Potential of optimized NOνA for large $\theta_{13}$ & combined performance with a LArTPC & T2K

Sanjib Kumar Agarwalla,$^a$ Suprabh Prakash,$^b$ Sushant K. Raut$^{b,c}$ and S. Uma Sankar$^{b,d}$

$^a$Instituto de Física Corpuscular, CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain

$^b$Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India

$^c$Physical Research Laboratory, Ahmedabad 380009, India

$^d$Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400005, India

E-mail: Sanjib.Agarwalla@ific.uv.es, suprabh@phy.iitb.ac.in, sushant@phy.iitb.ac.in, uma@phy.iitb.ac.in

ABSTRACT: NOνA experiment has reoptimized its event selection criteria in light of the recently measured moderately large value of $\theta_{13}$. We study the improvement in the sensitivity to the neutrino mass hierarchy and to leptonic CP violation due to these new features. For favourable values of $\delta_{\text{CP}}$, NOνA sensitivity to mass hierarchy and leptonic CP violation is increased by 20%. Addition of 5 years of neutrino data from T2K to NOνA more than doubles the range of $\delta_{\text{CP}}$ for which the leptonic CP violation can be discovered, compared to stand alone NOνA. But for unfavourable values of $\delta_{\text{CP}}$, the combination of NOνA and T2K are not enough to provide even a 90% C.L. hint of hierarchy discovery. Therefore, we further explore the improvement in the hierarchy and CP violation sensitivities due to the addition of a 10kt liquid argon detector placed close to NOνA site. The capabilities of such a detector are equivalent to those of NOνA in all respects. We find that combined data from 10kt liquid argon detector (3 years of $\nu$ + 3 years of $\bar{\nu}$ run), NOνA (6 years of $\nu$ + 6 years of $\bar{\nu}$ run) and T2K (5 years of $\nu$ run) can give a close to 2$\sigma$ hint of hierarchy discovery for all values of $\delta_{\text{CP}}$. With this combined data, we can achieve CP violation discovery at 95% C.L. for roughly 60% values of $\delta_{\text{CP}}$.

KEYWORDS: Neutrino Physics, CP violation

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1 Introduction

The recent measurements of $\theta_{13}$ by the reactor neutrino experiments Double Chooz [1, 2], Daya Bay [3, 4], and RENO [5, 6] are a very welcome news for future neutrino oscillation experiments. In addition to confirming the non-zero $\theta_{13}$ as hinted earlier by the accelerator experiments T2K [7, 8] and MINOS [9, 10], these experiments have determined the value of $\theta_{13}$ quite precisely. Global fits to the world neutrino data [11, 12] give a best fit value $\sin^2 2\theta_{13} = 0.095$ with a 1$\sigma$ uncertainty of about 10% [12]. Daya Bay experiment is expected to reduce the uncertainty to 5% level by the time it finishes running in 2016 [13]. Since the value of $\sin^2 2\theta_{13}$ is moderately large (in fact, it is just below the CHOOZ upper limit [14, 15]), the current (T2K) [16] and upcoming (NO$\nu$A) [17] experiments now have a chance of determining the remaining unknowns of neutrino oscillations: i.e. (a) neutrino mass hierarchy (equivalently the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$) and (b) existence of CP violation in the leptonic sector.

CP violation in the leptonic sector has drawn tremendous interest because of the possibility of leptogenesis leading to baryogenesis and the baryon asymmetry of the universe [18]. Leptogenesis requires the existence of CP violation in the leptonic sector; see [19] for a recent review. The possible connection between leptogenesis and neutrino oscillations has been discussed in [20–22]. It is likely that the CP violating phase in neutrino oscillations is not directly related to the CP violation leading to leptogenesis. But a demonstration
of CP violation in neutrino oscillations provides a crucial guidepost for models of leptonic CP violation and leptogenesis.

The experiments NO\(\nu\)A and T2K expect to achieve the above goals by measuring the \(\nu_\mu \to \nu_e\) oscillation probability \(P_{\mu e}\) and its charge conjugate \(\bar{\nu}_\mu \to \bar{\nu}_e\) oscillation probability \(P_{\bar{\mu} \bar{e}}\). Since these experiments have moderately long baselines (295 km for T2K and 810 km for NO\(\nu\)A), the matter effects due to neutrino propagation through Earth [23] are important, especially for NO\(\nu\)A [24]. The matter term modifies \(P_{\mu e}\) (and also \(P_{\bar{\mu} \bar{e}}\)) differently for normal hierarchy (NH where \(\Delta m^2_{31}\) is positive) and for inverted hierarchy (IH where \(\Delta m^2_{31}\) is negative). Thus these experiments are capable of distinguishing between the two hierarchies. The matter term also changes sign when we switch from neutrino mode to anti-neutrino mode. Hence the matter effects induce a CP like change in the oscillation probabilities. Thus we have an entanglement of changes caused by matter effects and the genuine CP violating phase \(\delta_{CP}\). Due to this, we get two degenerate solutions for a given experiment: one with the right hierarchy and the right value of \(\delta_{CP}\) and one with the wrong hierarchy and a wrong value of \(\delta_{CP}\). These degenerate solutions can be unravelled if data from two different experiments with different baselines is available [25–30].

It was shown that the data from T2K and NO\(\nu\)A should be synergistically combined to obtain the best possible sensitivity to hierarchy [31]. The presently planned runs of T2K and NO\(\nu\)A will not be able to determine the hierarchy for the whole range of \(\delta_{CP}\) [32–34]. Matter effects increase \(P(\nu_\mu \to \nu_e)\) for NH and decrease it for IH and vice versa for \(P_{\bar{\mu} \bar{e}}\). For \(\delta_{CP}\) in the lower half-plane (LHP, \(-180^\circ \leq \delta_{CP} \leq 0\)), \(P(\nu_\mu \to \nu_e)\) is larger and for \(\delta_{CP}\) in the upper half-plane (UHP, \(0 \leq \delta_{CP} \leq 180^\circ\)), \(P(\nu_\mu \to \nu_e)\) is smaller. Hence, for the combination (NH, LHP), the values of \(P(\nu_\mu \to \nu_e)\) are much higher than those for IH (and \(P_{\bar{\mu} \bar{e}}\) values are much lower). Similarly, for the combination (IH, UHP), the values of \(P(\nu_\mu \to \nu_e)\) are much lower than those of NH (and \(P_{\bar{\mu} \bar{e}}\) values are much higher). Thus, LHP is the favourable half-plane for NH and UHP is for IH [35]. Therefore, NO\(\nu\)A by itself can determine the hierarchy if \(\delta_{CP}\) happens to be in the favourable half-plane [33, 35]. The range of \(\delta_{CP}\) values, for which the hierarchy can be determined, increases to some extent if the T2K data is included. It was shown that the hierarchy can be determined for the entire range of \(\delta_{CP}\) if there is 50% more data from NO\(\nu\)A and twice the data from T2K [35].

In light of the moderately large value of \(\theta_{13}\), NO\(\nu\)A experiment has reoptimized their event selection criteria, with more events in both signal and background [36, 37]. These new criteria improve the hierarchy determination ability significantly in the favourable half-planes of \(\delta_{CP}\) but not in the unfavourable half-planes. The hierarchy sensitivity, for the unfavourable \(\delta_{CP}\) half-planes, can be improved only with a much larger data sample. In this paper, we explore the expected improvement in the sensitivity to both hierarchy and leptonic CP violation because of increased data from experiments with 810 km baseline. Liquid argon time projection chamber (LArTPC) are emerging as a very good option for neutrino detector technology for future neutrino experiments both in Europe [38–41] and in the U.S.A. [42–44]. Recently, LBNE collaboration has explored the possibility of building a 10 to 30 kt LArTPC at either NO\(\nu\)A or MINOS site [45]. We calculate the combined sensitivity of a 10 kt LArTPC at the NO\(\nu\)A site, in conjunction with NO\(\nu\)A and T2K detectors, to hierarchy and to the existence of leptonic CP violation.
The paper is organized as follows. In section 2, we discuss the detectors we consider in this analysis, paying particular attention to the improvements implemented in NOνA [36] and contrasting them with old NOνA event selection. We also detail how these improvements have been implemented in our simulations. We briefly describe the LArTPC and compare its properties with those of NOνA. Sections 3 and 4 describe the event spectrum and our numerical procedure respectively. In section 5, we present our sensitivity results for the determination of hierarchy and the detection of CP violation for various combinations of experiments. Finally, in section 6, we mention our conclusions.

2 Detectors

In this section, we briefly describe the main features of the detectors considered in this report.

2.1 NOνA

NOνA is a 14 kt totally active scintillator detector (TASD) at a distance of 810 km from Fermilab, at a location which is 0.8° off-axis from the NuMI beam. Because of the off-axis location, the flux of the neutrinos is reduced but is sharply peaked around 2 GeV. This leads to two important advantages:

- The peak flux is close to the first oscillation maximum energy of 1.7 GeV. This leads to a large number of signal events.

- The most problematic background is neutral current (NC) interactions which mostly consists of the single π^0 production. However, the measured energy of this background is shifted to values of energy below the region where the flux is significant. Hence this background can be rejected using a simple kinematic cut.

The experiment is scheduled to run for three years in neutrino mode and three years in anti-neutrino mode with a NuMI beam power of 0.7 MW, corresponding to $6 \times 10^{20}$ protons on target per year.

Previously, the event selection criteria were optimized to have the least background even under the most pessimistic assumption of $\sin^2 2\theta_{13} = 0$. This gave the best possible background rejection, at the cost of reduced signal efficiency, which was required in the event of very small $\sin^2 2\theta_{13}$. With the present, moderately large value of $\sin^2 2\theta_{13}$, NOνA has relaxed the cuts for the event selection criteria which allow more signal events along with more background events. Additional backgrounds, mostly NC, are reconstructed at energies lower compared to the true neutrino energy and can be managed by a kinematic cut. The main differences between the old criteria and new criteria are listed below [34, 36, 37].

- The signal efficiencies for new NOνA are higher than that of old one by roughly a factor of 2 for neutrino events. We now assume 45% signal efficiency for both neutrino and anti-neutrino events as opposed to 26% for $\nu$ and 40% for $\bar{\nu}$ previously.
Detector characteristic | LArTPC @ NOνA | TASD @ NOνA
--- | --- | ---
Fiducial mass | 5 or 10 kt | 14 kt
Neutrino energy threshold | 0.5 GeV | 0.5 GeV
Detection efficiency | 85% for $\mu^\pm$(CC), 80% for $e^\pm$ | 100% for $\mu^\pm$(CCQE), 45% for $e^\pm$
Energy resolution (GeV) | $0.1 \sqrt{E/\text{GeV}}$ for CC $\mu^\pm$ and $e^\pm$ sample | $0.06 \sqrt{E/\text{GeV}}$ for CC $\mu^\pm$ and $0.085 \sqrt{E/\text{GeV}}$ for $e^\pm$ sample
NC background smearing | Migration matrices | Migration matrices
NC background acceptance | 1% (both $\nu$ and $\bar{\nu}$) | 2% ($\nu$), 3% ($\bar{\nu}$)
Mis-ID muons acceptance | 1% (both $\nu$ and $\bar{\nu}$) | 0.83% ($\nu$), 0.22% ($\bar{\nu}$)
Int. beam $\nu_e/\bar{\nu}_e$ contamination | 80% (both $\nu$ and $\bar{\nu}$) | 26% ($\nu$), 18% ($\bar{\nu}$)
Signal normalization error | 5% | 5%
Background normalization error | 5% | 10%

Table 1. Detector properties of LArTPC and TASD.

- The background acceptance has also increased. For the NC interactions, present value is about 7 times (2% vs. 0.3%) for $\nu$ and 3 times (3% vs. 0.9%) for $\bar{\nu}$, compared to the old criteria. For misidentified muons also, it is about 6 times (0.83% vs. 0.13%) and 2 times (0.22% vs. 0.13%) the older numbers, for $\nu$ and $\bar{\nu}$ respectively.

- Earlier, the number of NC background events was moderate. In such a situation, using a Gaussian energy resolution function to obtain the smearing of the background events is not a bad approximation. At present though, the NC backgrounds are higher by a factor of 5 and but their measured energy, in general, will be in a range below the region of large flux. The NC spectrum shift to the measured energies is implemented through migration matrices.

- In our analysis, we have taken care of the neutrino contamination in the anti-neutrino beam for both appearance and disappearance channels. It should be stressed that while anti-neutrino contamination can be ignored in the neutrino beam, the reverse is not true.

The above optimization criteria were developed by using the event spectra for the case of $\nu_\mu \rightarrow \nu_e$ vacuum oscillations with $\delta_{CP} = 0$ and maximizing the signal events while keeping the background events relatively small. We calculated the same event spectrum under the same assumptions and adjusted the signal and background efficiencies in the simulations, until we obtained the same number of signal events and background events as in [36].

In table 1, we summarize the main characteristics of TASD and LArTPC which we discuss next.

2.2 Liquid Argon TPC

Here we consider a 10 kt LArTPC constructed close to NOνA. LArTPC has excellent particle identification and we assume a signal efficiency of 80% for $e^\pm$ compared to 45% for TASD. The energy resolution and background rejection for the LArTPC and TASD are comparable. In our simulations, we have taken the efficiencies and migration matrices of
LArTPC from [44]. It is expected, of course, that such a detector will come on line much later than NO\textnu A. In considering NO\textnu A + LArTPC, we assume equal 6 years \nu and \bar{\nu} runs for NO\textnu A and equal 3 years \nu and \bar{\nu} runs for LArTPC. The cross-sections for LArTPC are slightly different from those of TASD. To obtain the LArTPC cross-sections, we have scaled the inclusive charged current (CC) cross sections by 1.06 (0.94) for the \nu (\bar{\nu}) case compared to those for water [46, 47].

2.3 T2K

T2K uses the 50 kt Super-Kamiokande water Cerenkov detector (fiducial volume 22.5 kt) as the end detector for the neutrino beam from J-PARC. The detector is at a distance of 295 km from the source at an off-axis angle of 2.5° [16]. The neutrino flux is again peaked sharply at the first oscillation of 0.7 GeV. The experiment is scheduled to run for 5 years in the neutrino mode with a power of 0.75 MW. Because of the low energy of the peak flux, the NC backgrounds are small and they can be rejected based on energy cut. The signal efficiency is 87%. The background information and other details are taken from [32, 48].

3 Event rates and spectrum

We use GLoBES [49, 50] software to simulate the data for various experiments. For the atmospheric/accelerator neutrino parameters, we take the following central (true) values:

$$|\Delta m^2_{\text{eff}}| = 2.4 \times 10^{-3} \text{eV}^2, \quad \sin^2 2\theta_{23} = 1.0,$$

where $\Delta m^2_{\text{eff}}$ is the effective mass-squared difference measured by the accelerator experiments in $\nu_\mu \to \nu_\mu$ disappearance channel [51]. It is related to the $\Delta m^2_{31}$ (larger) and $\Delta m^2_{21}$ (smaller) mass-square differences through the expression [52]

$$\Delta m^2_{\text{eff}} = \Delta m^2_{31} - \Delta m^2_{21} (\cos^2 \theta_{12} - \cos \delta_{\text{CP}} \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23}),$$

where $\Delta m^2_{21} = m^2_2 - m^2_1$. The best fit for $\theta_{23}$ is taken from atmospheric neutrino data [53]. For $\theta_{13}$, we take the global best fit $\sin^2 2\theta_{13} = 0.101$ [12].\footnote{The best fit value for $\sin^2 2\theta_{13}$ and its uncertainty are taken from the 2nd version of [12], dated 21 May 2012. The values quoted in the introduction are taken from the 3rd version of the same paper, dated 13 Aug 2012, by which time our calculations were finished. The 3rd version includes the data presented at the Neutrino 2012 conference at Kyoto and hence the values have changed a little. We have checked that our conclusions are not affected by these small changes.} The uncertainties in the above parameters are taken to be $\sigma(\sin^2 \theta_{13}) = 13\%$ [12], $\sigma(|\Delta m^2_{\text{eff}}|) = 4\%$ and $\sigma(\sin^2 2\theta_{23}) = 2\%$ [16]. We take the solar parameters to be [12]

$$\Delta m^2_{21} = 7.62 \times 10^{-5} \text{eV}^2, \quad \sin^2 \theta_{12} = 0.32.$$
Figure 1. (Colour online.) Left panel portrays the expected signal and background event rates including the efficiency and background rejection capabilities in the $\nu_e$ appearance channel for $\sin^2 2\theta_{13} = 0.101$ and $\delta_{\text{CP}} = 0^\circ$, as a function of the reconstructed neutrino energy for the off-axis NO$\nu$A site with 14 kt TASD detector running for 3 years exposed to 0.7 MW NuMI beam. Right panel shows the same for a 10 kt LArTPC detector running at off-axis NO$\nu$A site for 3 years exposed to 0.7 MW NuMI beam. A normal hierarchy has been assumed. In all the panels, the blue dot-dashed and the orange dotted vertical lines display the locations of the first and second oscillation maxima.

Recently, MINOS experiment found the best fit for $\sin^2 2\theta_{23}$ to be 0.97 rather than 1 [10]. Hence we must consider the possibility that best fit value for $\sin^2 2\theta_{23}$ is 0.413. From the Daya Bay experiment, the best fit value for $\sin^2 2\theta_{13}$ is 0.089 [4], which is 10% smaller than the global best fit 0.101 we have used. In appendix A, we show how hierarchy and CP sensitivities change if these conservative input values are used.

The signal and different background event spectra are shown in figure 1 for NO$\nu$A (left panel) and for LArTPC (right panel). Even though the mass of the LArTPC detector is smaller, the event numbers in the two cases are comparable due to the higher signal acceptance. The NC background spectrum is shifted to lower energies due to the use of migration matrices and can easily be suppressed by an energy cut.

In table 2, we list the number of signal and background events for the old NO$\nu$A detector, new reoptimized NO$\nu$A detector and for a 10 kt LArTPC, for both $\nu_\mu \rightarrow \nu_e$ appearance channel and $\nu_\mu \rightarrow \nu_\mu$ disappearance channel. In the calculation of the event numbers for the disappearance channel, we match the numbers with the plot given in NO$\nu$A website [54]. The background events in the appearance channel arise from three possible sources: (a) intrinsic $\nu_e/\bar{\nu}_e$ content of the beam, (b) mis-identified muons and (c) NC reactions. In this study we have taken into account the $\nu_e$ contamination in the $\bar{\nu}_\mu$ beam, which is a significant source of the background. In the disappearance channel backgrounds mainly arise from the $\bar{\nu}_\mu (\nu_\mu)$ contamination in $\nu_\mu (\bar{\nu}_\mu)$ beam with a small number coming from NC reactions. The signal events are shown for both neutrino and anti-neutrino runs and for both normal and inverted hierarchies.
Table 2. Total number of signal and background events for old NOνA, new NOνA and LArTPC, in both appearance ($\nu_\mu \rightarrow \nu_e$) and disappearance ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) modes. The backgrounds are subdivided into three parts: (a) intrinsic beam $\nu_e/\bar{\nu}_e$ (Int.), (b) mis-identified muons (Mis-ID) and (c) single $\pi^0$ events from neutral current interactions (NC). In the disappearance mode, wrong-sign muon indicates the background coming from $\bar{\nu}_\mu$ ($\nu_\mu$) contamination in $\nu_\mu$ ($\bar{\nu}_\mu$) beam.

We see from table 2 that both the signal and background event rates are larger for new NOνA compared to old NOνA. The rise in the signal is only 50% whereas the background rises by a factor 3. But the number of signal events increases by 30 whereas the number of background events rises by 20. Thus overall, there is a gain in signal relative to the background. The background events are fixed and do not change with a change in hierarchy or with a variation of $\delta_{CP}$, whereas the signal events do. Since we are interested in measuring these changes in the signal events with hierarchy and $\delta_{CP}$, it is more advantageous to have a larger signal event sample, even at the expense of a larger background sample.

In figure 2, we plot the signal event numbers (along with statistical error bars) as a function of $\delta_{CP}$ for new NOνA, both for NH and IH. The left panel shows the event numbers for three years of running in the neutrino mode and the right panel depicts the event numbers for three years in the anti-neutrino mode. We see that for the combination NH and LHP ($-180^\circ \leq \delta_{CP} \leq 0$), the neutrino event numbers are much greater than the IH event numbers for any $\delta_{CP}$. Similarly for the combination IH and UHP ($0 \leq \delta_{CP} \leq 180^\circ$), the event numbers are much lower than NH event numbers for any $\delta_{CP}$. Hence NOνA has good hierarchy discrimination for these two combinations. For the other two combinations, it is possible to have two solutions with different hierarchies for the same event numbers. This feature occurs, not only for the total event numbers but also for the spectrum. Thus, for unfavourable $\delta_{CP}$ half-planes, hierarchy determination is not possible with NOνA.

4 Numerical simulation

We use the minimization of $\Delta \chi^2$ to estimate the hierarchy and CP violation sensitivities. For hierarchy sensitivity, we first assume NH to be the true hierarchy and we choose a true value of $\delta_{CP}$. We compute the NH event spectrum for these assumptions and the
above true values of neutrino parameters and label it to be data. Then we compute a theoretical event spectrum assuming IH and varying the test values of neutrino parameters within their ±2σ ranges and δCP in the full allowed range (−180°, 180°). In doing this marginalization, we impose Gaussian priors on the measured neutrino parameters. We compute a Δχ² between the event spectra of the data and the theory and demand that its minimum value Δχ²_{min} ≥ 2.71 (3.84) for a 90% (95%) C.L. hint of hierarchy. If this condition is satisfied, then the hierarchy can be determined at the appropriate confidence level, for the assumption of hierarchy being NH and δCP being the assumed true value. The calculation is repeated for various other assumed true values of δCP. If Δχ²_{min} ≥ 2.71 (3.84) for all values of true δCP, then we can say that the normal hierarchy can be established for all possible values of neutrino parameters. The whole calculation then has to be repeated for the case of true hierarchy being IH. If Δχ²_{min} ≥ 2.71 (3.84) for all true values of δCP, then the hierarchy can be determined for all possible values of neutrino parameters.

In computing the above spectra, it should be noted that the values of Δm²_{31} for NH and for IH are different. They are to be calculated from the expression in eq. (3.2) with Δm²_{eff} positive for NH and negative for IH. Since Δm²_{21} is always positive, this leads to different magnitudes for Δm²_{31} for NH and for IH. This difference must be taken into account while calculating the NH and IH spectra. Otherwise, there will be a spurious hierarchy sensitivity in the disappearance channel.

As mentioned in the introduction, for a given experiment, we will get two degenerate solutions: one with the correct hierarchy and true δCP and one with the wrong hierarchy and a wrong δCP. It was shown in [31] that two experiments with different baselines, with flux peaking at the first oscillation maximum, can pick the correct hierarchy and δCP because the wrong hierarchy solutions for different experiments occur for different values of δCP. But, the statistics of each of the two experiments have to be large enough for a
clean separation. We will see in the next section that the presently planned runs of T2K and NOνA are not enough for this separation to occur for the full range of $\delta_{CP}$. Therefore, for the existence of CP violation, we pose the following question: for what values of true $\delta_{CP}$ can NOνA and T2K establish that the CP phase differs from 0 or 180°, independently of the hierarchy? To answer this question, we compute the data spectrum say for NH and for a true value of $\delta_{CP}$, as described above. We compute the theoretical spectrum for the following four combinations of hierarchy and CP conservation (NH, $\delta_{CP} = 0$), (NH, $\delta_{CP} = 180^\circ$), (IH, $\delta_{CP} = 0$) and (IH, $\delta_{CP} = 180^\circ$). We compute the $\Delta \chi^2$ between the data and each of these four combinations and choose its minimum value. If $\Delta \chi^2_{\text{min}} \geq 2.71 (3.84)$, then CP violation is established at 90% (95%) C.L. for true hierarchy being NH and for $\delta_{CP}$ being the assumed true value. We repeat the calculation for the full range of $\delta_{CP}$ and determine the values of true $\delta_{CP}$ for which CP violation can be established. As in the case of hierarchy determination, these calculations are again repeated for the case where IH is the true hierarchy.

It must be mentioned that this method only establishes that the CP conservation is ruled out. But it is possible that the data may not be able to determine the hierarchy. In such a situation, the data must be analyzed under the assumption that either of the two hierarchies is correct. If the data is analyzed with the assumption of the right hierarchy, we get a region of allowed $\delta_{CP}$ surrounding the true $\delta_{CP}$. If the data is analyzed under the assumption of the wrong hierarchy, then the allowed $\delta_{CP}$ region may not include the true $\delta_{CP}$. The above procedure only requires that, for each of the hierarchies, the allowed $\delta_{CP}$ region should not include the CP conserving cases $\delta_{CP} = 0$ and $180^\circ$. If this condition is satisfied, the CP violation in neutrino sector is established independent of the hierarchy. We will not be able to know the true value of $\delta_{CP}$ without determining the hierarchy [35]. But proving the existence of of leptonic CP violation will be an important step forward in our understanding of the leptonic masses and mixings.

5 Results

In this section, we describe the capabilities of the experimental setups considered in this work, for the determination of mass hierarchy and CP violation.

5.1 Mass hierarchy discrimination

In figure 3, we plot the hierarchy discrimination sensitivity of the old NOνA, the new NOνA and the combined sensitivity of new NOνA and T2K, as a function of the true value of $\delta_{CP}$, in the left (right) panel for NH (IH) as the true hierarchy. We see that the wrong hierarchy can be ruled out very effectively for $\delta_{CP}$ in the favourable half-plane, which is LHP (UHP) for NH (IH).

The new event selection criteria of NOνA make the experiment even more effective in ruling out the wrong hierarchy for $\delta_{CP}$ in the favourable half-plane. In the unfavourable half-plane, both the old and the new criteria are equally ineffective. However, the addition of T2K data improves the situation significantly and $\Delta \chi^2$ increases from 0 to $\geq 2$ for all the true values of $\delta_{CP}$, thus making it possible to get a 90% C.L. hint of hierarchy with
some additional data. We have checked that a further increment in the exposure of T2K or addition of antineutrino data from T2K does not improve the hierarchy sensitivity much.

In figure 4, we plot the mass hierarchy discrimination capability of NOνA and a stand alone LArTPC with three possible masses: 5 kt, 10 kt and 14 kt. Before the reoptimization of NOνA event selection criteria, it was argued that a 5 kt LArTPC has the same capability as of the 15 kt TASD detector, because the signal acceptance of the former was three times that of the latter \[^{55}\]. But with the new event selection criteria the performance of NOνA
Figure 5. (Colour online.) Mass hierarchy discovery as a function of true value of $\delta_{\text{CP}}$. Combined performance of new NO$\nu$A, T2K and LArTPC. Left (right) panel is for NH (IH) as true hierarchy.

has dramatically improved. We see from the figure 4 that only a LArTPC of mass 10 kt can be as effective as NO$\nu$A. But, once again, it must be noted that none of the detectors are effective if the true value of $\delta_{\text{CP}}$ is in the unfavourable half-plane.

Finally, in figure 5 we plot the combined hierarchy discovery sensitivity of NO$\nu$A, T2K and a LArTPC (of mass 5 kt and 10 kt) and compare it with the hierarchy sensitivity of combined NO$\nu$A and T2K data. We find that the addition of even a 5 kt LArTPC leads to a very significant improvement in the sensitivity when values of true $\delta_{\text{CP}}$ are in the unfavourable half-plane. With the addition of a 10 kt LArTPC, we see that close to 95% C.L. hierarchy discrimination becomes possible for all the values of $\delta_{\text{CP}}$.

5.2 CP violation discovery

Reoptimization of the event selection criteria of NO$\nu$A has the most dramatic effect on the CP violation discovery potential of the experiment. In figure 6, we plot the sensitivity to rule out CP conservation scenarios, as a function of true $\delta_{\text{CP}}$ in the left (right) panel for NH (IH) being the true hierarchy. We notice that, while in the case of old NO$\nu$A there is no CP violation sensitivity at all at 90% C.L., there is such a sensitivity in new NO$\nu$A, for about one third fraction of the favourable half-plane. Addition of T2K data leads to CP violation sensitivity for about half the region in both favourable half planes at 90% C.L. It can be shown that, T2K by itself, has no CP violation sensitivity. But, the synergistic combination of NO$\nu$A and T2K leads to much better CP violation sensitivity compared to the individual capabilities.

In figure 7, we present a comparison of new NO$\nu$A with stand alone LArTPC of different masses. As in the case of the mass hierarchy discrimination, the performance of a 10 kt LArTPC detector is closest to the performance of the new NO$\nu$A.
Figure 6. (Colour online.) CP violation discovery as a function of true value of $\delta_{\text{CP}}$. Left (right) panel is for NH (IH) as true hierarchy.

Figure 7. (Colour online.) CP violation discovery as a function of true value of $\delta_{\text{CP}}$, for different LArTPC detector masses and new NOvA. Left (right) panel is for NH (IH) as true hierarchy.

In figure 8, we plot the CP violation discovery potential of the combined data from new NOνA with a (6ν + 6$\bar{\nu}$) run, LArTPC of mass 5 kt and 10 kt with a (3ν + 3$\bar{\nu}$) run and T2K along with that of combined new NOνA with a (3ν + 3$\bar{\nu}$) run and T2K data. The net effect of new NOνA with (6ν + 6$\bar{\nu}$) run plus a 10 kt LArTPC with a (3ν + 3$\bar{\nu}$) is equivalent to tripling the data of NOνA with (3ν + 3$\bar{\nu}$) run. We note that the addition of the LArTPC leads to a very significant improvement in the range of true $\delta_{\text{CP}}$ for which CP conservation can be ruled out at 95% C.L. This range goes up from about half of the allowed values to about 60% of the allowed values.
Figure 8. (Colour online.) CP violation discovery as a function of true value of $\delta_{\text{CP}}$. Combined performance of new NO$\nu$A, T2K and LArTPC. Left (right) panel is for NH (IH) as true hierarchy.

| Setups                                               | Fraction of $\delta_{\text{CP}}$ (true) |
|------------------------------------------------------|----------------------------------------|
|                                                     | MH                                      |
| NO$\nu$A (3+3)                                       | 0.48 (0.43)                             |
| NO$\nu$A (3+3) + T2K (5+0)                          | 0.55 (0.45)                             |
| NO$\nu$A (6+6) + T2K (5+0) + 5 kt LArTPC (3+3)      | 1 (0.64)                                |
| NO$\nu$A (6+6) + T2K (5+0) + 10 kt LArTPC (3+3)     | 1 (0.71)                                |
|                                                     | CPV                                     |
| NO$\nu$A (3+3)                                       | 0.46 (0.41)                             |
| NO$\nu$A (3+3) + T2K (5+0)                          | 0.54 (0.43)                             |
| NO$\nu$A (6+6) + T2K (5+0) + 5 kt LArTPC (3+3)      | 1 (0.64)                                |
| NO$\nu$A (6+6) + T2K (5+0) + 10 kt LArTPC (3+3)     | 1 (0.71)                                |

Table 3. Fractions of true values of $\delta_{\text{CP}}$ for which a discovery is possible for MH and CPV. The numbers without (with) parentheses correspond to 90% (95%) C.L. The results are shown for both NH and IH as true hierarchy.

A summary of our results is given in table 3. For different combinations of experiments and different exposures, we have shown the fraction of $\delta_{\text{CP}}$ values for which mass hierarchy can be determined/CP violation can be detected.

6 Summary and conclusions

In light of the recent measurements indicating a moderately large value of $\sin^2 2\theta_{13}$, the NO$\nu$A collaboration has revisited their background rejection cuts. The relaxed acceptance cuts have resulted in a higher number of signal events. Hence, the variations induced by the change in hierarchy or a change in $\delta_{\text{CP}}$ are magnified and become more easy to detect.

In this work, we have studied the physics reach of the reoptimized NO$\nu$A (in conjunction with T2K) to determine the mass hierarchy and CP violation. With the presently planned runs of these two experiments, the above goals can be achieved for less than half...
the allowed values of $\delta_{CP}$. There is considerable enthusiasm in the NO$\nu$A and LBNE collaborations for an additional small liquid argon detector at the Ash River site. In this study we have also considered the possibility of such a module.

For favourable values of $\delta_{CP}$, NO$\nu$A in its original configuration can determine the mass hierarchy by itself. The reoptimized new NO$\nu$A allows us to determine the hierarchy with greater confidence in the favourable half-plane of $\delta_{CP}$. However, in the unfavourable half-plane, the sensitivity is negligible. Addition of data from T2K helps to break the parameter degeneracy and increases the $\Delta \chi^2$ significantly in the unfavourable half-plane. But the currently planned runs of NO$\nu$A and T2K are not sufficient to raise the $\Delta \chi^2$ above 2.71 and give us a 90% hint of hierarchy for $\delta_{CP}$ in the unfavourable half-plane.

A 10 kt LArTPC is found to be equivalent to new NO$\nu$A in its ability to exclude the wrong hierarchy. Thus, addition of such a module to the existing NO$\nu$A detector will help increase the statistical significance of the experimental data. We find that for increased exposure for NO$\nu$A, the combination of data from NO$\nu$A, LArTPC and T2K (nominal) can determine hierarchy at almost 2$\sigma$ level for all the values of $\delta_{CP}$. We have checked that increasing the exposure of T2K or adding antineutrino data from T2K does not improve the results much.

Discovering CP violation is more difficult than determining the hierarchy. NO$\nu$A by itself can discover CP violation only for a small fraction of the favourable half-plane, and only at 90% C.L. Addition of data from T2K causes a remarkable increase, by a factor of 2.4, in the range of $\delta_{CP}$ for which CP violation can be established. This includes a significant part of the unfavourable half-plane also. Once again, we find that a 10 kt LArTPC has capabilities similar to NO$\nu$A. The combination of additional data from the LArTPC detector with boosted NO$\nu$A and nominal T2K greatly improves the ability. For around 60% of the entire $\delta_{CP}$ range, CP violation can be discovered at 95% confidence level.

In conclusion, we find that after reoptimizing NO$\nu$A for large $\theta_{13}$, the sensitivity of the experiment to mass hierarchy and CP violation is increased. Adding data from T2K breaks the hierarchy-$\delta_{CP}$ degeneracy but is not enough to determine hierarchy for unfavourable $\delta_{CP}$ values. Additional data from a LArTPC will lead to a significant boost in both hierarchy and CP violation sensitivities when combined with NO$\nu$A and T2K.

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Table 4. The values of $\sin^2 \theta_{13}$ and $\sin^2 \theta_{23}$ taken in Best-fit 1 and Best-fit 2. The values of other oscillation parameters are the same for the two cases considered.

|           | Best-fit 1 | Best-fit 2 |
|-----------|-----------|-----------|
| $\sin^2 \theta_{13}$ | 0.101     | 0.089     |
| $\sin^2 \theta_{23}$ | 0.5       | 0.413     |

Figure 9. (Colour online.) Mass Hierarchy discovery as a function of true value of $\delta_{\text{CP}}$ for the conservative values of input parameters, of new NO$\nu$A and of LArTPC of various masses. Left (right) panel is for NH (IH) as true hierarchy.

A Performance with conservative choices of central values

Here we consider how the sensitivities of various setups will change if the conservative input values of neutrino mixing angles, mentioned in section 3, are used. In table 4, we list the values considered in the main paper (called Best-fit 1) and the conservative values considered in this appendix (called Best-fit 2).

Figures 9 and 10 show, respectively, the mass hierarchy and the CP violation sensitivities of the new NO$\nu$A and the LArTPC of different masses, for the conservative parameters (Best-fit 2). These figures are to compared with the corresponding figures 4 and 7. We find that both the sensitivities are, in general, worse.

Table 5 lists the fraction of $\delta_{\text{CP}}$ values for which we can obtain mass hierarchy sensitivity and CP violation sensitivity at 90\% C.L. and at 95\% C.L. Comparing the corresponding entries in table 3 and 5, we find that the mass hierarchy sensitivity is worse for all the combinations with one exception. A 90\% C.L. hint of mass hierarchy can be obtained for all the $\delta_{\text{CP}}$ values if we have $(6\nu + 6\bar{\nu})$ run of NO$\nu$A, $(5\nu + 0)$ run of T2K and $(3\nu + 3\bar{\nu})$ run of a 10kt LArTPC. But, for all other cases, the mass hierarchy sensitivity is worse because the leading term in $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability is down by 30\%, causing the number of events also to be down by a similar fraction. This is also reflected in figure 11, which compares the combined sensitivities for the two sets of parameters.
Figure 10. (Colour online.) CP violation discovery as a function of true value of $\delta_{CP}$ for the conservative values of input parameters, of new NO$\nu$A and of LArTPC of different masses. Left (right) panel is for NH (IH) as true hierarchy.

| Setups                          | Fraction of $\delta_{CP}$ (true) |
|---------------------------------|-----------------------------------|
|                                | MH                                 | CPV                                |
|                                | NH true                           | IH true                            | NH true                           | IH true                            |
| NO$\nu$A (3+3)                 | 0.39 (0.33)                       | 0.37 (0.31)                        | 0.2 (0.1)                         | 0.22 (0.13)                        |
| NO$\nu$A (3+3) + T2K (5+0)     | 0.41 (0.34)                       | 0.39 (0.31)                        | 0.28 (0.22)                       | 0.3 (0.25)                        |
| NO$\nu$A (6+6) + T2K (5+0) + 5 kt LArTPC (3+3) | 0.78 (0.5)                       | 0.89 (0.48)                        | 0.68 (0.45)                       | 0.71 (0.51)                        |
| NO$\nu$A (6+6) + T2K (5+0) + 10 kt LArTPC (3+3) | 1 (0.54)                         | 1 (0.54)                           | 0.7 (0.53)                        | 0.73 (0.63)                        |

Table 5. Fractions of true values of $\delta_{CP}$ for which a discovery is possible for MH and CPV. The numbers without (with) parentheses correspond to 90% (95%) C.L. Here we take the central value for $\sin^2 \theta_{13}$ to be 0.089 as predicted by Daya Bay. For $\sin^2 \theta_{23}$, the best fit value that we consider is 0.413. The results are shown for both NH and IH as true hierarchy.

Regarding CP violation sensitivity, there is a small improvement, with these conservative parameters. In this sensitivity, we are constraining the situation of CP violation with $\delta_{CP} = 0$ and with $\delta_{CP} = 180^\circ$. Thus, in the numerator of $\Delta \chi^2$, the 30% change in the leading term of $P(\nu_\mu \rightarrow \nu_e)$ cancels out. And the sub-leading term, which depends on $\delta_{CP}$, changes by less than 5%. In the denominator of $\Delta \chi^2$, the leading term of $P(\nu_\mu \rightarrow \nu_e)$ still dominates, thus the $\Delta \chi^2$ becomes larger. This is true for all the $\delta_{CP}$ values except for those in the range where the marginalization over hierarchy brings $\Delta \chi^2$ down, as shown in figure 12. Because of this, CP violation sensitivity becomes possible for a slightly larger fraction of $\delta_{CP}$ values. In figure 12, comparison is done for only two of the setups but table 5 shows the sensitivities with new inputs for all the setups. The higher sensitivity to CP violation for smaller values of $\theta_{13}$ was noted before in [56, 57].
Figure 11. (Colour online.) Mass Hierarchy discovery as a function of true value of $\delta_{CP}$ for the conservative values of input parameters. Combined performance of new NOvA, T2K and LArTPC. Left (right) panel is for NH (IH) as true hierarchy.

Figure 12. (Colour online.) CP violation discovery as a function of true value of $\delta_{CP}$ for the conservative values of input parameters. Combined performance of new NOvA, T2K and LArTPC. Left (right) panel is for NH (IH) as true hierarchy.
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