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Hierarchy independent sensitivity to leptonic δ_{CP} with low energy atmospheric neutrinos

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One of the important unknowns in neutrino oscillation physics is the leptonic CP phase δ_{CP}. Because of the ambiguity between δ_{CP} and neutrino mass hierarchy, experiments have to be designed in such a way as to measure these parameters independent of each other. Long baseline experiments like DUNE is exclusively designed to measure δ_{CP} in regions without hierarchy ambiguity and atmospheric neutrino experiments like INO are designed to measure hierarchy without δ_{CP} ambiguity. However atmospheric neutrinos are not usually used to probe δ_{CP}. Here we present that, sub–GeV energy atmospheric neutrinos can be used to probe δ_{CP} irrespective of mass hierarchy. We show that when the events are binned as a function of $(E_l^{\rm obs}, \cos\theta_l^{\rm obs})$, the observed energy and direction of the final state leptons in charged current interactions of ν and $\overline{\nu}$, a consistent distinction between various δ_{CP} values is obtained. Since there is no sensitivity to the mass ordering/hierarchy, δ_{CP} can be measured without hierarchy ambiguity at these energies. Sensitivity studies with ideal as well as realistic cases are discussed.

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1. Introduction

The value of the leptonic CP violating phase δ_{CP} is one of the major unknowns currently in neutrino oscillation physics. The global fit to neutrino data indicates that the value of δ_{CP} is around 221° (282°) for normal hierarchy (inverted hierarchy), with the 3σ ranges from [144°, 357°] ([205°, 348°]) for NH (IH) [1]. Several accelerator long baseline experiments like T2K and NOνA are currently taking data and future experiments like DUNE, HK, T2HK, ESSνSB [2] are being planned to probe this value. These experiments can give a good sensitivity to δ_{CP} by themselves and combined with the reactor anti-neutrino data. Sub GeV energy atmospheric neutrinos can also be used to probe δ_{CP}. Their flux peaks at these low energies thus giving a large number of events. Unlike the accelerator neutrino experiments, atmospheric neutrino experiments [3] offer a wide range of L/E, where L (km) is the distance travelled by a neutrino of energy E (GeV). Thus, if certain L/E conditions are met, we can obtain a hierarchy independent measurement of δ_{CP} as discussed in section. 2. The generation of events, χ^2 analysis and results are discussed in sections 3 and 4 respectively.

2. Mass hierarchy independence at low energies-analytic approach

The 3-flavour vacuum oscillation probability of a flavour $\nu_\alpha \to \nu_\beta$: $\overset{(-)}{P}{}^{vac}_{\alpha\beta} =$

$$\delta_{\alpha\beta} - 4\sum_{i>j} Re\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) \pm 2\sum_{i>j} Im\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin\left(\frac{2.53\Delta m^2_{ij}L}{E}\right), \tag{2.1}$$

where $\alpha,\beta = e,\mu,\tau$ represent the neutrino flavour indices, and the $\pm$ sign corresponds to ν and $\overline{\nu}$ respectively. $U_{\alpha i}$ are the elements of the 3×3 PMNS neutrino mixing matrix in vacuum; $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$; θ_{ij} are the mixing angles, δ_{CP} is the leptonic CP violation phase, L (in km) is the distance travelled by a neutrino of energy E (in GeV).

When E is small, say a few hundred MeV, the corresponding oscillatory terms average out when L/E is large compared to Δm^2_{ij}. $|\Delta m^2_{3j}| \sim 2.4\times10^{-3}\ eV^2 \gg \Delta m^2_{21} \sim 7.6\times10^{-5}\ eV^2$, $j = 1,2$. Hence this applies to the "*atmospheric*" terms: $1.27\Delta\, m^2_{3j}\ L/E \approx \pi\,[(L/100\text{ km})/(E/0.1\text{ GeV})]$, rather than to "*solar*" terms: $1.27\Delta\, m^2_{21}\ L/E \approx \pi\,[(L/3000\text{ km})/(E/0.1\text{ GeV})]$. Thus, event rates at sub GeV energies with $L \geq$ a few 100 km are independent of Δm^2_{3j} and thus the unknown mass hierarchy. Though Δm^2_{21} remains, its magnitude and sign are well known.

The hierarchy independent probability in vacuum is :
$P^{vac}_{\alpha\beta} = -4Re[U_{\alpha2}U^*_{\beta2}U^*_{\alpha1}U_{\beta1}]\sin^2(1.27\Delta m^2_{21}L/E)$
$-2Re[U_{\alpha3}U^*_{\beta3}(\delta_{\alpha\beta} - U^*_{\alpha3}U_{\beta3})] + 2Im[U_{\alpha2}U^*_{\beta2}U^*_{\alpha1}U_{\beta1}]\sin(2.53\Delta m^2_{21}L/E)$. Also, $P_{\alpha\beta} = \overline{P}_{\beta\alpha}$. Transition probabilities $P_{e\mu}, P_{\mu\ e}, \overline{P}_{e\mu}$ and $\overline{P}_{\mu\ e}$ are more sensitive to δ_{CP}. $P_{e\mu} = A + B\cos\delta - C\sin\delta = \overline{P}_{\mu e}$; $P_{\mu e} = A + B\cos\delta + C\sin\delta = \overline{P}_{e\mu}$, where, $A = c^2_{13}\sin^2(2\theta_{12})(c^2_{23} - (s_{23}s_{13})^2)\sin^2(\delta_{21}/2) + \frac{1}{2}s^2_{23}\sin^2(2\theta_{13})$, $B = (1/4)c_{13}\sin(4\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin^2(\delta_{21}/2)$,
$C = (1/4)c_{13}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin(\delta_{21})$ and $\delta_{21} = 2.534\Delta m^2_{21}L/E$, only limited by measurements of oscillation parameters. The oscillation parameters and hence the probabilities will be modified in presence of Earth matter according to PREM profile [4]. Since $\Phi_{\nu_\mu} \simeq 2\Phi_{\nu_e}$, the oscillated events from $P_{\mu e}$ and $\overline{P}_{\mu e}$ will be about double of those from $P_{e\mu}$ and $\overline{P}_{e\mu}$.

Hierarchy independence of the matter oscillation probabilities at sub–GeV energies is shown in Fig. 1. For neutrino energy $E = 0.2$ GeV, the oscillation probabilities for $\delta_{CP} = \pm 90^\circ$ can be distinguished from each other irrespective of hierarchy, in certain zenith angle regions. The regions vary with varying neutrino energy. The values of oscillation parameters used are given in Table. 1.

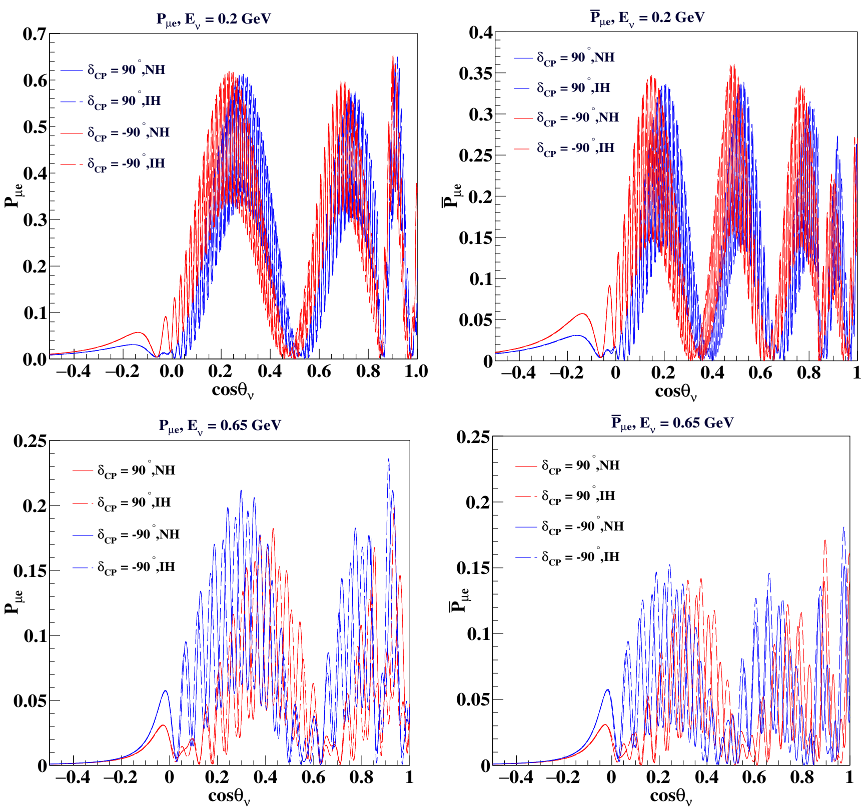

Figure 1: (Top row) $P_{\mu e}$, $\overline{P}_{\mu e}$ vs $\cos\theta_\nu$ for $E_\nu = 0.2$ GeV. (Bottom row) $P_{\mu e}$, $\overline{P}_{\mu e}$ vs $\cos\theta_\nu$ for $E_\nu = 0.65$ GeV for $\delta_{CP} = \pm 90^\circ$; NH and IH with $\theta_{13} = 8.5^\circ$.

The oscillated event spectrum follows the oscillation probabilities when the events are binned as a function of the neutrino direction $\cos\theta_\nu$. But when binned as a function of the final state lepton direction $\cos\theta_l$, $l = e, \mu$ the spectra show clear distinction for different δ_{CP} values as shown in Fig. 2. This is because events in different $\cos\theta_\nu$ can contribute to the events in the same $\cos\theta_l$ bins. When summed over all $\cos\theta_l$ bins, the oscillated events exhibit hierarchy independence over $E_l = 0.1$–2.0 GeV also.

3. Generation of events and χ^2 analysis

Two different analyses are performed, an idealistic and a realistic ones. The oscillation channels of interest here are $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$, $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$, for charged current $\overset{(-)}{\nu}_e$ (CCE) events and $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$, $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$, for charged current $\overset{(-)}{\nu}_\mu$ (CCMU) events. 100 years of unoscillated events are simulated using NUANCE [5] in a 50 kton isoscalar detector. In the perfect case, the entire 100 year sample is oscillated event by event applying the relevant 3–flavour oscillation probability in

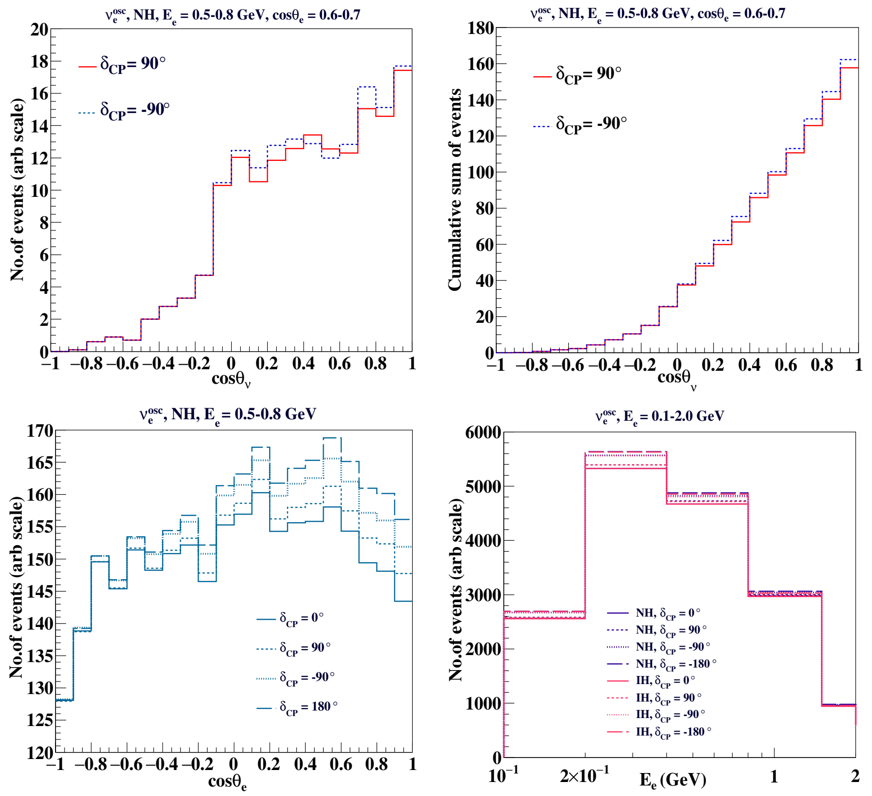

Figure 2: (Top-left) Oscillated ν_e events as a function of $\cos\theta_\nu$, for events with, E_e = 0.5–0.8 GeV and direction $\cos\theta_e$ = 0.6–0.7, with $\delta_{CP} = \pm 90°$ and NH. (Top-right) Cumulative sum of oscillated ν_e and $\overline{\nu}_e$ events contributing to this $\cos\theta_e$ bin, as a function of $\cos\theta_\nu$ for the same E_e bin. The last bin gives the total contribution to each $\cos\theta_e$ bin. (Bottom-left) Oscillated ν_e events as a function of the final state electron direction $\cos\theta_e$ for the bin E_e = 0.5–0.8 GeV. The distribution for $\overline{\nu}_e$ events are similar. (Bottom-right) Oscillated events with different δ_{CP} values in the E_e range 0.1–2.0 GeV for ν_e. Similarly for $\overline{\nu}_e$ events too.

matter. The central values of parameters given in Table. 1 are used to generate "data" while their values in the 3σ range are varied to generate theory. For the ideal *no fluctuation (nofluct)* scenario, the entire 100 years of oscillated events are scaled down to 10 years for both "data" and theory. In the realistic *with fluctuation (wfluct)* case, a set of 10 years of oscillated events is randomly chosen as "data" and the remaining 90 years are scaled down to 10 years for theory. The specifications of the two analyses done are listed in Table. 2.

Parameter	True value	Marginalization range
θ_{13}	8.5 (8.63)°	Not marginalised
$\sin^2\theta_{23}$	0.5	[0.39, 0.64]
Δm^2_{eff}	2.4×10^{-3} eV^2	[2.3, 2.6]$\times10^{-3}$ eV^2
$\sin^2_{12}$; Δm^2_{21}; δ_{CP}	0.304; 7.6×10^{-5} eV^2; 0, $\pm 90°$, $\pm 180°$	Not marginalised

Table 1: True values and 3σ ranges of parameters used to generate oscillated events. $\Delta m^2_{31} = \Delta m^2_{\rm eff} + \Delta m^2_{21}\left(\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\right)$;$\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$, for NH when $\Delta m^2_{\rm eff} > 0$. When $\Delta m^2_{\rm eff} < 0$, $\Delta m^2_{31} \leftrightarrow -\Delta m^2_{32}$ for IH.

Ideal	Realistic
No fluctuations $(E_l^{obs}, \cos\theta_l^{obs}, E_h'^{obs})$ bins E_l^{obs} = [0.1, 30.0] GeV No energy and direction smearing	With fluctuations $(E_l^{obs}, \cos\theta_l^{obs})$ bins E_l^{obs} = [0.1, 2.0] GeV E_l^{obs} is smeared; $E_{res} = 15\%/\sqrt{E}, 2.5\%\sqrt{E}$ for $e^{\pm}$
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$ can all be separated Has charge id	$\nu_e - \nu_\mu$ $(\overline{\nu}_e - \overline{\nu}_\mu)$ separation only, $\nu_e + \overline{\nu}_e$ No charge id
$\chi^2 = \sum_i \sum_j \sum_k 2\left[\left(T^0_{ijk} - D_{ijk}\right) - D_{ijk}\ln\left(\frac{T^0_{ijk}}{D_{ijk}}\right)\right]$	$\chi^2 = \sum_i \sum_j 2\left[\left(T_{ij} - D_{ij}\right) - D_{ij}\ln\left(\frac{T_{ij}}{D_{ij}}\right)\right] + \sum_{l=1}^{3}\xi_l^2$ $T_{ij} = T^0_{ij}\left(1 + \sum_{l=1}^{3}\pi^l_{ij}\xi_l\right)$
No systematic uncertainties Fixed and marginalised parameters	3 systematic uncertainties 5% “tilt”, 5% flux normalisation and 5% cross section Marginalisation only

Table 2: Specifications of analyses. Only charged current (CC) events are analysed. 100% reconstruction efficiency is assumed in both idealistic and realistic cases.

4. Results and conclusion

The sensitivities to δ_{CP} in the idealistic case with and without charge identification (cid) for CCE and CCMU type events are shown in Fig. 3 (a) and (b). Fig. 3 (c) (effect of systematic uncertainties alone) and Fig. 3 (d) (effects of energy smearing as well as systematic uncertainties) show the sensitivities for the realistic case with CCE alone. In the absence of any systematic uncertainty, $\delta_{CP} \simeq 40^\circ - 110^\circ$ is disallowed at 3σ. With only the 2% flux normalisation and 2% cross section errors alone all regions are allowed at 2σ. But the addition of 5% tilt error helps in ruling out $\delta_{CP} \simeq 40^\circ - 100^\circ$ at 2σ. Thus tilt error affects the sensitivity more than the other two uncertainties. Fig. 3(d) shows the effect of energy resolution without and with systematic uncertainties (5% flux normalisation, cross section and tilt error each). For a given systematic uncertainty, sensitivity worsens with worsening of energy resolution, for a given energy resolution. But the effect of adding systematic uncertainties drastically reduce δ_{CP} χ^2 more than energy smearing. Hence to determine δ_{CP} well the systematic uncertainties in fluxes and cross sections should be ∼2% and the energy resolution should be as small as possible. From the idealistic cases with and without cid, it is evident that a detector which can separate ν and $\overline{\nu}$ will have a better sensitivity to δ_{CP}. Doping water Cherenkov detectors with Gd and using LAr detectors like DUNE [6] can enable $\nu_e - \overline{\nu}_e$ separation and hence enhance the sensitivity to δ_{CP}.

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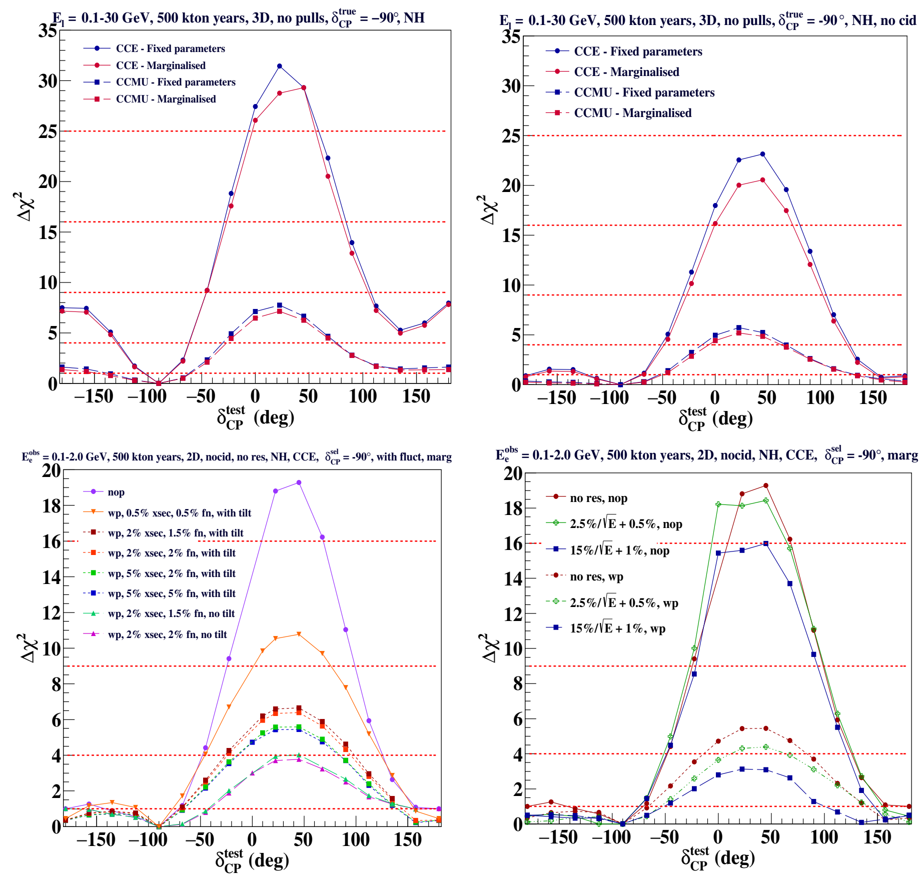

Figure 3: δ_{CP} sensitivities with $\delta^{true} = -90°$, NH and $\theta_{13} = 8.5°$ for (top-left) with cid & (top-right) no cid, idealistic cases. (Bottom-left) Effect of systematic uncertainties alone for CCE events with no smearing. (Bottom-right) Comparison of δ_{CP} sensitivities for the marginalised realistic case with energy smearing and without pulls for CCE type events alone; $\theta_{13} = 8.63°$.

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