A New Approach to Probe Non-Standard Interactions in Atmospheric Neutrino Experiments

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The Iron Calorimeter (ICAL) detector at the proposed India-based Neutrino Observatory (INO) [1] can play a key role in constraining non-standard interactions over a multi-GeV range of energies.

**ICAL@INO**: 50 kton magnetized iron detector

**Active detector element**: RPC, **Passive detector element**: iron

**Uniqueness**: CFD for muons, distinguishes $v_\mu$ and $\bar{v}_\mu$

**Muon energy range**: 1 – 25 GeV, Muon energy resolution: ~ 10%

**Baselines**: 15 – 12000 km, Muon zenith angle resolution: ~ 1°

**Non-Standard Interactions (NSI)**

Neutral-current NSI in propagation through matter

\[ \mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2} G_F e^2 \bar{\psi}(i\gamma_\mu P_\mu - i\gamma_\nu P_\nu f)(\gamma_\nu P_\nu f) \]

where, \( P_\mu = (1 - \gamma_\mu)/2, P_\nu = (1 + \gamma_\nu)/2 \) and \( C = L, R \).

\[ \epsilon_{\alpha\beta} = \sum_{f=e,\mu,\tau} \frac{V_f}{V_{CC}} \left( \epsilon_{gf}^\ell + \epsilon_{gf}^\nu \right) \]

where, \( V_{CC} = \sqrt{2} G_F N_c, V_f = \sqrt{2} G_F N_f, f = e, u, d \).

\[ H_{\text{mat}} = \sqrt{2} G_F N_c \left[ 1 + \epsilon_{\mu\tau} \epsilon_{\mu\mu} + \epsilon_{\tau\tau} \right] \]

In atmospheric neutrinos, $\mu \rightarrow \tau$ channel is dominant, hence, we choose to constrain $\epsilon_{\mu\tau}$ (only real values).

**Methodology**

- NUANCE neutrino event generator
- Neutrino flux at INO site
- Three-flavor matter oscillation with the PREM profile
- Migration matrices for muons from GEANT4 simulation of ICAL
- Ratio of upward-going (U) and downward-going (D) reconstructed muon events

**U/D ratio** (defined for $\cos \theta_{23}^{\text{rec}} < 0$)

\[ \frac{U/D}{E_{\text{rec}}^{\cos \theta_{23}^{\text{rec}}} = \frac{N(E_{\text{rec}}^{\mu} \cos \theta_{23}^{\text{rec}})}{N(E_{\text{rec}}^{\mu} \cos \theta_{23}^{\text{rec}})} \]

where, \( N(E_{\text{rec}}^{\mu} \cos \theta_{23}^{\text{rec}}) \) is the number of events with energy \( E_{\text{rec}}^{\mu} \) and zenith angle $\theta_{23}^{\text{rec}}$.

The oscillation valley [2] bends in the presence of NSI parameter $\epsilon_{\mu\tau}$ [3]

**Summary and Conclusion**

- Using good reconstruction efficiency at ICAL for $\mu^-$ and $\mu^+$, oscillation dip and oscillation valley can be observed in reconstructed muon observables at ICAL.
- We propose a new approach to utilize oscillation dip and oscillation valley to probe neutral-current NSI parameter $\epsilon_{\mu\tau}$.
- A new variable representing the difference in the shifts in location of dips for $\mu^-$ and $\mu^+$ is used to constrain NSI parameter $\epsilon_{\mu\tau}$.
- The contrast in the curvatures of valleys for $\mu^-$ and $\mu^+$ is also used to constrain NSI parameter $\epsilon_{\mu\tau}$.

**References**

