PROCEEDINGS OF SCIENCE

Effect of 1–2 oscillation parameters on the sensitivity to δ_{CP} with low energy atmospheric neutrinos

D. Indumathi,[a,b] **S. M. Lakshmi**[c,*] **and M. V. N. Murthy**[a]

[a] *The Institute of Mathematical Sciences, 600 113,Taramani, Chennai, India*
[b] *Homi Bhabha National Institute, 400 094, City, Country*
[c] *National Centre for Nuclear Research, Ludwika Pasteura 7, Warsaw, Poland*

E-mail: indu@imsc.res.in, Lakshmi.Mohan@ncbj.gov.pl, murthy@imsc.res.in

The leptonic CP violation phase δ_{CP} and the neutrino mass–ordering are two current unknowns in neutrino oscillation physics. We have shown earlier that the value of δ_{CP} can be estimated, *irrespective of the neutrino mass–ordering*, using sub–GeV atmospheric neutrinos. This enables the possibility of studying the effects of other oscilliation parameters on δ_{CP}. Here we perform a study of the effect of the 1–2 oscillation parameters θ_{12} and $\Delta m^2{}_{21}$ on the δ_{CP} sensitivity.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker

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1. Introduction

Existing and upcoming accelerator based long base–line neutrino experiments like T2K, NOνA and DUNE are probing and will probe the leptonic CP phase, δ_{CP}. We have shown earlier [1] that sub–GeV atmospheric neutrinos can be used to estimate δ_{CP} irrespective of neutrino mass–ordering (MO). The absence of δ_{CP}–MO degeneracy at these energies means that we can study the effect of other oscillation parameters on the sensitivity to δ_{CP}. Here we perform the study of the effect of θ_{12} and $\Delta m^2{}_{21}$ on the sensitivity to δ_{CP} with sub–GeV atmospheric ν_e and $\bar{\nu}_e$ events.

2. Event generation and analysis

To estimate the δ_{CP} sensitivity, we simulate the charged–current interactions of ν_e and $\bar{\nu}_e$ with a detector with an isoscalar target. The transition channels $\alpha \to \beta$, $\alpha \neq \beta$ for electron and muon neutrinos and anti-neutrinos are more sensitive to δ_{CP} than the survival channels. Since the flux ratio of ν_μ and ν_e events in atmospheric neutrinos is $\sim$ 2:1, the major contribution to the events come from the $\nu_\mu \to \nu_e$ channel. The simulation of unoscillated events using NUANCE [2], the event–by–event application of oscillation probabilities, χ^2 analyses and application of systematic uncertainties follow the procedure described in [1]. The central values and the marginalization ranges of oscillation parameters used in the analysis are listed in Table. 1. The specifications used for the analysis are presented in Table. 2.

Parameter	Input value	Marginalization range
θ_{13}	8.585°	Not marginalized
$\sin^2\theta_{23}$	0.574	[0.415, 0.617]
Δm^2_{eff}	2.4523×10^{-3} eV^2	$[2.3569, 2.5301]\times10^{-3}$ eV^2
θ_{12}	(27.56, 33.44, 36.63°)	Not marginalized
Δm^2_{21}	$(6.82, 7.42, 8.04)\times10^{-5}$ eV^2	Not marginalized
δ_{CP}	-120.5°	Not marginalized

Table 1: Central values of oscillation parameters and their 3σ ranges used to generate oscillation probabilities in matter [3]. For the analysis, $\Delta m^2_{31} = \Delta m^2_{\rm eff} + \Delta\, m^2_{21}\left(\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\right)$; $\Delta m^2_{32} = \Delta\, m^2_{31} - \Delta m^2_{21}$, for normal hierarchy with $\Delta m^2_{\rm eff} > 0$. $\Delta m^2_{31} \leftrightarrow -\Delta m^2_{32}$ for inverted hierarchy when $\Delta m^2_{\rm eff} < 0$.

Specifications
• No fluctuations in theory
• Events in bins of observed lepton and hadron energies, E_l^{obs}, $E_h'^{obs}$, and lepton direction, $\cos\theta_l^{obs}$
• E_l^{obs} = [0.1, 2.0] GeV; remaining parameters fixed, analysis both with/without systematic pulls
• 3 systematic uncertainties; 5% "tilt", 5% flux normalisation and 5% cross section
• Analyses with E_l^{obs} both perfectly reconstructed and smeared
• Electron energy resolution $E_{res} = 2.5\%\sqrt{E}$[4]; no direction smearing; charge identification of lepton
• Assume charged current ν_e, ν_μ, $\overline{\nu}_e$, $\overline{\nu}_\mu$ events can all be separated from one another

Table 2: Specifications of the analysis performed. Only charged current (CC) ν_e and $\bar{\nu}_e$ events are analyzed.

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3. Results

The variation of δ_{CP} sensitivity with θ_{12} and $\Delta m^2{}_{21}$ when other oscillation parameters are fixed are shown in Fig. 1. Here "no res" stands for a detector with perfect resolutions and "with res" indicates the case where the resolution of lepton energy is taken into account. As expected the "no res–no pull" case has a large sensitivity to δ_{CP} for all values of θ_{12} and $\Delta m^2{}_{21}$. When the energy resolutions as well as the systematic uncertainties are taken into account, the sensitivities decrease drastically. It can be seen that the sensitivity decreases with decrease in both θ_{12} and $\Delta m^2{}_{21}$. The difference is significantly large if θ_{12} is as low as 27.56°.

With marginalization over other parameters, the difference between sensitivities may be washed out. So in general we may not be able to study the effects of 1–2 oscillation parameters on δ_{CP} using sub-GeV atmospheric neutrinos, since the effects of both $P_{\mu e}$ and P_{ee} are present for ν_e events. This means that we need to look for these effects in a clean $P_{\mu e}$ GeV energy beam experiment. From the oscillograms in Fig. 1 it can be deduced that long baseline accelerator neutrino experiments with E_ν in the 0.1–0.4 GeV and $\cos\theta_\nu$ (L_ν (km)) in the [~0.3, 1.0] ([~ 4000, 12000] km) will be best suited for this.

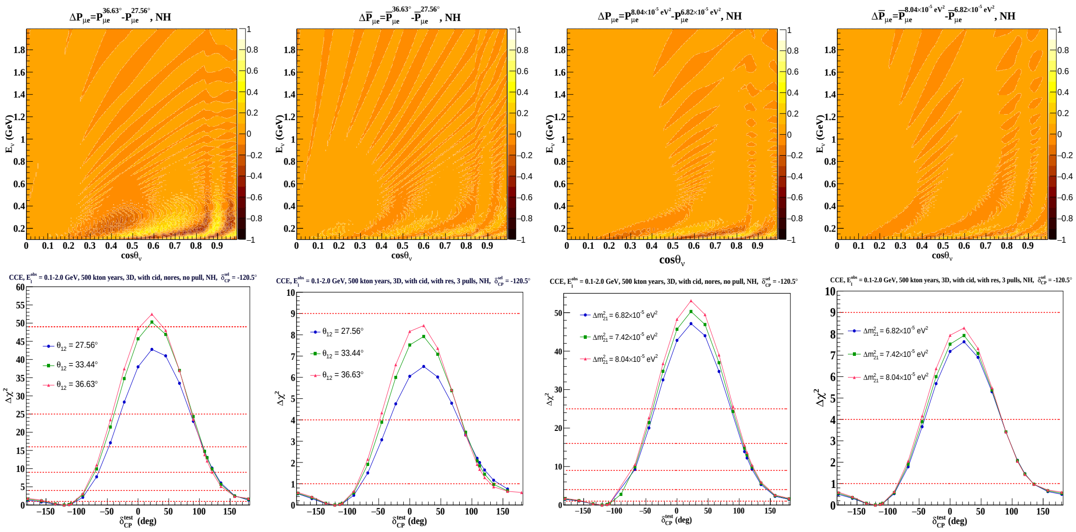

Figure 1: Effect of (left–set) θ_{12} and (right–set) $\Delta m^2{}_{21}$ on δ_{CP} measurement with charged current ν_e and $\bar{\nu}_e$ events in the 0.1–2.0 GeV energy range.

Acknowledgements : Nandadevi cluster and system administrators, IMSc, Chennai; ICHEP2020 organizers; Warsaw Neutrino Group.

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