Sensitivity to leptonic δ_{CP} and θ_{12} with low energy atmospheric neutrinos

D. Indumathi,[1,2] Lakshmi .S. Mohan,[3] M. V. N. Murthy[1]

[1] The Institute of Mathematical Sciences, Chennai 600 113, India [2] Homi Bhabha National Institute, Mumbai, India [3] National Center for Nuclear Research, Warsaw, Poland

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Introduction

Currently, the main two unknowns in neutrino oscillation physics are neutrino mass hierarchy and the leptonic CP violating phase δ_{CP}. Several accelerator based long baseline neutrino oscillation experiments like T2K, NOνA, DUNE etc are probing/will probe the leptonic Dirac δ_{CP}. Oscillations of atmospheric neutrinos and anti-neutrinos whose fluxes peak at sub-GeV energies can also be used to probe δ_{CP}. This work illustrates that δ_{CP} can be measured *irrespective* of neutrino mass hierarchy at sub-GeV energies. When binned in the observed final state lepton energy and direction ($E_l^{obs}, \cos\theta_l^{obs}$), the event spectra show a significant distinction between various δ_{CP} values. We also study the sensitivity to 1–2 oscillation parameters with sub–GeV atmospheric neutrino events.

Analytic approach

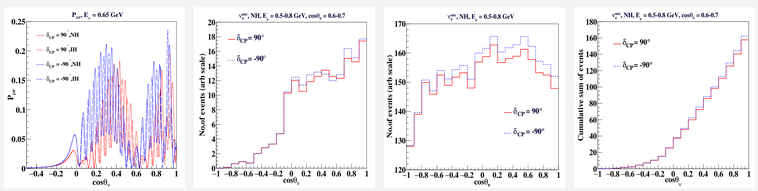
- The 3-flavour vacuum oscillation probability of $\nu_\alpha \to \nu_\beta$ is :

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

  where $\alpha, \beta = e, \mu, \tau$, and the $\pm$ are for ν and $\overline{\nu}$ respectively.
- $$U^{vac}_{\alpha i} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta_{CP}} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta_{CP}} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix},$$

  where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$; $i, j = 1, 2, 3$, $\Delta m^2_{ij} = m^2_i - m^2_j$ $(j < i)$, θ_{ij} are the mixing angles and δ_{CP} is the leptonic CP violation phase. Here L (in km) is the distance travelled by a neutrino of energy E (in GeV).
- When E is small, of the order of a few 100 MeV, the corresponding oscillatory terms average out when L/E is large compared to Δm^2_{ij}. Since $|\Delta m^2_{3j}| \sim 2.4 \times 10^{-3}\ eV^2 \gg \Delta m^2_{21} \sim 7.6 \times 10^{-5}\ eV^2$, $j = 1, 2$; this applies to the "atmospheric" terms rather than to "solar" terms.
- $1.27\Delta m^2_{3j}\frac{L}{E} \approx \pi\frac{(L/100\ \text{km})}{(E/0.1\ \text{GeV})}$ - Atmospheric neutrino event rates at sub GeV energies and for $L \geq$ a few 100 km become independent of Δm^2_{32} and Δm^2_{31} and hence of their ordering. $\to$ Independent of the unknown hierarchy.
- $1.27\Delta m^2_{21}\frac{L}{E} \approx \pi\frac{(L/3000\ \text{km})}{(E/0.1\ \text{GeV})}$ - The solar mass-squared difference remains, but its magnitude and sign are well known.
- Values of $\theta_{13}, \Delta m^2_{21}$ change in matter.

Neutrino oscillation probabilities and events at sub GeV energies in the presence of Earth matter



(a) (b) (c) (d)

Figure: (a) $P_{\mu e}$ for $E_\nu = 0.65$ GeV for normal and inverted hierarchies (NH and IH) as a function of $\cos\theta_\nu$ (b) oscillated ν_e events from charged current interactions, as a function of $\cos\theta_\nu$, for events with $E_l = 0.5$–0.8 GeV and $\cos\theta_l = 0.6$–0.7, with $\delta_{CP} = \pm 90^\circ$ and NH; (c) ν_e oscillated events $\cos\theta_l$, for events with $E_l = 0.5$–0.8 GeV, with $\delta_{CP} = \pm 90^\circ$ and true NH; (d) cumulative sum of oscillated ν_e contributing to $\cos\theta_l = 0.6$–0.7, as a function of $\cos\theta_\nu$ for the bin $E_l = 0.5$–0.8 GeV with $\delta_{CP} = \pm 90^\circ$ and true NH. The last bin in each plots gives the total contribution to each $\cos\theta_l$ bin. Similarly for $\overline{\nu}_e$ events.

Sensitivity to δ_{CP} with sub GeV atmospheric neutrinos

Number of charged current ν_e events

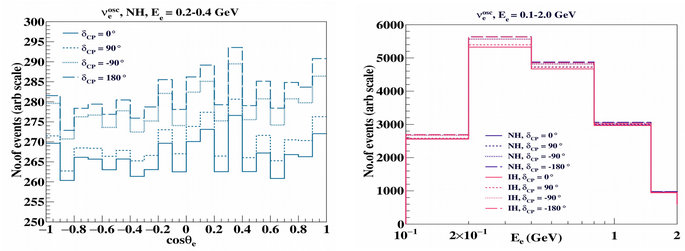
$$\mathcal{N}^e = t \times n_d \times \int d\sigma_{\nu_e} \times \left[P^m_{ee}\frac{d^3\Phi_{\nu_e}}{dE_{\nu_e}\, d\cos\theta_{\nu_e}\, d\phi_{\nu_e}} + P^m_{\mu e}\frac{d^3\Phi_{\nu_\mu}}{dE_{\nu_\mu}\, d\cos\theta_{\nu_\mu}\, d\phi_{\nu_\mu}}\right],$$

where $P^m_{\alpha\beta}$ are the oscillation probabilities in Earth matter; t = exposure time (10 years here), n_d = number of targets in the detector (50 kton here), $d\sigma_{\nu_e}$ = differential neutrino interaction cross section (differential in E_e and/or $\cos\theta_e$ respectively), and $d\Phi_{\nu_\mu}$ and $d\Phi_{\nu_e}$ are the ν_μ and ν_e fluxes. Similarly for $\overline{\nu}_e, \nu_\mu$ and $\overline{\nu}_\mu$ with relevant fluxes and probabilities.

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]$\times 10^{-3}$ eV^2
$\sin^2_{12}$	0.304	Not marginalised
Δm^2_{21}	7.6×10^{-5} eV^2	Not marginalised
δ_{CP}	0, $\pm 90°$, $\pm 180°$	Not marginalised

δ_{CP} sensitivity independent of neutrino mass hierarchy at sub-GeV energies.

Hierarchy sensitivity independent of δ_{CP} from higher energy events.

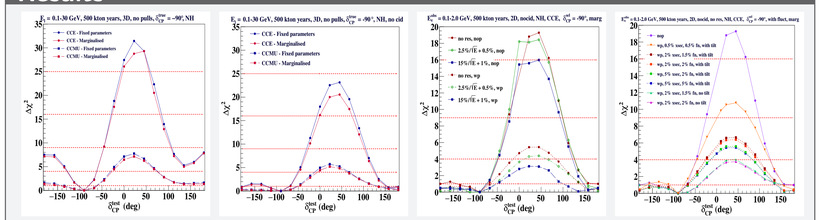


Idealistic	Realistic
No fluctuations $(E_l^{obs}, \cos\theta_l^{obs}, E_h^{obs})$ bins E_l^{obs} = [0.1, 30.0] GeV No energy & direction smearing	With fluctuations $(E_l^{obs}, \cos\theta_l^{obs})$ bins E_l^{obs} = [0.1, 2.0] GeV E_l^{obs} is smeared; $E_{res} = 15\%/\sqrt{E}, 2.5\%\sqrt{E}$ for $e^\pm$
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$ can all be separated Has charge id	$\nu_e - \nu_\mu$ ($\overline{\nu}_e - \overline{\nu}_\mu$) separation only No charge id
No systematic uncertainties	3 systematic uncertainties 5% "tilt", 5% flux normalisation and 5% cross section
Fixed and marginalised parameters	Marginalisation only

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

$$\chi^2 = \sum_i\sum_j 2\left[(T_{ij} - D_{ij}) - D_{ij}\ln\left(\frac{T_{ij}}{D_{ij}}\right)\right] + \sum_{l=1}^3 \xi_l^2;\ T_{ij} = T^0_{ij}\left(1 + \sum_{l=1}^3 \pi^l_{ij}\xi_l\right)$$

Results

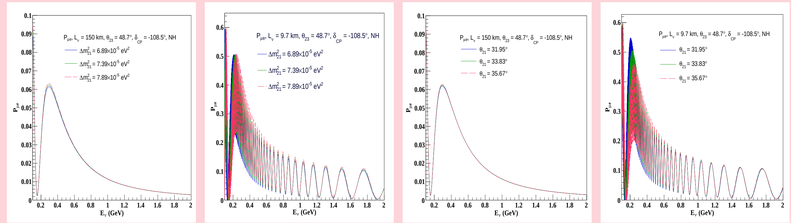


(a) (b) (c) (d)

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

Sensitivity to 1–2 oscillation parameters

$P_{\mu e}$, E_ν = 0.1–2.0 GeV



(a) (b) (c) (d)

Figure: Variation of $P_{\mu e}$ with Δm^2_{21} and θ_{12} for L = 150 and 9700 km, in the energy range 0.1–2.0 GeV.

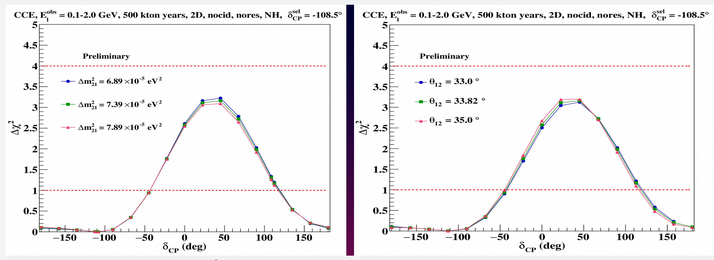


Figure: Effect of (a) Δm^2_{21} and (b) θ_{12} on δ_{CP} sensitivity from low energy CCE events. There is no significant sensitivity to 1–2 parameters from the sub–GeV electron like events. 1–2 parameters do not have any effect on δ_{CP} sensitivity from sub-GeV electron like events. Sensitivities from 500 kton year exposure of an isoscalar detector – no cid, perfect resolutions and 3 pulls are presented.

Conclusions and future prospects

- *Leptonic δ_{CP} can be probed irrespective of neutrino mass hierarchy using sub–GeV atmospheric neutrinos, thus breaking the ambiguity between δ_{CP} and hierarchy.*
- Detector resolutions and systematic uncertainties affect the sensitivity – systematic uncertainty causes drastic reduction in the sensitivity to δ_{CP}.
- Lesser sensitivity to δ_{CP} with detectors having no separation between ν_e and $\overline{\nu}_e$.
- Methods to separately identify ν_e and $\overline{\nu}_e$ at sub GeV energies?
- Will Gadolinium (Gd) doping of water Cerenkov detectors help in separating sub–GeV atmospheric ν_e and $\overline{\nu}_e$? Other techniques, say liquid Xenon TPCs for better energy resolution?
- Separately identified CC ν_μ and $\overline{\nu}_\mu$ events can add a small contribution to δ_{CP} χ^2. $\to$ Use magnetized detectors?
- Improve resolutions and efficiencies at sub GeV energies.
- Sub–GeV CCE events have no significant sensitivity to 1–2 oscillation parameters.
- The effect of 1–2 oscillation parameters on δ_{CP} sensitivity from sub–GeV CCE events is also very insignificant.

References

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Lakshmi.Mohan@ncbj.gov.pl