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

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The leptonic CP violation phase $\delta_{CP}$ and the neutrino mass–ordering are two current unknowns in neutrino oscillation physics. We have shown earlier that the value of $\delta_{CP}$ 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 $\delta_{CP}$. Here we perform a study of the effect of the 1–2 oscillation parameters $\theta_{12}$ and $\Delta m^2_{21}$ on the $\delta_{CP}$ sensitivity.

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1. Introduction

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

2. Event generation and analysis

To estimate the $\delta_{CP}$ sensitivity, we simulate the charged–current interactions of $\nu_e$ and $\bar{\nu}_e$ with a detector with an isoscalar target. The transition channels $\alpha \rightarrow \beta$, $\alpha \neq \beta$ for electron and muon neutrinos and anti-neutrinos are more sensitive to $\delta_{CP}$ than the survival channels. Since the flux ratio of $\nu_\mu$ and $\nu_e$ events in atmospheric neutrinos is $\sim 2:1$, the major contribution to the events come from the $\nu_\mu \rightarrow \nu_e$ channel. The simulation of unoscillated events using NUANCE [2], the event–by–event application of oscillation probabilities, $\chi^2$ 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
<th>Marginalization range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{13}$</td>
<td>$8.585^\circ$</td>
<td>Not marginalized</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.574</td>
<td>$[0.415, 0.617]$</td>
</tr>
<tr>
<td>$\Delta m^2_{31}$</td>
<td>$2.4523 \times 10^{-3}$ eV$^2$</td>
<td>$[2.3569, 2.5301] \times 10^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$(27.56, 33.44, 36.63)^\circ$</td>
<td>Not marginalized</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>-120.5$^\circ$</td>
<td>Not marginalized</td>
</tr>
</tbody>
</table>

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

- 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 $\nu_e$, $\nu_\mu$, $\bar{\nu}_e$, $\bar{\nu}_\mu$ events can all be separated from one another

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

The variation of $\delta_{CP}$ sensitivity with $\theta_{12}$ 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 $\delta_{CP}$ for all values of $\theta_{12}$ 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 $\theta_{12}$ and $\Delta m^2_{21}$. The difference is significantly large if $\theta_{12}$ 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 $\delta_{CP}$ using sub-GeV atmospheric neutrinos, since the effects of both $P_{\mu e}$ and $P_{ee}$ are present for $\nu_e$ 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 $E_{\nu}$ in the 0.1–0.4 GeV and $\cos \theta_{\nu}$ ($L_{\nu}$ (km)) in the [−0.3, 1.0] ([−4000, 12000] km) will be best suited for this.

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

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References