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:** CID for muons, distinguishes ν_μ and $\bar{\nu}_\mu$
- **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

$$\mathscr{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\varepsilon^{Cf}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\rho P_L\nu_\beta)(\bar{f}\gamma_\rho P_C f)$$

where, $P_L = (1-\gamma_5)/2, P_R = (1+\gamma_5)/2$, and $C = L, R$.

$$\varepsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{V_f}{V_{CC}}\left(\varepsilon^{Lf}_{\alpha\beta} + \varepsilon^{Rf}_{\alpha\beta}\right)$$

where, $V_{CC} = \sqrt{2}G_F N_e, V_f = \sqrt{2}G_F N_f, f = e, u, d$.

$$H_{mat} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

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

Methodology

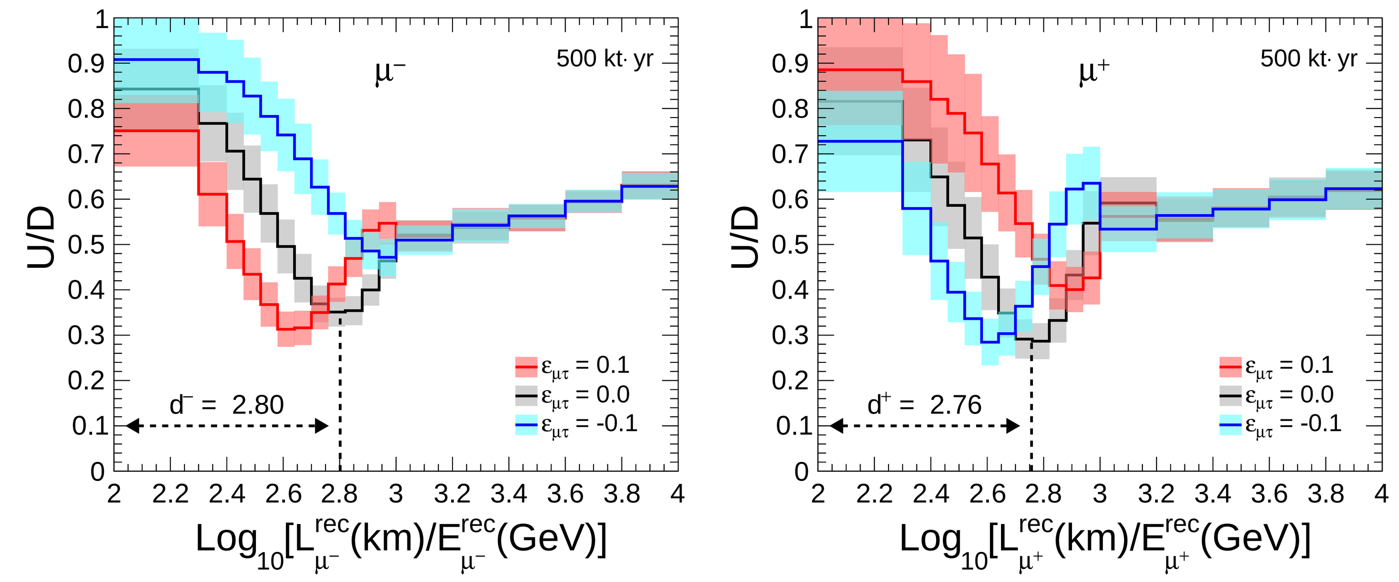
- NUANCE neutrino event generator
- Neutrino flux at INO site
- Three-flavor matter oscillation with the PREM profile
- Migration matrices for muons from GEANT4 simulation of ICAL
- Ratio of upward-going (U) and downward-going (D) reconstructed muon events

U/D ratio (defined for $\cos\theta^{\text{rec}}_\mu < 0$)

$$\text{U/D}(E^{\text{rec}}_\mu, \cos\theta^{\text{rec}}_\mu) \equiv \frac{N(E^{\text{rec}}_\mu, -|\cos\theta^{\text{rec}}_\mu|)}{N(E^{\text{rec}}_\mu, +|\cos\theta^{\text{rec}}_\mu|)},$$

where $N(E^{\text{rec}}_\mu, \cos\theta^{\text{rec}}_\mu)$ is the number of events with energy E^{rec}_μ and zenith angle θ^{rec}_μ.

Shift in Reconstructed Oscillation Dip

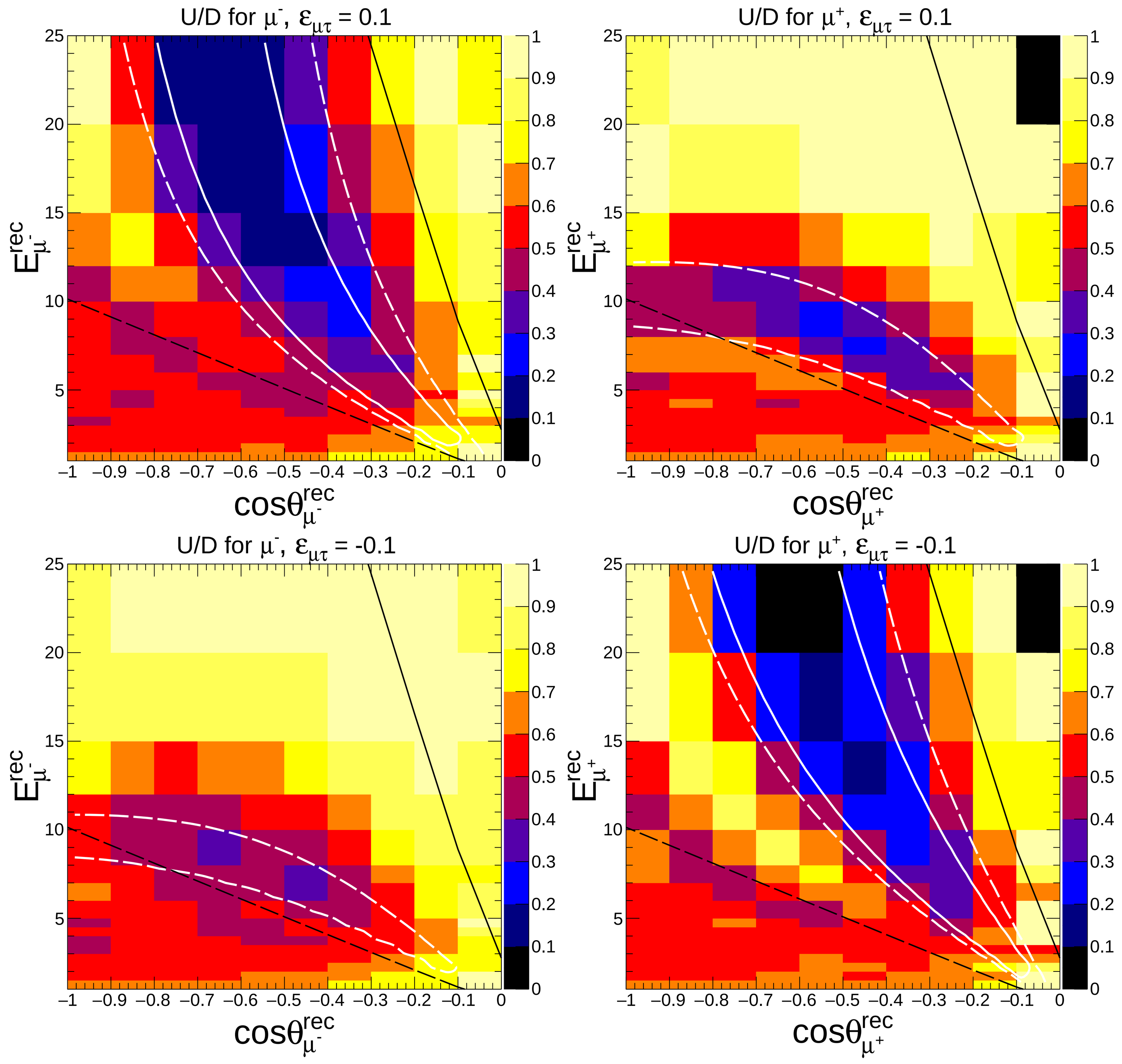


Oscillation dip [2] shifts in the opposite directions for μ^- and μ^+ in the presence of NSI parameter $\varepsilon_{\mu\tau}$ [3]

Curvature in Reconstructed Oscillation Valley

The parameter α in the fitting function $f(x,y)$ is the measure of the curvature of oscillation valley

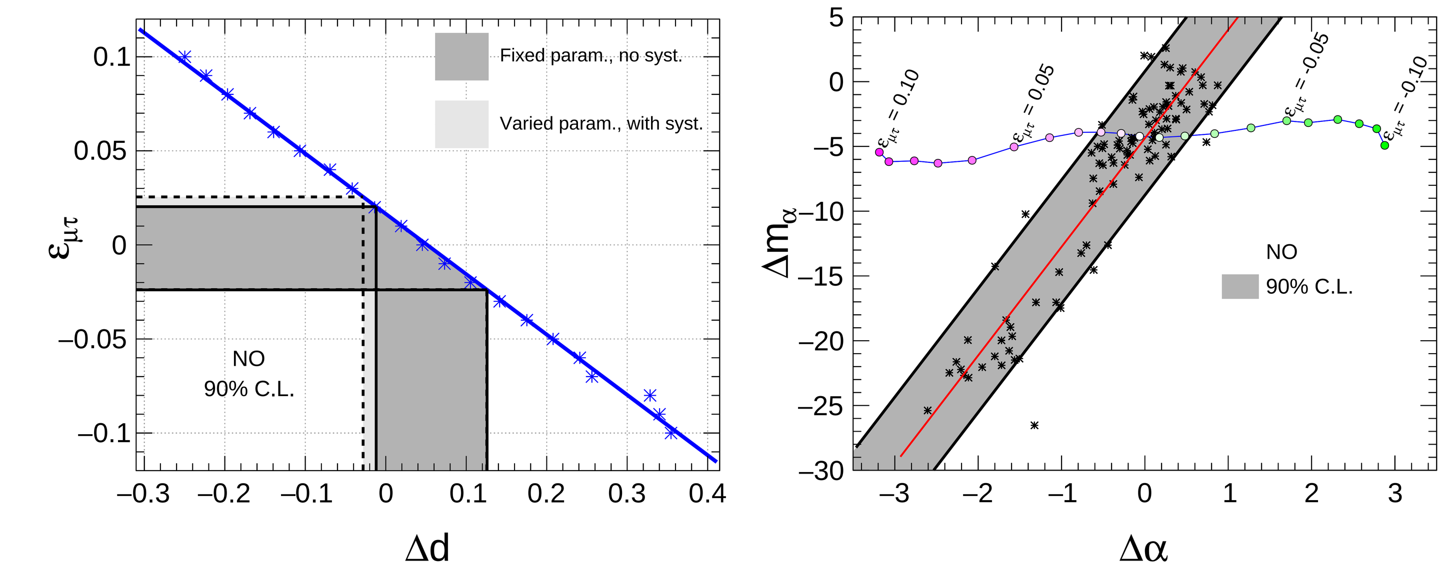
$$f(x,y) = z_0 + N_0\cos^2\left(m_\alpha\frac{x}{y} + \alpha x^2\right), \quad \text{where, } x \equiv \cos\theta^{\text{rec}}_\mu \text{ and } y \equiv E^{\text{rec}}_\mu.$$



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

Constraining $\varepsilon_{\mu\tau}$ using Osc. Dip & Valley

- $\Delta d = d^- - d^+$ • $\Delta m_\alpha = m_{\alpha^-} - m_{\alpha^+}$ • $\Delta\alpha = \alpha^- - \alpha^+$ • Calibration curve using 1000-yr MC • Gray bands using multiple simulated data sets for 10 years



Estimated bounds on $\varepsilon_{\mu\tau}$ at 90% C. L. with 500 kt·yr exposure:

	Oscillation dip	Oscillation valley
Fixed param., no syst.	$-0.024 < \varepsilon_{\mu\tau} < 0.020$	$-0.022 < \varepsilon_{\mu\tau} < 0.021$
Varied param., with syst.	$-0.025 < \varepsilon_{\mu\tau} < 0.024$	$-0.024 < \varepsilon_{\mu\tau} < 0.020$

Existing bounds on $\varepsilon_{\mu\tau}$ at 90% C. L.:

Experiment	Their convention ($\tilde{\varepsilon}_{\mu\tau}$)	Our convention ($\varepsilon_{\mu\tau} = 3\tilde{\varepsilon}_{\mu\tau}$)
IceCube	$-0.006 < \tilde{\varepsilon}_{\mu\tau} < 0.0054$	$-0.018 < \varepsilon_{\mu\tau} < 0.0162$
DeepCore	$-0.0067 < \tilde{\varepsilon}_{\mu\tau} < 0.0081$	$-0.0201 < \varepsilon_{\mu\tau} < 0.0243$
Super-K	$\lvert\tilde{\varepsilon}_{\mu\tau}\rvert < 0.011$	$\lvert\varepsilon_{\mu\tau}\rvert < 0.033$

Summary and Conclusion

- Using good reconstruction efficiency at ICAL for μ^- and μ^+, 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 $\varepsilon_{\mu\tau}$.
- A new variable representing the difference in the shifts in location of dips for μ^- and μ^+ is used to constrain NSI parameter $\varepsilon_{\mu\tau}$.
- The contrast in the curvatures of valleys for μ^- and μ^+ is also used to constrain NSI parameter $\varepsilon_{\mu\tau}$.

References:

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[2] Anil Kumar et al. "From oscillation dip to oscillation valley in atmospheric neutrino experiments". In: *Eur. Phys. J. C* 81.2 (2021), p. 190. DOI: 10.1140/epjc/s10052-021-08946-8. arXiv: 2006.14529 [hep-ph].

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