Can atmospheric neutrino experiments provide the first hint of leptonic CP violation?

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The measurement of a non-zero value of the 1-3 mixing angle has paved the way for the determination of leptonic CP violation. However the current generation long-baseline experiments T2K and NOvA have limited sensitivity to $\delta_{CP}$. In this paper we show, for the first time, the significance of atmospheric neutrino experiments in providing the first hint of CP violation in conjunction with T2K and NOvA. In particular, we find that adding atmospheric neutrino data from the ICAL detector at the India-based Neutrino Observatory (INO) to T2K and NOvA results in a two-fold increase in the range of $\delta_{CP}$ values for which a 2$\sigma$ hint of CP violation can be obtained. In fact in the parameter region unfavorable for the latter experiments, the first signature of CP violation may well come from the inclusion of atmospheric neutrino data.

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Introduction: CP symmetry refers to invariance under simultaneous transformation of charge conjugation and parity. A small violation of this symmetry is observed in the quark sector, in the decays of K and B mesons \[3\]. This can be explained by the complex phases in the CKM matrix. Thus it is natural to expect that CP violation (CPV) occurs in the lepton sector as well \[2\]. This is reinforced by the observation of neutrino oscillations which establishes non-zero masses and mixing of these particles. The MNSP matrix in such a situation would contain complex phases. In the basis where the charged leptons do not mix amongst each other this matrix is characterized by three mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$) and three phases. Oscillation experiments are sensitive to the so-called Dirac phase $\delta_{CP}$. This could also be linked to the origin of the observed matter-antineutrton asymmetry of the universe through the mechanism of leptogenesis \[6\]. Thus, understanding the origin of CPV is one of the central themes in particle physics and cosmology.

Global fits of world neutrino data give the best-fit values for the neutrino oscillation parameters (and their 1$\sigma$ ranges) as $\sin^2 \theta_{12} = 0.31 \pm 0.02$, $\sin^2 \theta_{23} = 0.39 \pm 0.02$, $|\Delta_{31}| = (2.43 \pm 0.1) \times 10^{-3}$ eV$^2$, $\Delta_{21} = (7.54 \pm 0.26) \times 10^{-5}$ eV$^2$ \[4\]. Here $\Delta_{ij} = m_i^2 - m_j^2$ denotes the mass-squared differences. Recently the third mixing angle $\theta_{13}$ has been measured by reactor \[8\] and accelerator \[6\] neutrino experiments and the best-fit value is $\sin^2 2\theta_{13} \approx 0.10 \pm 0.01$ \[4\]. Thus, the remaining unknown quantities are the neutrino mass hierarchy (normal hierarchy (NH): $\Delta_{31} > 0$ or inverted hierarchy (IH): $\Delta_{31} < 0$), the octant of $\theta_{23}$ and the CP-phase $\delta_{CP}$.

In the MNSP matrix $\delta_{CP}$ is associated with $\theta_{13}$. Thus a non-zero $\theta_{13}$ is required for any measurement of $\delta_{CP}$. The 1$\sigma$ signature for non-zero $\theta_{13}$ leads naturally to the question of whether and to what extent CPV discovery is possible by the current superbeam experiments T2K and NOνA. In these experiments, the sensitivity to $\delta_{CP}$ comes mainly from the $\nu_\mu - \nu_\tau$ (and $\overline{\nu}_\mu - \overline{\nu}_\tau$) oscillation probability, $P_{\mu \tau}$ ($P_{\mu e}$). Since the probabilities increase with $\theta_{13}$, the relatively large value of $\theta_{13}$ is expected to be conducive to the measurement of $\delta_{CP}$ because of increased statistics. However, the statistical error coming from the $\delta_{CP}$-independent dominant term in $P_{\mu \tau}$ also increases, which tends to reduce the sensitivity \[7\].

In addition, the correct signal can also be faked by a wrong hierarchy-wrong $\delta_{CP}$ combination \[8\]. This hierarchy-$\delta_{CP}$ degeneracy makes the measurement of $\delta_{CP}$ difficult in practice, and higher intensity and/or longer baseline beam-based experiments have been proposed \[9\]. However till the new experiments dedicated for $\delta_{CP}$ are built one can ask whether the LBL experiments T2K and NOνA can provide any hint for CP violation.

In \[10\], it was shown that a prior knowledge of the hierarchy facilitates the measurement of $\delta_{CP}$ by NOνA and T2K. However, the determination of the hierarchy by NOνA and T2K itself suffers from being dependent on the ‘true’ value of $\delta_{CP}$ in nature. For the favorable combinations ($\{\delta_{CP} \in [-180^\circ, 0^\circ]$, NH$\}$ or $\{\delta_{CP} \in [0^\circ, 180^\circ]$, IH$\}$), NOνA and T2K will be able to determine the hierarchy at 90% C.L. with their planned runs. But their hierarchy determination ability and hence their CP sensitivity will be poor if nature has chosen the unfavorable combinations \[11\]. On the other hand, the hierarchy sensitivity of atmospheric neutrino experiments is independent of $\delta_{CP}$ \[12\]. Hence, a combination of long-baseline (LBL) and atmospheric data can determine the hierarchy for all $\delta_{CP}$ values including the adverse ones. This can substantially improve the ability of the LBL experiments to detect CPV in the unfavorable regions of $\delta_{CP}$. In this paper 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 \[13\].

Since atmospheric neutrino experiments are not sensitive to CPV by themselves, their usefulness in determining this property has not been emphasized so far. We show that for unfavorable values of $\delta_{CP}$, atmospheric neutrino data from ICAL ameliorates the CP discovery
potential of NOνA and T2K. This leads to the possibility of obtaining a $\gtrsim 2\sigma$ hint of CPV using existing and upcoming facilities for a large fraction (> 50%) of $\delta_{\text{CP}}$ values.

**CP violation in neutrino oscillations:** 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 [10]

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

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 $\Delta$ are positive for NH and negative for IH and vice-versa for antineutrinos. The second term in Eq. (1) is the source of the hierarchy-$\delta_{\text{CP}}$ degeneracy [5].

**Experimental details:** For our study we consider the current generation LBL experiments NOνA and T2K and simulate them using the GLoBES package [11, 17]. For NOνA, we have assumed a 14 kT totally active scintillator detector and a 0.7 MW beam running for 5(µ) + 5(π) years. Since it is expected to start in 2014, this indicates a timeline up to about 2024. We have used a re-optimized NOνA set-up with refined event selection criteria [11, 18]. T2K is assumed to have a 22.5 kT Water Čerenkov detector, and a 0.77 MW beam running for 5(µ) + 0(π) years. Taking into account the current lower-power run and proposed upgrades, this will correspond to a timeline till about 2016. We have checked that a T2K run in the neutrino mode alone and a combined neutrino-antineutrino run give similar results when combined with NOνA. For these LBL experiments, we have used the systematic errors and background rejection efficiencies used in Ref. [11, 18].

For atmospheric neutrinos we consider ICAL@INO, which is capable of detecting muon events with charge identification, with a proposed mass of 50 kT [15]. For our analysis we use neutrino energy and angular resolutions of (10%,10°) unless noted otherwise. These are representative values which give similar sensitivity as obtained in [14] using energy and angular resolutions of muons from INO simulation code. The details of our atmospheric analysis can be found in [12]. The detector is expected to be operational by 2018/19. We present results for exposures of 500 (250) kT yr, corresponding to a 10(5)-year run i.e. a timeline till about 2028 (2023-24). We note that the latter is the expected time frame for NOνA to complete a 10-year run.

**CP sensitivity in atmospheric neutrinos:** The muon events in atmospheric neutrinos get contributions from both $P_{\mu\mu}$ and $P_{\mu\mu}$. In these probabilities, the $\delta_{\text{CP}}$-dependent term always appears along with a factor of $\cos \Delta$ or $\sin \Delta$. If we consider even a 10% error range in the zenith angle and energy of the neutrino, this oscillating term varies over an entire cycle in this range. As a result, the $\delta_{\text{CP}}$-sensitivity of the channel gets washed out because of smearing. In Fig. [1] we have plotted the quantity $S = S_\mu + S_\pi$ in the $\cos \theta_2 - E$ plane, which is a measure of the $\delta_{\text{CP}}$-sensitivity of the atmospheric neutrino experiment. Here, $S_\mu = \langle \delta N_\mu \rangle^2/N_\mu(\text{avg})$, where $\delta N_\mu$ is the maximum difference in events obtained by varying $\delta_{\text{CP}}$, and $N_\mu(\text{avg})$ is the average number of events over all values of $\delta_{\text{CP}}$ (and likewise $S_\pi$ for $\pi$ events). The quantity $S$ is thus a measure of the maximum possible relative variation in events due to $\delta_{\text{CP}}$ in each bin. In the left panel, we show the results for an ideal detector with an exposure of 500 kT yr, with infinite energy and angular precision. Here we see substantial sensitivity to $\delta_{\text{CP}}$, with $S$ exceeding 0.5 in some bins [10]. However, when we introduce realistic resolutions (10° in angle and 10% in energy), we see in the right panel that the sensitivity is lost. This is mostly due to the effect of angular smearing. Thus atmospheric neutrino experiments by themselves are not sensitive to $\delta_{\text{CP}}$. For beam experiments, since the direction of the neutrinos is known, angular smearing is not needed and hence the sensitivity to $\delta_{\text{CP}}$ is not compromised due to this reason.

**CP violation discovery:** The discovery potential for CPV is computed by considering a variation of $\delta_{\text{CP}}$ over the full range $[-180°, 180°]$ in the simulated true event spectrum, and comparing this with $\delta_{\text{CP}} = 0°$ or $180°$ in the test event spectrum. The statistical $\chi^2$ for our analysis is defined as

$$\chi^2_{\text{stat}} = \sum_{\text{bins}} \frac{(N_{\text{true}}(\delta_{\text{CP}}) - N_{\text{test}}(\delta_{\text{CP}} = 0, \pi))^2}{N_{\text{true}}(\delta_{\text{CP}})}. \quad (2)$$

We have accounted for systematic errors by using the method of pulls. For a particular value of $\delta_{\text{CP}}$ in the true spectrum, the resulting $\chi^2_{\text{stat+syst}}$ is evaluated for test $\delta_{\text{CP}} = 0$ and $\pi$ and test hierarchy NH and IH. We also marginalize over the atmospheric parameters and $\sin^22\theta_{13}$. The minimum over all these test parameter combinations is chosen as the final $\chi^2$. This is then studied as a function of (true) $\delta_{\text{CP}}$. In Fig. [2] we plot the CPV discovery potential of the LBL experiments NOνA and T2K and the ICAL detector with 500 kT yr exposure. The upper panels give the CP discovery for the combination NOνA+T2K, while the lower panels depict the results for NOνA+T2K+ICAL. The true neutrino hierarchy is assumed to be NH(IH) in the left(right) column.

From the figure, it may be observed that the CPV discovery of NOνA+T2K suffers a drop in one of the half-planes of $\delta_{\text{CP}}$, depending on the true hierarchy - in the region $[0°, 180°]$ if it is NH, and $[-180°, 0°]$ if it is IH. This is due to the fact that the hierarchy sensitivity of NOνA+T2K is highly sensitive to $\delta_{\text{CP}}$. and becomes.
low in the unfavorable regions $^{10}$. Consequently, for unfavorable $\delta_{CP}$ values, marginalization over the hierarchy causes the NO$\nu$A+T2K CPV discovery potential to drop, since the minimum for CPV discovery can then occur in conjunction with the wrong hierarchy.

However, an atmospheric neutrino detector like ICAL gives a hierarchy sensitivity which is remarkably stable over the entire range of $\delta_{CP}$, even though it does not offer any significant CPV discovery potential by itself. This hierarchy sensitivity excludes the wrong-hierarchy minimum for CPV discovery. When this information is added to NO$\nu$A+T2K, the drop in the CPV discovery in the unfavorable half-planes of $\delta_{CP}$ is resolved.

The results depend significantly on the true value of $\theta_{23}$. In the favourable $\delta_{CP}$ region the discovery potential becomes worse with increasing $\theta_{23}$. This is because the $\delta_{CP}$-independent leading term in Eq. 1 increases with $\theta_{23}$, giving a higher statistical error, while the CP dependent term has only a weak dependence on this parameter. In the unfavorable region since the $\chi^2$ minimum comes with the wrong hierarchy, the dependence of hierarchy sensitivity on $\theta_{23}$ also comes into play. This causes a drop in the value of $\chi^2$ for lower values of $\theta_{23}$.

The advantage offered by combining ICAL with the LBL data is most prominent for $\theta_{23} = 39^\circ$, and progressively diminishes with increasing $\theta_{23}$. For $\theta_{23} = 39^\circ$ or $45^\circ$ the hierarchy sensitivity of NO$\nu$A+T2K is poorer, with the minimum occurring for the wrong hierarchy. This can be ruled out by atmospheric neutrino data. For $\theta_{23} = 51^\circ$ the ICAL information is superfluous, since the hierarchy sensitivity of the NO$\nu$A+T2K combination itself is good enough to exclude the wrong hierarchy CPV discovery minima even for unfavorable $\delta_{CP}$ values. In general, the atmospheric neutrino contribution to the CPV discovery potential of NO$\nu$A+T2K+ICAL is effective till the wrong hierarchy solution is disfavored and the minimum comes with the true hierarchy. Once that is achieved, a further increase in hierarchy sensitivity of atmospheric neutrinos will not affect the CPV discovery results, since atmospheric neutrinos by themselves do not have CPV sensitivity for realistic resolutions.

To quantitatively understand the significance of the atmospheric neutrino contribution, we consider true NH and $\theta_{23} = 39^\circ$ ($45^\circ$). In this case, the ICAL contribution required to exclude the wrong hierarchy CPV minima is about $\chi^2 = 6.5(4)$. Thus a hierarchy sensitivity of $\sim 2.5(2)\sigma$ is enough to rule out the wrong hierarchy solutions and compensate for the drop in CPV discovery potential of NO$\nu$A+T2K in the unfavorable $\delta_{CP}$ region. For true NH(III), T2K+NO$\nu$A can discover CPV at $2\sigma$ for $\sim 32\%(35\%)$ fraction of $\delta_{CP}$ values for $\theta_{23} = 39^\circ$. By adding ICAL information, this improves to $\sim 58\%$. For maximal CPV ($\delta_{CP} = \pm90^\circ$), inclusion of ICAL gives a $\sim 3\sigma$ signal for both hierarchies. Without the ICAL contribution this is true only in one of the half-planes depending on the hierarchy.

To study the effect of ICAL detector resolutions on the results, we plot in Fig. 3 the CPV discovery potential of NO$\nu$A+T2K+ICAL for $\theta_{23} = 39^\circ$ and true NH assuming two sets of energy and angular smearings for ICAL - (15%,15°) and (10%,10°). In the former case, although an indication of CPV at $2\sigma$ is seen to be achieved in the unfavorable half-plane, the $\chi^2$ minima still occur with the wrong hierarchy, as evident from the shape of the curve. For the wrong hierarchy the shape is dictated by a mismatch in both $\delta_{CP}$ and hierarchy between the true and test event spectra, and one does not get a smooth dependence on $\delta_{CP}$. For the latter (better) smearing set, the $\chi^2$ minimum shifts to the true-hierarchy regime and the sensitivity comes only from $\delta_{CP}$. Hence the smooth behavior of the curve is restored. An improvement in the resolution beyond (10%,10°) would not affect the CPV discovery potential significantly (with the same exposure), since the minima already occur with the true

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**FIG. 1:** $S_\mu + S_\tau$, a measure of ICAL $\delta_{CP}$-sensitivity in the $E - \cos \theta_\chi$ plane for $\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$ and NH. The grid represents bins in energy and $\cos \theta_\chi$. The left panel is with ideal detector resolution and the right panel is with a resolution of $10^\circ$ in angle and 10% in energy.
hierarchy where the atmospheric neutrino contribution is negligible. However, for a superior angular resolution there can be a slight increase in the CPV discovery $\chi^2$ coming from atmospheric neutrinos themselves.

In order to gauge the contribution from ICAL with a reduced exposure, we plot in Fig. 3 the CPV discovery as a function of $\delta_{CP}$ for NO$\nu$A+T2K and NO$\nu$A+T2K+ICAL for two ICAL resolutions for $\theta_{23} = 39^\circ$, $\sin^2 2\theta_{13} = 0.1$ and true NH. The figure shows that even though the hierarchy-$\delta_{CP}$ degeneracy is not fully resolved with an ICAL exposure of 250 kT yr, a $2.5\sigma$ hint for CPV is still achieved over a large part of the unfavorable half-plane even with this exposure, corresponding to a 5-year run till 2023/2024. Hence a chronologically matched run-time of NO$\nu$A and ICAL is still conducive to a significant gain in giving a hint of CPV when ICAL is combined. However, irrespective of the time scale of the different experiments, for parameter values in the unfavorable half-plane, the first signature of CPV may come after adding atmospheric neutrino data to T2K/NO$\nu$A.

**Conclusions:** In this paper we emphasize the critical impact that atmospheric neutrinos can have in obtaining the first hint of CPV from the LBL experiments T2K/NO$\nu$A. This is achieved by the ability of the atmospheric neutrino data to exclude the degenerate wrong-hierarchy solutions. Taking ICAL@INO as the representative detector, we show that adding this data to T2K and NO$\nu$A can provide a signature of CPV at $2\sigma$ for almost twice the range of $\delta_{CP}$ values ($\sim 58\%$). For maximal CPV the significance of the signal can reach $3\sigma$ in the unfavorable half-plane also. The effect of adding ICAL data is more prominent if $\theta_{23}$ is in the lower octant, where the current best-fit value lies. In fact, if nature has chosen such unfavorable combinations of parameters then it is the addition of atmospheric neutrino data to
T2K+NOνA which may give us the first signal of CPV.

We note that the idea discussed in this paper can be of importance and interest to other atmospheric and/or reactor experiments sensitive to the mass hierarchy and can initiate similar studies. This aspect should also be taken into account in planning strategies for future experiments to measure CPV more precisely [21].

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