Measuring the deviation from maximal mixing of atmospheric muon neutrinos at INO

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- **Neutrino factfile and** $D \equiv 1/2 - \sin^2\theta_{23}$
- $\nu_\mu, \bar{\nu}_\mu$ **survival probabilities and binned up-down asymmetries**
- **Error analysis and sensitivity to** D

This talk is based on my work [1] with S. Choubey.

• Neutrino factfile

We take a CPT-conserving framework with only three active light neutrinos: $\nu_{e,\mu,\tau}$ as flavor eigenstates and $\nu_{1,2,3}$ as mass eigenstates with real, positive mass eigenvalues $m_{1,2,3}$ and use $\Delta_{ij} \equiv m_i^2 - m_j^2$. We relate the two sets of eigenstates by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_\nu \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad U_\nu \equiv U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta). \tag{1}$$

Here U_{PMNS} is defined in the standard CKM parametrization with possible Majorana phases ignored. We define

$$D \equiv 1/2 - \sin^2\theta_{23}. \tag{2}$$

$0.0085 \text{ eV} < \sqrt{m_2^2 - m_1^2} < 0.0094 \text{ eV}$
$0.041 \text{ eV} < \sqrt{\lvert m_3^2 - m_2^2\rvert} < 0.057 \text{ eV}$
$30^\circ < \theta_{12} < 38^\circ$
$36^\circ < \theta_{23} < 54^\circ$, i.e. $-0.16 < D < 0.16$
$\theta_{13} < 12^\circ$
$\delta = ?$

Table 1. Known 3σ limits on neutrino parameters

The known 3σ limits on the relevant neutrino mass and mixing parameters are given in Table 1. It is also instructive to keep in mind that $-0.10 < D < 0.10$ at 2σ and $-0.07 < D < 0.07$ at 1σ levels.

• $\nu_\mu, \bar{\nu}_\mu$ **survival probabilities and binned up-down asymmetries**

We explore the measurability of D from atmospheric muon neutrino and antineutrino studies in a large magnetized iron calorimeter like ICAL – as proposed [2] in the India-based Neutrino Observatory INO. Effects due to matter and subleading oscillations on account of the solar neutrino mass scale Δ_{21} cause departures from the simple $\sin^2 2\theta_{23}$ dependence of 2-flavor vacuum oscillations in the survival probability $P_{\mu\mu}$ ($P_{\bar{\mu}\bar{\mu}}$) for a ν_μ ($\bar{\nu}_\mu$). Both these effects as well as vacuum oscillation terms play a role in the measurement of $|D|$. However, matter effects are found to be crucial in resolving the octant ambiguity $\sin^2\theta_{23} \leftrightarrow 1-\sin^2\theta_{23}$, i.e. whether θ_{23} is greater or less than $\pi/4$, through a determination of the sign of D. Our numerical code exactly solves the three generation neutrino equations of motion in earth matter with the PREM density profile. We assume normal neutrino mass ordering, but we can do the analysis for the inverted case. We fix some of the oscillation parameters at chosen benchmark values, to wit $\Delta_{31} = 2\times 10^{-3}$ eV^2, $\Delta_{21} = 8\times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.28$, $\sin^2 2\theta_{13} = 0.1$, $\delta = 0$. Using the atmospheric neutrino flux of Honda et al [3] and the DIS cross sections of the CTEQ collaboration [4], we have simulated 14000 (7000) ν_μ ($\bar{\nu}_\mu$) events for 1 MtonY of exposure for ICAL assuming a 50% trigger efficiency. We have binned our data *both* in energy E and the cosine of the zenith angle ξ. The difference between the ν_μ and $\bar{\nu}_\mu$ up-down asymmetry ratios $U_N/D_N - U_A/D_A$ is shown in Fig. 1 with solid (dashed) pink and black lines corresponding to $\sin^2\theta_{23} = 0.36$ and 0.5 respectively in matter (vacuum). The largest usable effects are in the topmost right panel (the lowermost right panel having problems due to earth-core uncertainties) with the 5-7 GeV energy bin corresponding to a maximum SPMAX in $P_{\mu\mu}$.

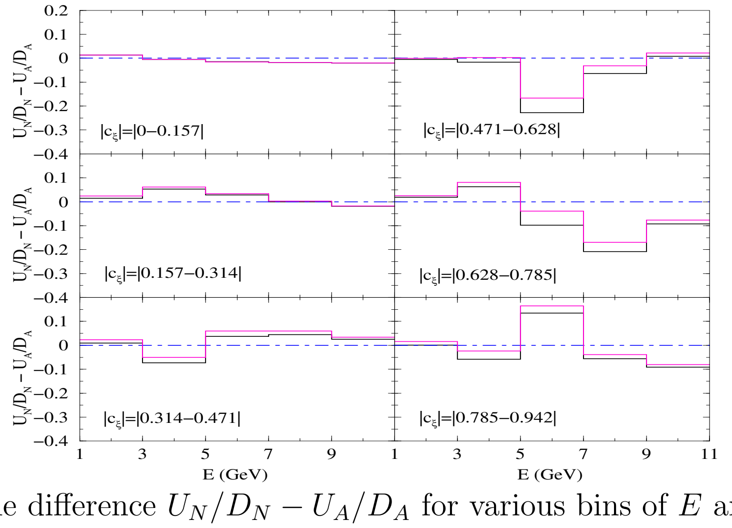

Fig. 1. The difference $U_N/D_N - U_A/D_A$ for various bins of E and $|c_\xi|$.

• **Error analysis and sensitivity to D**

We have done a χ^2 analysis using the pull approach, as detailed in [1]. Fig. 2 shows the regions of $\sin^2\theta_{13}$ for which a maximal θ_{23} can be rejected at 3σ (yellow), 2σ (green) and 1σ (magenta) levels. The capability to resolve the octant ambiguity

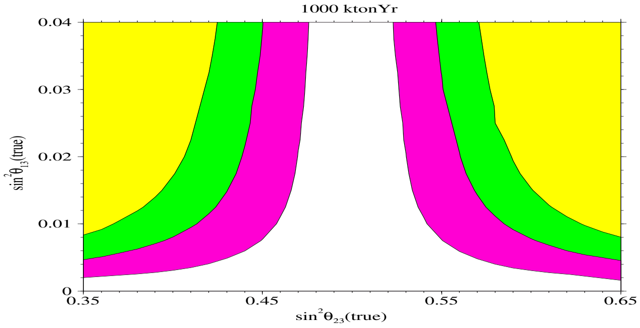

Fig. 2. Sensitivity to deviation from maximal θ_{23} in terms of θ_{13}

in θ_{23} is shown in the $\Delta\chi^2$ vs. $\sin^2\theta_{23}$ plot of Fig. 3 where $\Delta\chi^2$ is the difference in χ^2 for 'true octant' and 'false octant' values. The latter is made possible by the unique capability of a large magnetized iron calorimeter to isolate matter effects by distinguishing between ν_μ and $\bar{\nu}_\mu$ events.

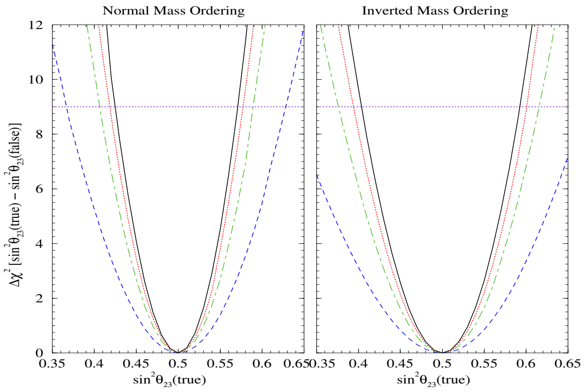

Fig. 3. Capability of octant ambiguity resolution

[1] S. Choubey and P. Roy, hep-ph/0509197, to appear in Phys. Rev. D.

[2] http:\\www.imsc.res.in\ ∼ ino\.

[3] M. Honda et al., Phys. Rev. D**70**, 043008 (2004).

[4] http:\\user.pa.msu.edu\wkt\cteq6\cteq6pdf.html