Evidence for leptonic CP phase from NOνA,T2K and ICAL

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Abstract

The phenomenon of neutrino oscillation is now well understood from the solar, atmospheric, reactor and accelerator neutrino experiments. This oscillation is characterized by a unitary PMNS matrix which is parametrized by three mixing angles and one phase known as the leptonic CP phase. Though there are already significant amount of information about the three mixing angles but the CP phase is still unknown. The long baseline experiments(LBL) have CP sensitivity coming from the appearance channel but atmospheric neutrinos known to have negligible CP sensitivity. In this work we study the synergy between the LBL experiment NOνA, T2K and the atmospheric neutrino experiment ICAL@INO for obtaining the first hint of CP violation in the lepton sector. We find that due to the lack of knowledge of hierarchy and octant CP sensitivity of NOνA/T2K is poorer for some parameter ranges. Addition of ICAL data to T2K and NOνA can exclude these spurious wrong-hierarchy and/or wrong-octant solutions and cause a significant increase in the range of δ_{CP} values for which a hint of CP violation can be achieved. Similarly the precision with which δ_{CP} can be measured also improves with inclusion of ICAL data.

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I. INTRODUCTION

CP symmetry refers to invariance under simultaneous transformation of charge conjugation and parity. CP violation has been observed in the quark sector and this can be explained by the complex phase of the CKM matrix [1]. The complex phase, analogous to the CKM phase, in the leptonic mixing matrix can lead to CP violation in the lepton sector [2]. However experimental detection of this phase is necessary to establish this expectation on a firm footing. The determination of the leptonic CP phase is interesting not only in the context of fully determining the PMNS mixing matrix but also because it could be responsible for the observed matter-antimatter asymmetry through the mechanism of leptogenesis [3].

A potential problem in determining δ_{CP} comes from the lack of knowledge of hierarchy and octant which gives rise to fake solutions coming from wrong hierarchy and wrong octant. A prior knowledge of hierarchy and octant can help to eliminate these fake solutions thereby enhancing the CP sensitivity. Since the baselines of the current superbeam experiments T2K and NOνA are not too large they have limited hierarchy and octant sensitivity and thus causing a significant fall in the CP sensitivity. On the other hand, the hierarchy and octant sensitivity of atmospheric neutrino experiments is independent of δ_{CP} [4]. Hence, a combination of long-baseline (LBL) and atmospheric data can substantially improve the ability of the LBL experiments to measure δ_{CP}. In this work we demonstrate that the CP sensitivity of T2K and NOνA can be enhanced significantly by including atmospheric neutrino data in the analysis. For the latter we consider a magnetized iron calorimeter detector (ICAL) which is being developed by the INO collaboration [5].

II. THE APPEARANCE CHANNEL

In matter of constant density, $P_{\mu e}$ can be expressed in terms of the small parameters $\alpha = \Delta_{21}/\Delta_{31}$ and s_{13} as [6]

$$P_{\mu e} = 4 s_{13}^2 s_{23}^2 \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} + \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta - \delta CP) \times \frac{\sin \hat{A}\Delta}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} + \mathcal{O}(\alpha^2) , \quad (1)$$

where $\Delta = \Delta_{31} L/4E$, $s_{ij}(c_{ij}) \equiv \sin\theta_{ij}(\cos\theta_{ij})$, $\hat{A} = 2\sqrt{2} G_F n_e E/\Delta_{31}$, G_F is the Fermi constant and n_e is the electron number density. For neutrinos, the signs of $\hat{A}$ and Δ are positive for NH and negative for IH and vice-versa for antineutrinos. We can see that CP appears in the subleading second term in Eq. 1 which is also the source of the hierarchy-δ_{CP} degeneracy [7].

III. EXPERIMENTAL SPECIFICATION

For the long-baseline experiments NOνA and T2K, simulation is done using the GLoBES package [8]. T2K (L = 295 Km) is assumed to have a 22.5 kt Water Ĉerenkov detector running effectively for $5(\nu) + 0(\overline{\nu})$ years. For NOνA (L = 812 Km), we consider a 14 kt

TASD detector running for $5(\nu) + 5(\overline{\nu})$ years. Detailed specifications of these experiments are given in [9, 10].

For atmospheric neutrinos we consider ICAL@INO, which is capable of detecting muon events with charge identification, with a proposed mass of 50 kT [5]. For our analysis we use neutrino energy and angular resolutions of (10%,10°).

IV. CPV DISCOVERY POTENTIAL OF NOνA, T2K AND ICAL

The discovery potential of an experiment for CP violation is defined by

$$\chi^2 = min \frac{(N_{ex}(\delta_{CP}^{tr}) - N_{th}(\delta_{CP}^{test} = 0, 180°))^2}{N_{ex}(\delta_{CP}^{tr})} \tag{2}$$

where N_{ex} and N_{th} are the true and test events respectively.

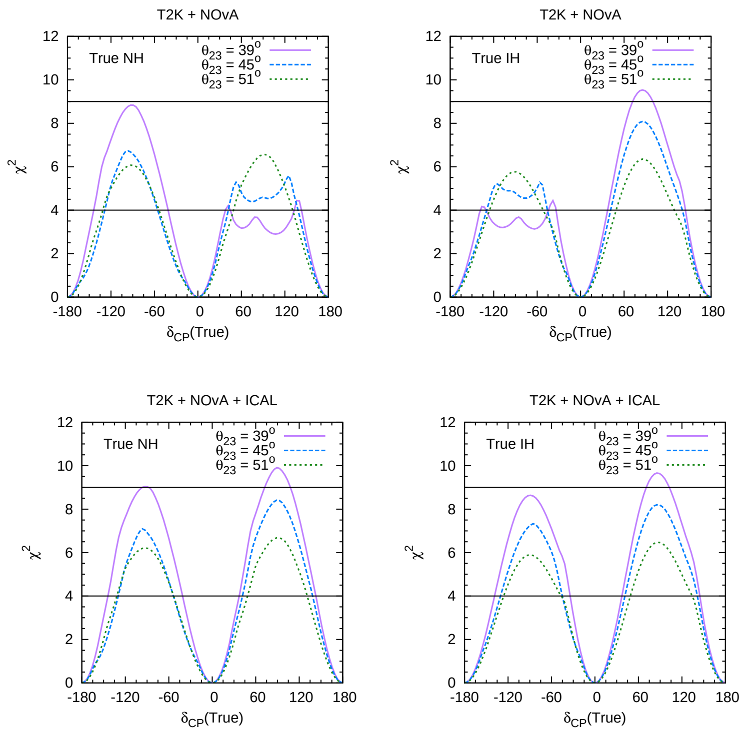

FIG. 1: CPV discovery vs true δ_{CP} for NOνA+T2K (upper row) and NOνA+T2K+ICAL (lower row), for three values of θ_{23}, $\sin^2 2\theta_{13} = 0.1$ and a true normal (left panels) or inverted (right panels) mass hierarchy, with 500 kT yr exposure for ICAL

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From the upper panels of Fig 1 it may be observed that the CPV discovery of NOνA+T2K suffers a drop in the region $+90^o$ if it is NH, and -90^o if it is IH. This is due to the fact that the minimum for CPV discovery occur in the wrong hierarchy. In atmospheric neutrinos the baselines are related to the zenith angle θ_z. As the δ_{CP} term always appears along with a factor of $\cos\Delta$ or $\sin\Delta$, even a 10% error range in θ_z this oscillating term varies over an entire cycle. As a result, the δ_{CP}-sensitivity gets washed out. Thus atmospheric neutrino experiments by themselves are not sensitive to δ_{CP} but gives a hierarchy sensitivity due to large matter effect. This hierarchy sensitivity can exclude the wrong-hierarchy solutions and this is shown in lower panels of Fig 1 that when ICAL is added to NOνA+T2K, the drop in the CPV discovery is resolved . The results depend significantly on the true value of θ_{23}. As θ_{23} increases, hierarchy sensitivity increases but CP sensitivity decreases. As a result for $\theta_{23} = 51^o$, the χ^2 minima for NOνA+T2K comes in the correct hierarchy and the ICAL information becomes superfluous.

V. CP PRECISION OF NOνA, T2K AND ICAL

The the precision χ^2 is defined as

$$\chi^2 = min\frac{(N_{ex}(\delta_{CP}^{tr}) - N_{th}(\delta_{CP}^{test}))^2}{N_{ex}(\delta_{CP}^{tr})} \tag{3}$$

In Fig. 2, we plot the CP precision in δ_{CP}(true) vs δ_{CP}(test) plane for NOνA, T2K and ICAL. In this figures we have used $\sin\theta_{23} = \sin\theta_{\mu\mu}/\cos\theta_{13}$ to take care of the intrinsic octant degeneracy that arises at $\theta_{\mu\mu}$ and $90^o - \theta_{\mu\mu}$ in the disappearance channel. The allowed values

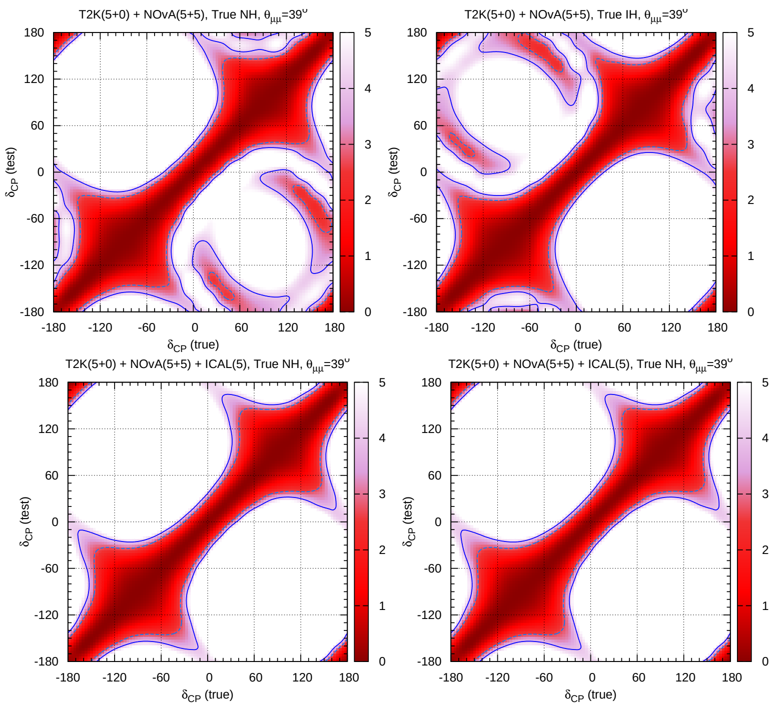

FIG. 2: CP precision at 90%/95% C.L. for NOνA+T2K (upper row) and NOνA+T2K+ICAL (lower row), for $\theta_{23} = 39^o$, $\sin^2 2\theta_{13} = 0.1$ and a true normal (left panels) or inverted (right panels) mass hierarchy, with 250 kT yr exposure for ICAL

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of δ_{CP} are represented by the shaded regions. For an ideal measurement, the allowed values would be very close to the true value. However, due to the hierarchy-δ_{CP} degeneracy, we see that for NOνA+T2K, other δ_{CP} values are also getting allowed(upper panels of Fig 2).

However addition of 5 years of ICAL data is sufficient enough to rule out those degenerate allowed regions to give a finer CP precision(lower panels of Fig 2) though it should be noted that the act of adding ICAL data does not help in the diagonal regions.

VI. θ_{13} AND θ_{23} DEPENDENCE IN CPV DISCOVERY χ^2

As seen in Eqn.1, $P_{\mu e}$ has a leading order CP dependent term $\sim \sin^2\theta_{13}\sin^2\theta_{23}$ and a sub-leading CP independent term $\sim \sin 2\theta_{13}\sin 2\theta_{23}$. Thus θ_{13} and θ_{23} is expected to have similar dependence on δ_{CP}. For illustrative purposes, the CP χ^2 can be written as

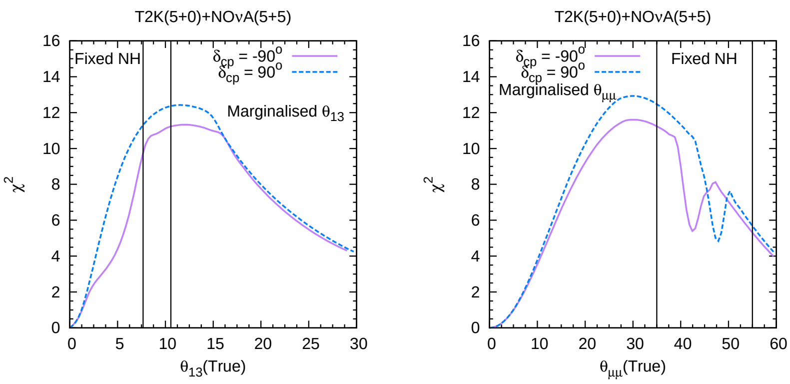

FIG. 3: CP violation discovery potential of NOνA+T2K as a function of true θ_{i3} and a fixed NH is assumed

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$$\chi^2 \sim \frac{P(\delta_{CP})\sin^2 2\theta_{i3}}{Q\sin^2\theta_{i3} + R(\delta_{CP})\sin 2\theta_{i3}}\ , \qquad (4)$$

where P, Q, R are functions of the other oscillation parameters apart from δ_{CP} and i=1,2. For small values of θ_{i3}, $\chi^2 \sim \theta_{13}$ which is an increasing function and when θ_{13} is close to 90° $\chi^2 \sim (90° - \theta_{13})^2$ which decreases with θ_{13}. Therefore, CP sensitivity initially increases with θ_{i3}, peaks at an optimal value, and then decreases with θ_{i3}.

These features are clearly reflected in Fig. 3. The left panel shows that the sensitivity to CP violation is maximum for NOνA+T2K in the current 3σ range of θ_{13}(region between the vertical black lines). From the right panel we find that for $40° < \theta^{tr}_{\mu\mu} < 49°$, there is a wiggle signaling the octant-δ_{CP} degeneracy. The behaviour is different for $\delta^{tr}_{CP} = \pm 90°$ depending on the true octant. This is illustrated in Fig. 4. where we can notice a drop at -90^o for $\theta_{\mu\mu} = 43^o$ and at $+90^o$ for $\theta_{\mu\mu} = 49^o$ for NOνA+T2K when the octant is assumed to be unknown. But when ICAL is added, it restricts the δ_{CP}-octant degeneracy to $41 < \theta_{\mu\mu} < 48$. Thus we can see a partial improvement at $\theta_{\mu\mu} = 43^o$ but the degeneracy is fully resolved at $\theta_{\mu\mu} = 49^o$ with the help of ICAL.

VII. CONCLUSION

In this work we have studied CP sensitivity of the current and upcoming long-baseline experiments T2K and NOνA and the atmospheric neutrino experiment ICAL@INO. We

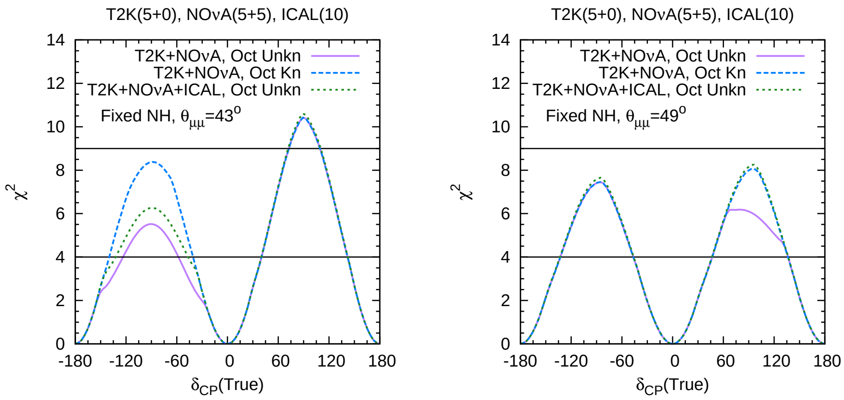

FIG. 4: CP violation discovery potential of NOνA, T2K and ICAL as a function of true δ_{CP} for $\theta_{\mu\mu}^{tr} = 43^\circ$ (left panel) and 49° (right panel). $\sin^2 2\theta_{13}^{tr} = 0.1$ and a fixed NH is assumed

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see that due to hierarchy-δ_{CP} degeneracy, there is a drop in CP sensitivity for NOνA and T2K in the degenerate region. The main role of the atmospheric data is to exclude the wrong hierarchy solutions to lift the degeneracy in the unfavourable parameter regions for T2K/NOνA. We have also shown that the current values of θ_{13} lies in a region where CP sensitivity is maximum. There is also a degeneracy of δ_{CP} with the octant in the rage $40^\circ < \theta_{\mu\mu}^{tr} < 49^\circ$ for T2K+NOνA. Addition of ICAL data helps to restrict the degeneracy at $41^\circ < \theta_{\mu\mu}^{tr} < 48^\circ$.

More detailed discussions and results can be found in [11, 12] on which this article is based.

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