{23} in the HO. As can be seen from the figures the two bands overlap with each other for some values of δ_{CP} and are distinct for others. The overlap regions are the unfavorable ones for the determination of the θ_{23} octant.

3. Octant Resolution as a Function of θ_{23}

In this section we present the results of our analysis on octant sensitivity of θ_{23} for T2K, NOνA, 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 [32–34], here we would like to revisit the octant resolution potential of these experiments with the updated specification details. For NOνA, we consider its scheduled ($3\nu + 3\overline{\nu}$) years of run, for T2K ($3\nu + 2\overline{\nu}$) years of run, and for T2HK ($3\nu + 7\overline{\nu}$) years of run. Furthermore, we also investigate the following situation: if NOνA continues to run for the next 10 years what would be the potential for resolving octant degeneracy for ($5\nu + 5\overline{\nu}$) as well as ($7\nu + 3\overline{\nu}$) years of running? We also see the synergy between T2K, NOνA, and T2HK experiments for their scheduled runs.

The indistinguishability of θ_{23} and $(\pi/2 - \theta_{23})$ is known as octant degeneracy. The relevant oscillation probability
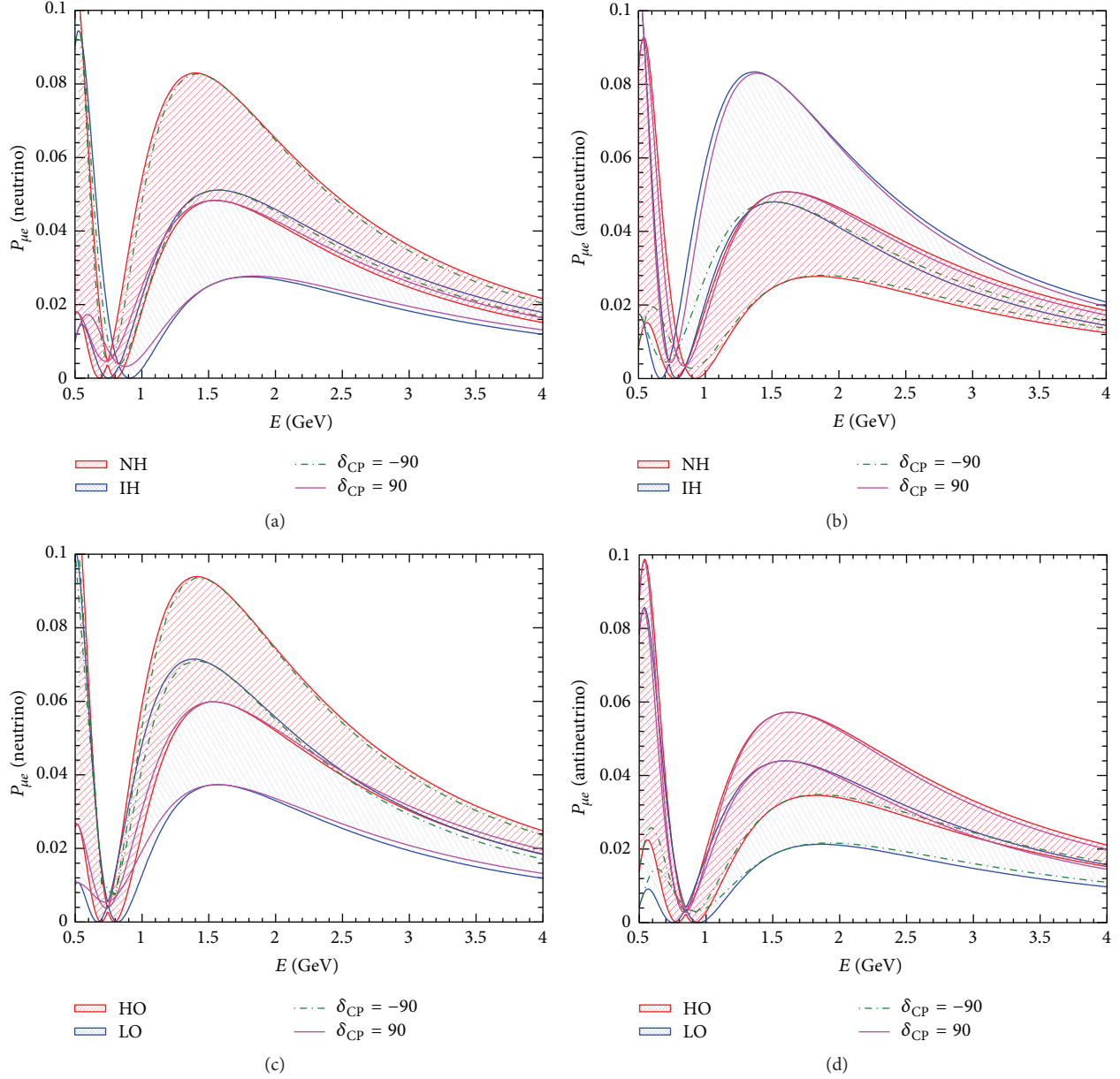
Figure 1: $P_{\mu e}$ energy spectrum for NOνA experiment. The left (right) panel is for neutrino (antineutrino). The red (blue) band in the top panel corresponds to NH (IH), where we have used $\sin^2\theta_{23} = 0.5$, $\sin^2 2\theta_{13} = 0.1$, and baseline $L = 810$ km and vary δ_{CP} between $-\pi$ and π. 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. Inside each band the probability for $\delta_{CP} = 90°$ ($-90°$) case is shown by magenta (green) line.

expressions for long-baseline experiments NOνA, T2K, and T2HK with negligible matter effects are given as

$$P_{\mu\mu}^{\nu} = 1 - \sin^2 2\theta_{23}\sin^2\left[1.27\frac{\Delta m_{31}^2 L}{E}\right]$$

$$+ 4\sin^2\theta_{13}\sin^2\theta_{23}\cos 2\theta_{23}\sin^2\left[1.27\frac{\Delta m_{31}^2 L}{E}\right], \quad (2)$$

$$P_{\mu e}^{\nu} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left[1.27\frac{\Delta m_{31}^2 L}{E}\right].$$

The leading order term in the ν_μ 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, whereas in the case of $P_{\mu e}^{\nu}$ the degeneracy of the octant with the parameter θ_{13} comes into play, since it depends on the parameter combination $\sin^2\theta_{23}\sin^2 2\theta_{13}$. The values of θ_{23} in opposite octant for different values of θ_{13} and δ_{CP} can have the same probabilities; that is, $P_{\mu e}^{\nu}(\theta_{23}, \theta_{13}, \delta_{CP}) = P_{\mu e}^{\nu}(\pi/2 - \theta_{23}, \theta_{13}', \delta_{CP}')$. This also gives rise to octant degeneracy.
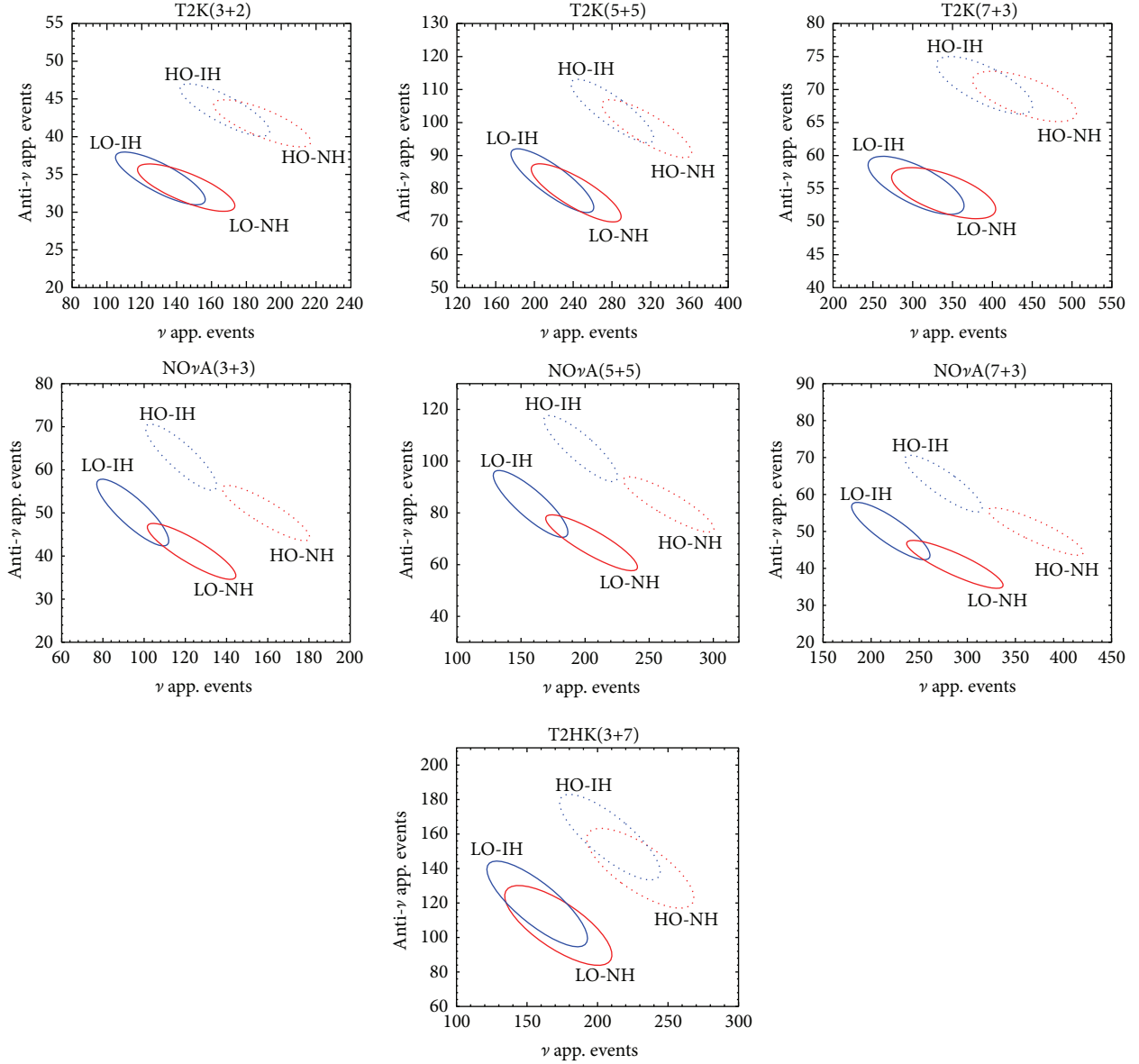
FIGURE 2: Neutrino and antineutrino appearance events for the $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$ channels by assuming both IH and NH and for lower and higher octants of θ_{23}.

Before presenting the main results, we would like to discuss what one can expect about the determination of mass hierarchy and octant of θ_{23} from the biprobability plots, that is, neutrino-antineutrino appearance event rates. Figure 2 shows ν versus $\bar{\nu}$ events for all octant-hierarchy combinations. The blue curves are obtained by considering inverted hierarchy mass ordering and both of the values of θ_{23}; that is, $\sin^2\theta_{23} = 0.41$ (LO) and 0.59 (HO). The red curves are obtained by considering normal hierarchy mass ordering and LO/HO values for $\sin^2\theta_{23}$. These ellipses are plotted by obtaining event spectra for $(3 + 3)$ yrs, $(5 + 5)$ yrs, and $(7 + 3)$ yrs in ν and $\bar{\nu}$ mode for all values of δ_{CP} for NOνA, T2K, and $(3 + 7)$ yrs for T2HK. Each point on x-axis (y-axis) represents the number of events measured by the respective

experiments in neutrino (antineutrino) 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 NOνA 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 and inverted mass orderings overlap with each other for both the octants whereas for NOνA 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 NOνA experiment.

Before doing the simulation, here we would like to emphasize that the relation between atmospheric parameters
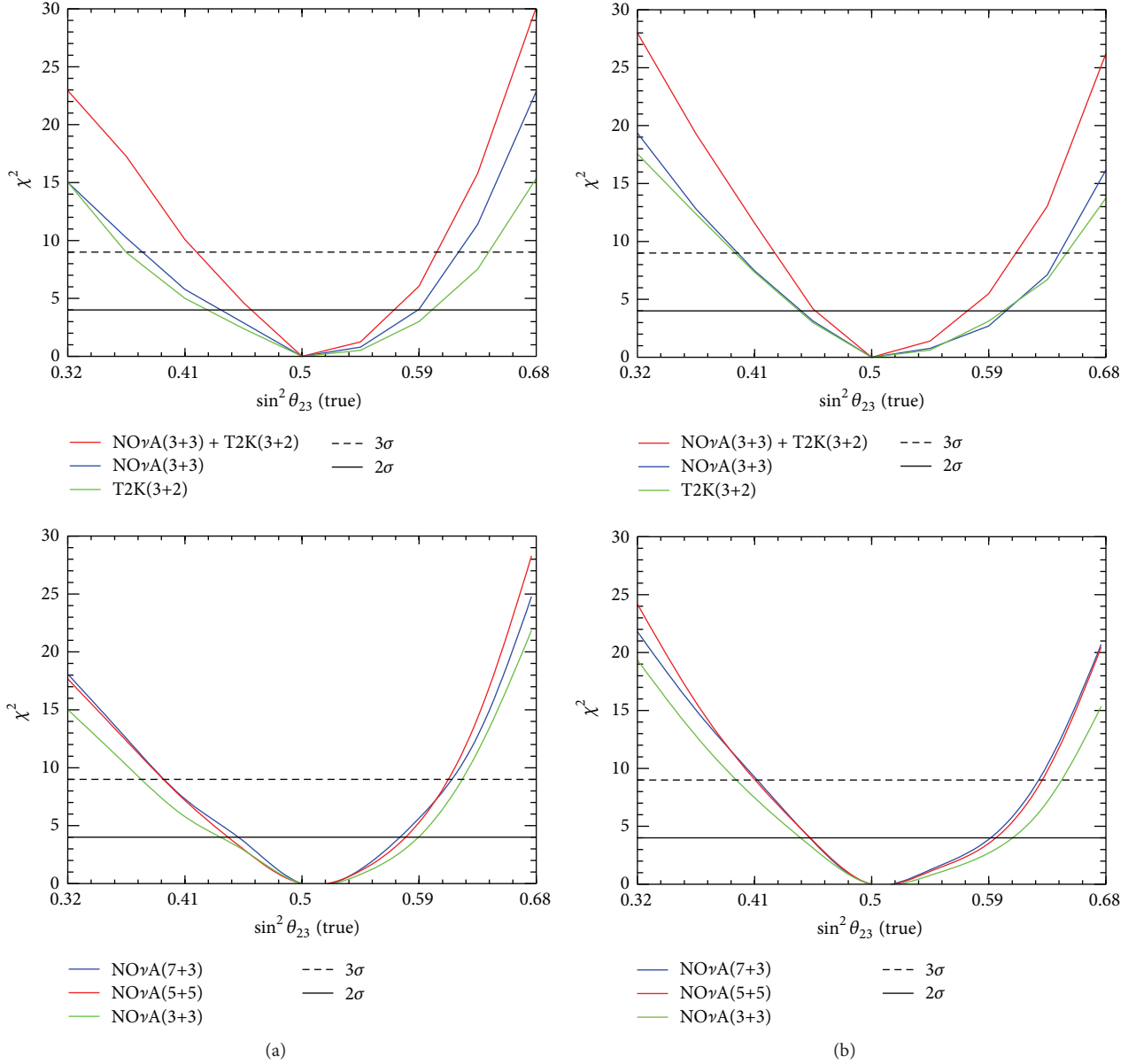
FIGURE 3: Octant sensitivity for a combination of T2K and NOνA for the case of normal (left panel) and inverted (right panel) hierarchy.

(Δm_{atm}^2) and $\theta_{\mu\mu}$, measured in MINOS, and the standard oscillation parameters in nature are given as [35, 36]

$$\sin \theta_{23} = \frac{\sin \theta_{\mu\mu}}{\cos \theta_{13}},$$

$$\Delta m_{31}^2$$

$$= \Delta m_{atm}^2$$

$$+ \left(\cos^2 \theta_{12} - \cos \delta_{CP} \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23} \right) \Delta m_{21}^2. \quad (3)$$

It is clear from the above relations that the observed value of moderately large θ_{13} significantly affects the oscillation parameters. So here we use corrected definitions of these

parameters to analyze octant sensitivity. We allocate measured values Δm_{atm}^2 and $\theta_{\mu\mu}$ and calculate oscillation probabilities in terms of Δm_{31}^2 and θ_{23}.

We consider the true values of oscillation parameters given in Table 3 and vary the test values of $\sin^2\theta_{23}$ in LO (HO) for true higher octant (lower octant). We also marginalize over $\sin^2 2\theta_{13}$ in the range [0.07 : 0.13], δ_{CP} in its full range, and Δm_{atm}^2 in the range $[2.05 : 2.75] \times 10^{-3}$ eV^2 for NH. The parameters θ_{12} and Δm_{21}^2 have been kept fixed in the analysis and priors for $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$ with $\sigma(\sin^2 2\theta_{13}) = 0.01$ and $\sigma(\sin^2\theta_{23}) = 0.05$ are also added.

We simulate the long-baseline experiments T2K and NOνA using the GLoBES package. For T2K, we assume 3 years of running in neutrino mode and 2 years in antineutrino
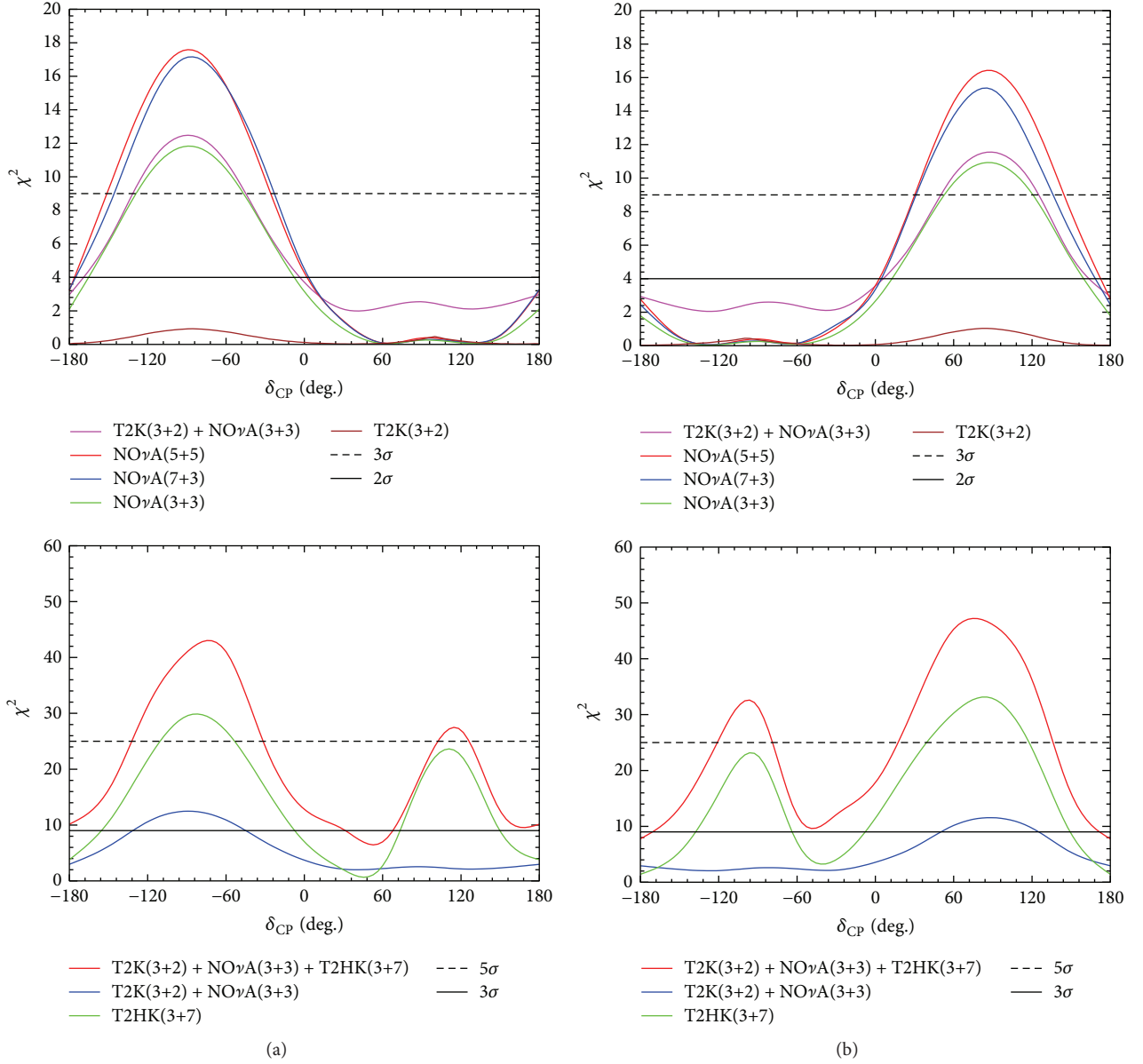
FIGURE 4: Mass hierarchy significance as a function of true δ_{CP}. In the left panel normal hierarchy is considered as true hierarchy and inverted is taken as test hierarchy and in the right panel inverted hierarchy is considered true hierarchy and normal is taken as test hierarchy.

mode and for NOνA, we consider 3 years of neutrino running followed by 3 years of antineutrino running. 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 Figure 3, we illustrate the ability of NOνA experiment to determine the octant as a function of the true value of θ_{23}. The values of χ^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 NOνA with $(3 + 3)$, $(5 + 5)$, and $(7 + 3)$ yrs of runs in ν and $\bar{\nu}$ modes, respectively. From Figure 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 2σ 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.

4. 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
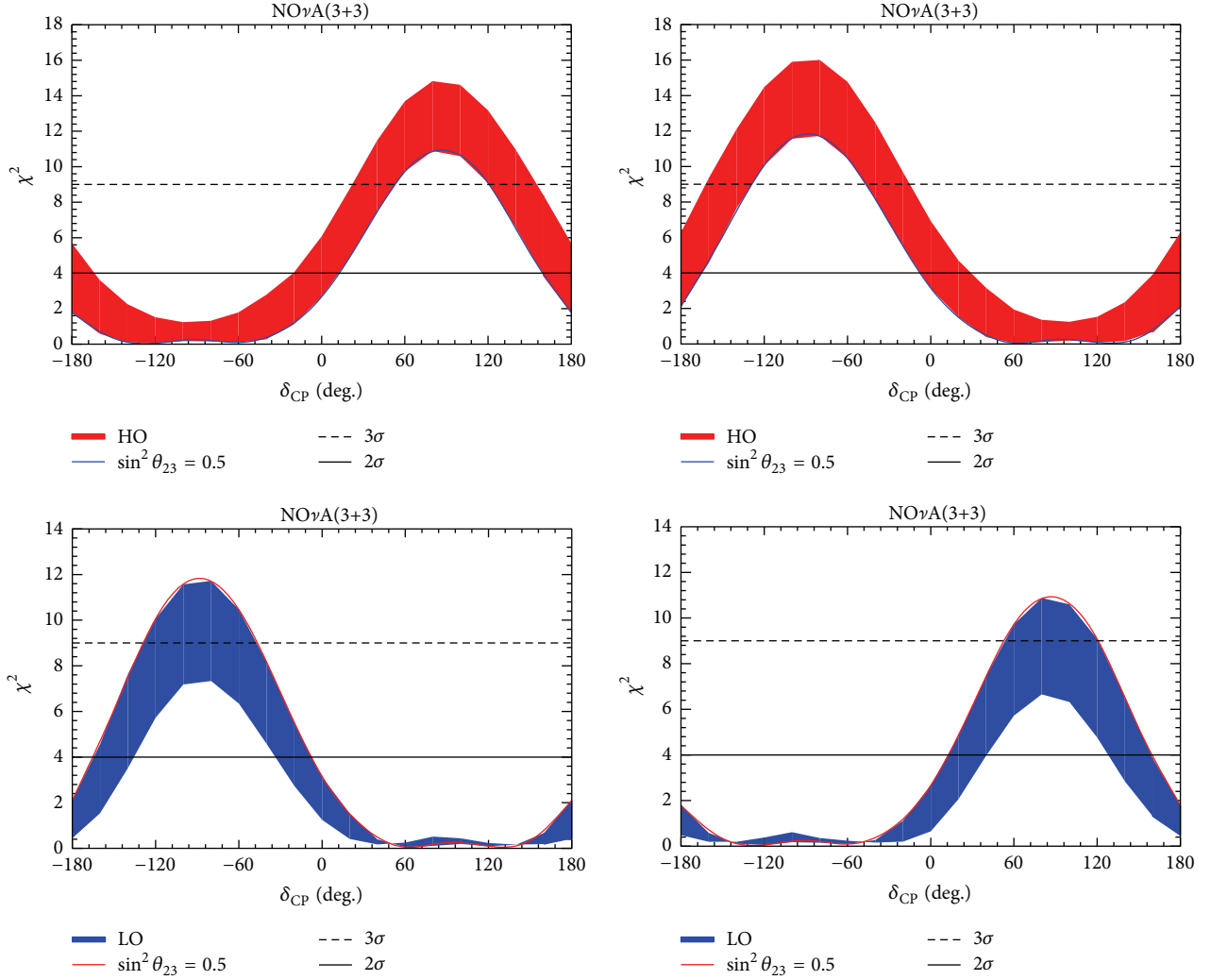
FIGURE 5: Mass hierarchy significance with the octant of θ_{23} for the scheduled run of NOνA experiment.

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, NOνA, and T2HK experiments for the determination of mass hierarchy.

The value of χ^2 has been obtained by using the true parameters as listed in Table 3, except that of $\sin^2\theta_{23}$, which is taken to be 0.5. The true value of δ_{CP} is varied within its full range, that is, in $[-\pi, \pi]$, and test value of Δm^2_{atm} is varied in IH (NH) range for true NH (IH). We also marginalize over $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$ in their 3σ ranges and add prior to $\sin^2 2\theta_{13}$ with $\sigma(\sin^2 2\theta_{13}) = 0.01$.

In Figure 4, we present the hierarchy determination sensitivity of T2K, NOνA, and T2HK as a function of true value of δ_{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 cannot be determined

effectively for T2K and NOνA experiments. However, the combined data from these two experiments (T2K (3 + 2) and NOνA (3 + 3)) improves the situation significantly and the sensitivity increases to more than 1σ for all values of δ_{CP}. The mass hierarchy significance above 3σ has a δ_{CP} coverage of 75% for T2HK experiment alone and 90% for combined data of T2K, NOνA, and T2HK experiments.

Next, we would like to study the effect of θ_{23} octant on the MH sensitivity. We obtain the MH sensitivity by varying the true value of $\sin^2\theta_{23}$ in LO (HO) which has been shown in Figure 5 where the red (blue) band in the top (bottom) panel corresponds to HO (LO). It is clear from the figure that the MH sensitivity is significantly large if the value of $\sin^2\theta_{23}$ is in higher octant.

5. CP Violation Discovery Potential

Accelerator based long-baseline neutrino oscillation experiments can address CP violation problem through the appearance channels of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$. From (1) we can see
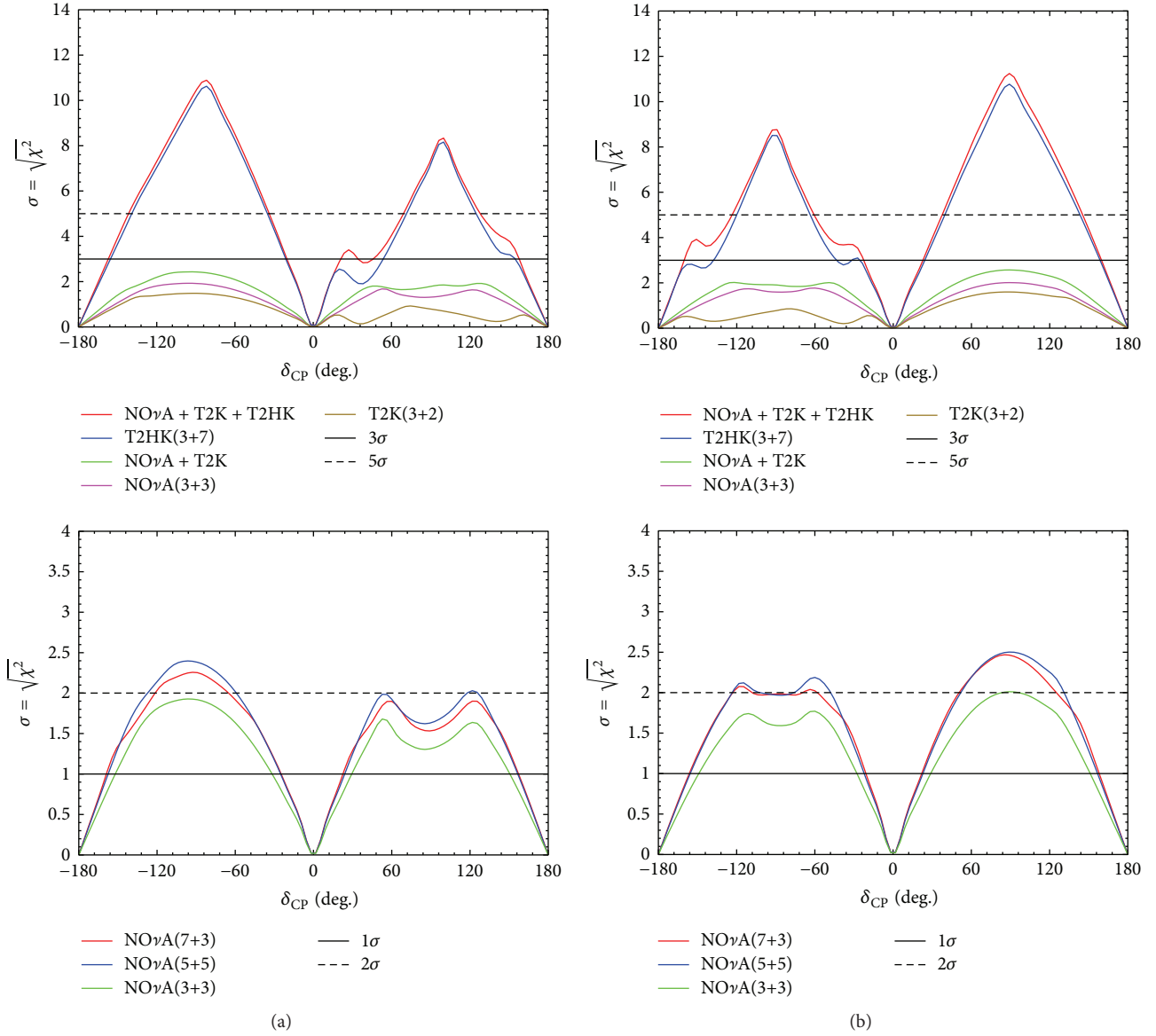
FIGURE 6: CP violation sensitivity for different combinations of run time of T2K, NOνA, and T2HK experiment for NH (IH) in the left (right) panel.

that the CP violating effects due to δ_{CP} are modified by all the three mixing angles and their combinations, thus resulting in an eightfold parameter degeneracy. In order to obtain the significance of CP violation sensitivity, we simulate the true event spectrum by keeping the true values of oscillation parameters as in Table 3 except for $\sin^2\theta_{23} = 0.5$ and vary the true value of δ_{CP} in the range $[-\pi, \pi]$. We then compare those with test event spectrum for $\delta_{CP} = 0$ or π and, thus, obtain the minimum χ^2. We consider the sign degeneracy of Δm_{31}^2 by marginalizing over it, in both NH and IH 3σ ranges. We also do marginalization over $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$ in their 3σ and added prior for $\sin^2 2\theta_{13}$.

In Figure 6, we plot the sensitivity to rule out the CP conserving scenarios, as a function of true δ_{CP} assuming NH (IH) to be the true hierarchy in the left panel (right panel).

From the figure one can notice that T2K by itself has no CP violation sensitivity at 2σ CL. For NOνA with $(3 + 3)$ years of running, there will be CP violation sensitivity above 1.5σ level for about one-third of the CP violating phase δ_{CP} space. Furthermore, the synergistic combination of NOνA and T2K leads to much better CP violation sensitivity compared to the individual capabilities. Even the combination of NOνA $(3+3)$ and T2K $(3 + 2)$ has comparable sensitivity as for 10-year running of NOνA. Owing to the fact that main goal of T2HK experiment is to determine CP violation, one can see that it has a significance of above 5σ CL for a fraction of two-fifths values of the CP violating phase δ_{CP} space. This in turn boosts up the sensitivity when its data is added to NOνA $(3 + 3)$ yrs and T2K $(3+2)$ yrs. From the plots in the lower panel, one can observe that the sensitivity of NOνA increases slightly for 10
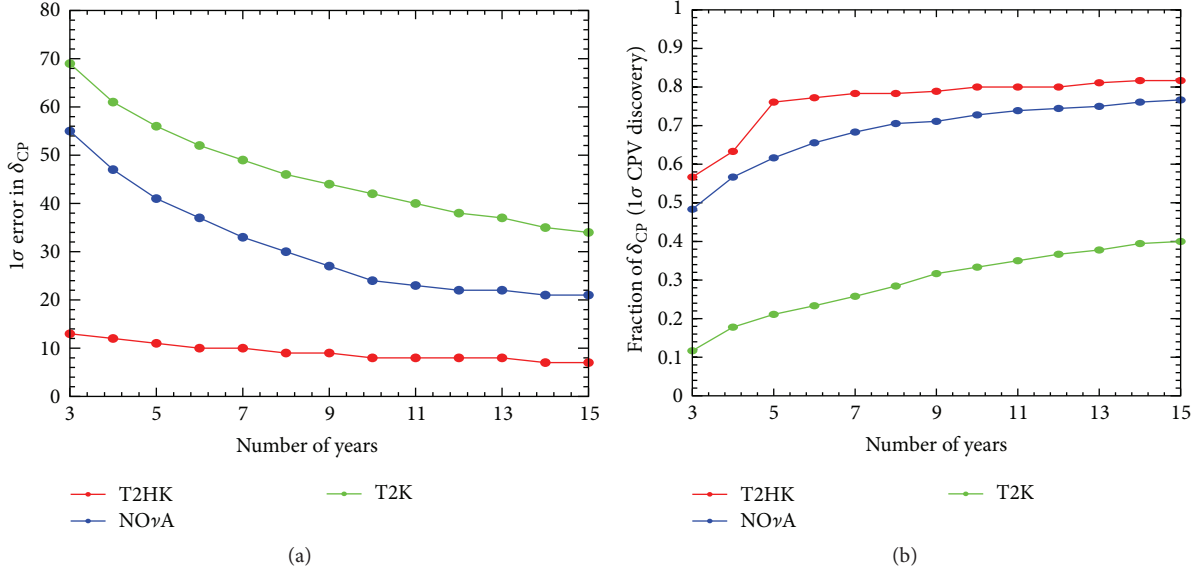
FIGURE 7: Sensitivity versus running time: 1σ error in δ_{CP} as a function of running time in years for true value of $\delta_{CP} = 0$ (left panel). The fraction of δ_{CP} for which $\delta_{CP} = 0°$, $180°$ is excluded with 1σ as a function of running time.

years of run time, with $(5\nu + 5\bar{\nu})$ combination having better sensitivity than that of $(7\nu + 3\bar{\nu})$ combination. From the figure, we can see that there is drop in the χ^2 values in the half planes of δ_{CP}, that is, in the region $[0, 180]°$ $([-180, 0]°)$ for NH (IH). Marginalization over both the hierarchies causes this drop in the CPV sensitivity for unfavorable values of δ_{CP}.

In Figure 7, the left panel shows the 1σ uncertainty of δ_{CP} as a function of running time (in years) for true value of $\delta_{CP} = 0$ and the right panel shows the CP violation sensitivity as a function of running time. In both cases, the ratio of neutrino and antineutrino modes is fixed to $1:1$ for T2K and NOνA and $3:7$ for T2HK. In this analysis, mass hierarchy is assumed to be unknown. Therefore, we have marginalized over both the hierarchies, and the result shown in Figure 7 is for the true hierarchy as normal hierarchy. From the left panel of the figure, we can see that the values of δ_{CP} can be determined to be better than $35°$ $(21°)$ for all values of δ_{CP} for T2K (NOνA). In the case of T2HK the values of δ_{CP} can be determined to be better than $9°$ for all values of δ_{CP}. From the right panel, we can see that CP violation can be observed with more than 1σ significance for 40 (75)% of the possible values of δ_{CP} for T2K (NOνA), whereas, for T2HK, CP violation can be observed with more than 1σ significance for 80% of the possible values of δ_{CP}.

5.1. Correlation between δ_{CP} and θ_{13}. The knowledge of reactor mixing angle θ_{13} plays a crucial role in the discovery potential of δ_{CP}. The recent discovery of large value of θ_{13} has established the need to study and understand the dependency between δ_{CP} and θ_{13}. In this subsection, we discuss the correlation between the oscillation parameters θ_{13} and δ_{CP}. To obtain the confidence region, we have fixed the true values as in Table 3 and considered 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 θ_{23} is not known. We have varied the test value of $\sin^2 2\theta_{13}$ in its 3σ range. In this analysis we have kept both true and test hierarchy as normal hierarchy.

Figure 8 shows the confidence regions in the $\sin^2 2\theta_{13}$-δ_{CP} plane for different combinations of T2K and NOνA experiments. One can see from these figures that at 2σ confidence level, the uncertainty in the knowledge of θ_{23} octant has a noticeable effect on the correlation between δ_{CP} and θ_{13}.

5.2. Correlation between δ_{CP} and θ_{23}. From the previous subsection, we can see that the uncertainty in θ_{23} has a very large impact on determination of neutrino oscillation parameters. Thus, it is important to understand the exclusive correlation between δ_{CP} and θ_{23} while keeping the true values of rest of the oscillation parameters fixed. In this subsection, we discuss the correlation between the oscillation parameters θ_{23} and δ_{CP}. For our analysis, we have kept true values of oscillation parameters as in Table 3. We vary the test values of $\sin^2\theta_{23}$ and δ_{CP} in their 3σ ranges. The obtained results of the confidence regions in $\sin^2\theta_{23}$-δ_{CP} plane are shown in Figures 9 and 10 for different combinations of T2K and NOA experiments.

6. Summary and Conclusion

With the recent discovery of the last unknown reactor mixing angle θ_{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 θ_{23}, the magnitude of the CP violating phase δ_{CP}, and the observation of CP violation in the neutrino sector. Therefore, the main focus of the current and future
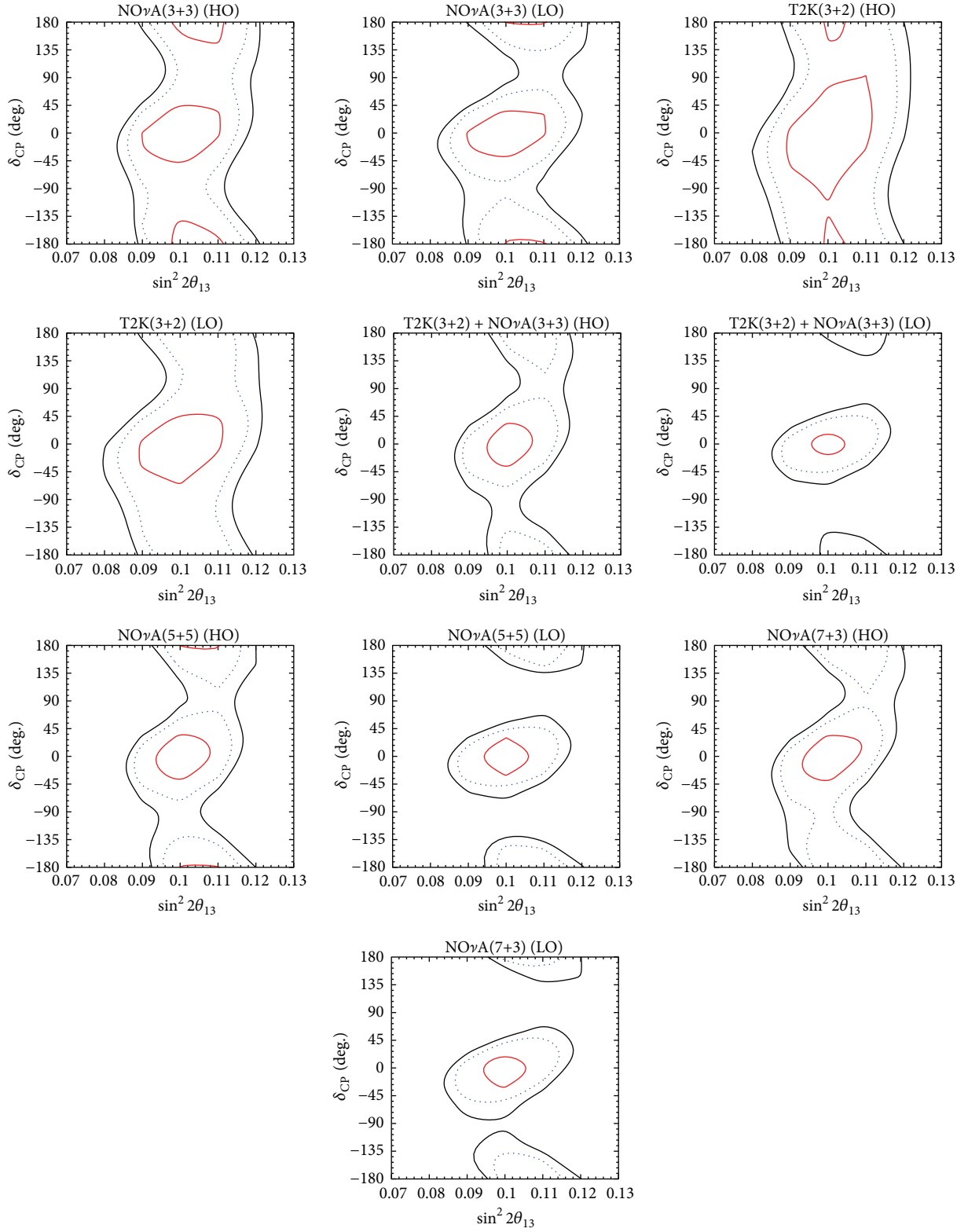
FIGURE 8: Confidence region in $\sin^2 2\theta_{13}$-δ_{CP} plane for δ_{CP} = 0 and for different run combinations of T2K and NOνA experiments, where the red, blue, and black contours represent the 1σ (68.3% CL), 1.64σ (90% CL), and 2σ (95.45% CL) values, respectively, for two degrees of freedom.
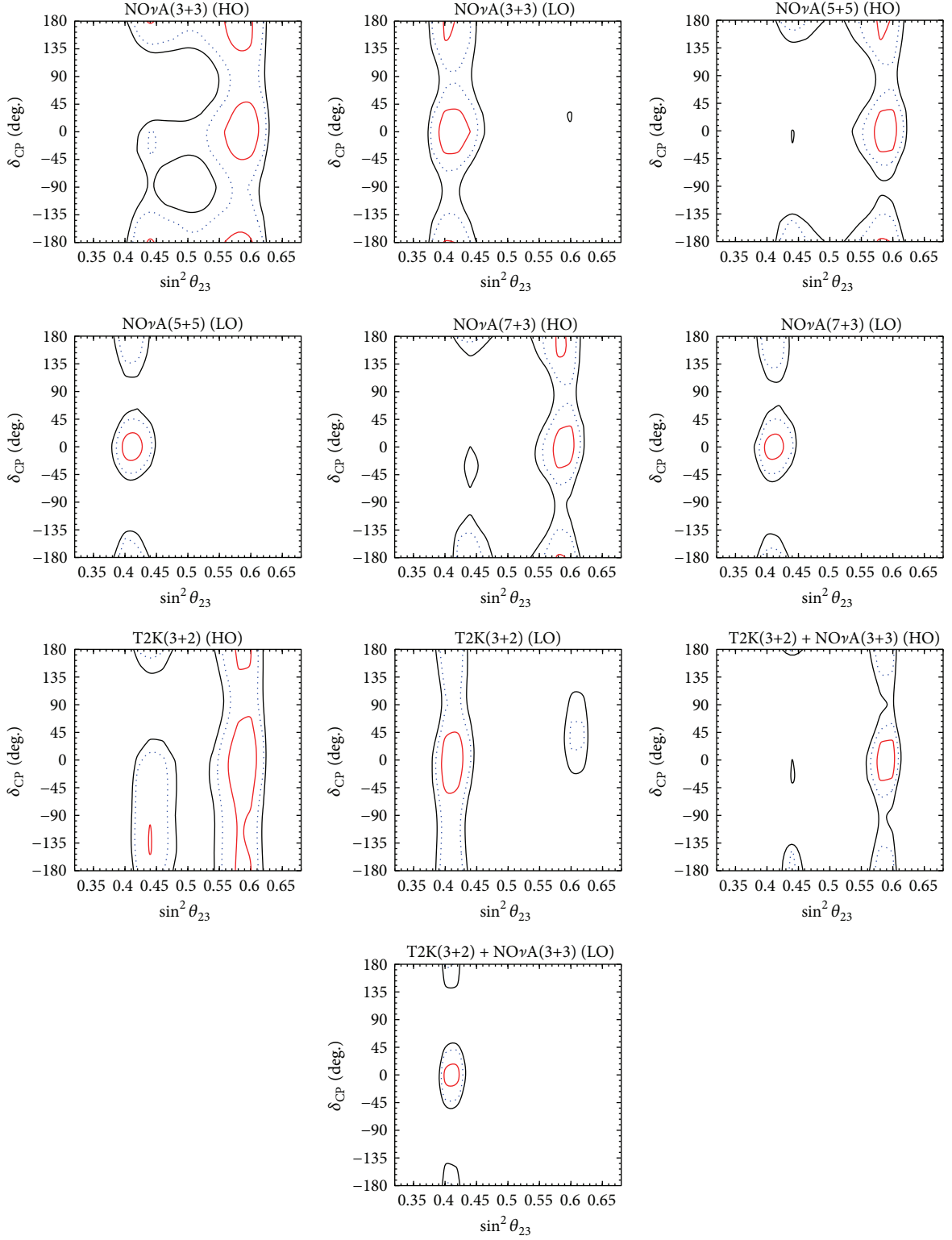
FIGURE 9: Confidence region in $\sin^2\theta_{23}$-δ_{CP} plane for true $\delta_{CP} = 0$, where red, blue, and black contours represent the 1σ (68.3% CL), 1.64σ (90% CL), and 2σ (95.45% CL) values, respectively, for two degrees of freedom. Here hierarchy is assumed to be IH.
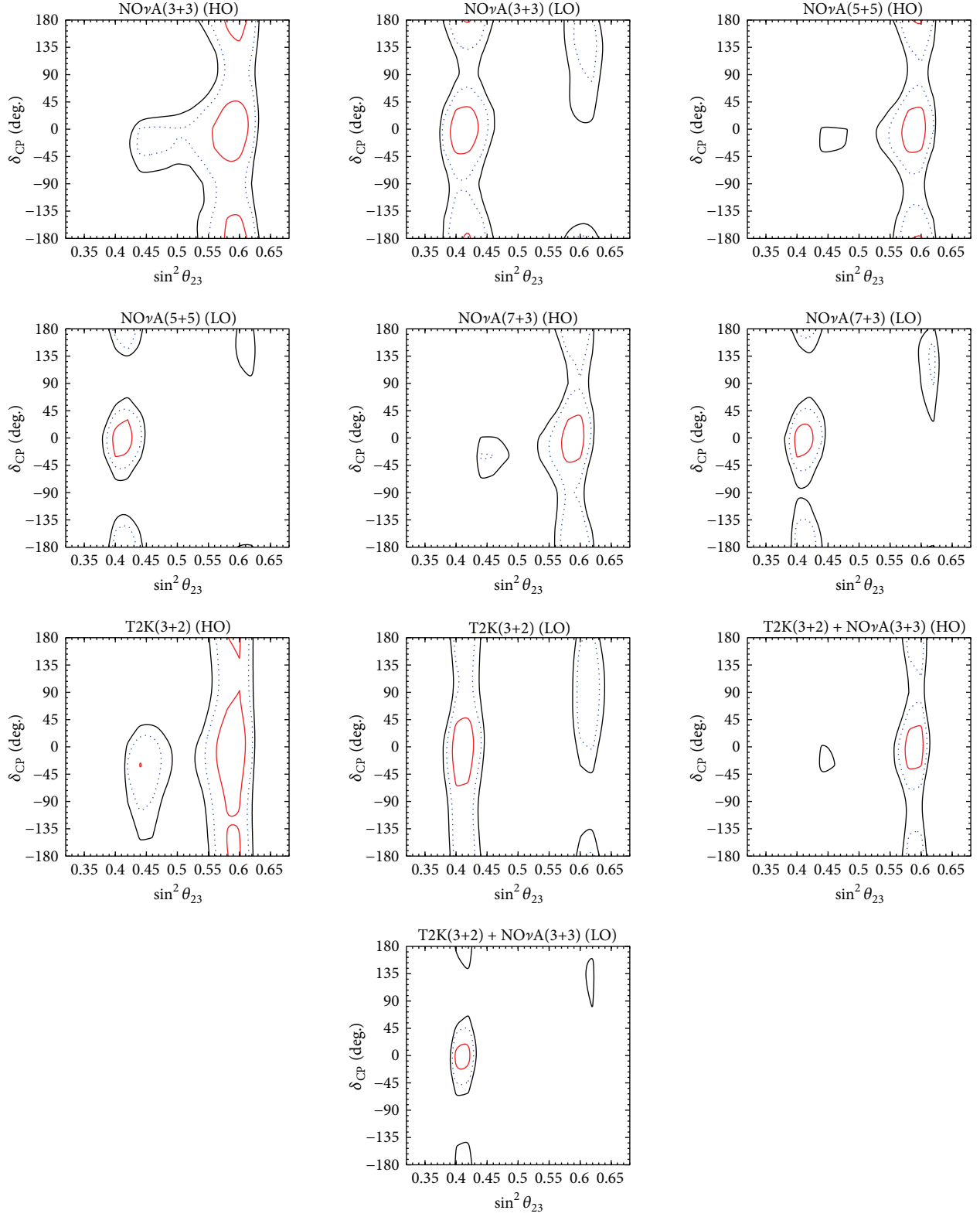
FIGURE 10: Confidence region in $\sin^2\theta_{23}$-δ_{CP} plane for true $\delta_{CP} = 0$, where red, blue, and black contours represent the 1σ, 1.64σ, and 2σ values, respectively, for two degrees of freedom. Here hierarchy is assumed to be NH.

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 θ_{23}, and the observation of CP violation in the neutrino sector due to δ_{CP} with the currently running accelerator based neutrino experiments NOνA and T2K and the forthcoming T2HK experiment. As the reactor mixing angle θ_{13} is now known to be significantly large, the oscillation probability $P(\nu_\mu \to \nu_e)$ and its corresponding antineutrino counterpart are sensitive for the determination of mass hierarchy and θ_{23} octant. We found that T2K experiment with $(3\nu + 2\overline{\nu})$ years of running can resolve the octant degeneracy with nearly 2σ CL if the true value of θ_{23} is around $\sin^2\theta_{23} = 0.41$ (LO) or $\sin^2\theta_{23} = 0.59$ (HO). The sensitivity increases to nearly 3σ with $(3\nu + 3\overline{\nu})$ years of running of NOνA. 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 NOνA continues data taking for 10 years then octant degeneracy can be resolved with NOνA experiment alone with more than 3σ significance. For the determination of mass hierarchy, it is also possible to rule out nearly one-third of the δ_{CP} space at 3σ CL if we use the synergy between NOνA and T2K experiments. In this case the sensitivity increases significantly for ten years of running of NOνA with $(5 + 5)$ combination that is found to be more suitable than the combination of $(7 + 3)$ years.

Measuring CP violation in the lepton sector is another important challenging problem today. We have also performed a systematic study of the CP sensitivity of the current long-baseline experiments T2K and NOνA. Although these experiments are not planned to study leptonic CP violation, we analyze the synergies between these setups which may aid in CP violation discovery by constraining the value of δ_{CP}. Although dedicated long-baseline experiments like DUNE, T2HK are planned to study CP violation in neutrino sector, we may have the first hand information on δ_{CP} from these experiments much before those dedicated facilities are operational. We found that T2K by itself has marginal CP violation sensitivity at 1σ CL. For NOνA with $(3 + 3)$ years of running there will be CP violation sensitivity above 1.5σ level for about one-third of the CP violating phase δ_{CP} space. The sensitivity increases slightly for 10 years of run time, with $(5\nu + 5\overline{\nu})$ combination having sensitivity compared to that of $(7\nu + 3\overline{\nu})$ combination. The data from T2HK experiment will improve the CPV sensitivity significantly. We have also found that the CP violating phase δ_{CP} can be determined to be better than $35°$, $21°$, and $9°$ for all values of δ_{CP} for T2K, NOνA, and T2HK experiments. We also obtained the confidence regions in the δ_{CP}-θ_{13} (θ_{23}) plane for both T2K and NOνA experiments.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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