

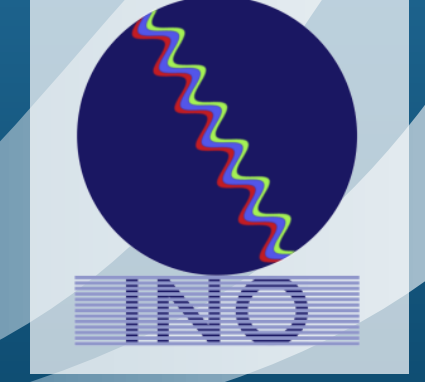
# A New Approach to Probe Non-Standard Interactions in Atmospheric Neutrino Experiments

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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  $\nu_\mu$  and  $\bar{\nu}_\mu$
- **Muon energy range:** 1 – 25 GeV, **Muon energy resolution:**  $\sim 10\%$
- **Baselines:** 15 – 12000 km, **Muon zenith angle resolution:**  $\sim 1^\circ$

## Non-Standard Interactions (NSI)

Neutral-current NSI in propagation through matter

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

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

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{V_f}{V_{CC}} (\epsilon_{\alpha\beta}^{Lf} + \epsilon_{\alpha\beta}^{Rf})$$

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

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

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

## Methodology

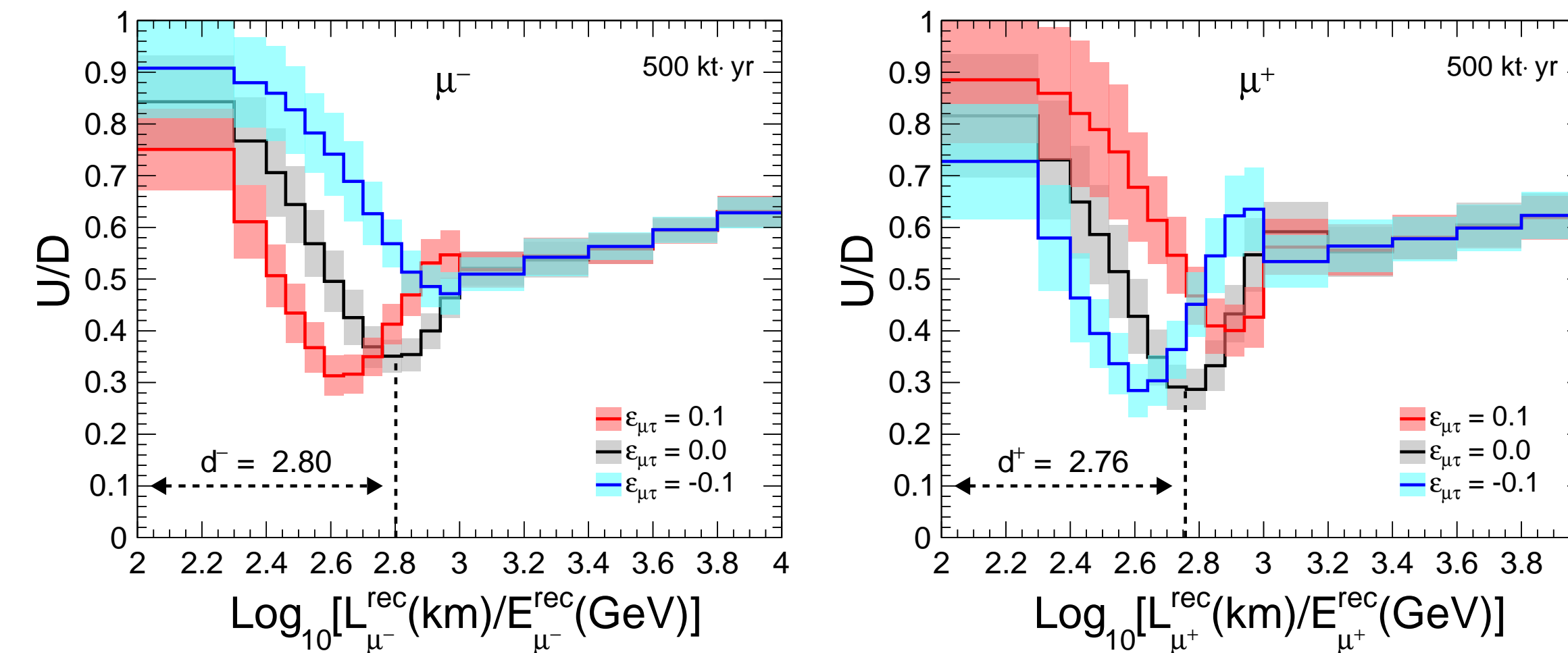
- NUANCE neutrino event generator
- Neutrino flux at INO site
- Three-flavor matter oscillation with PREM profile
- Migration matrices for muons from GEANT4 simulation of ICAL
- Ratio of upward-going (U) and downward-going (D) reconstructed muon events

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

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

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

## Shift in Reconstructed Oscillation Dip

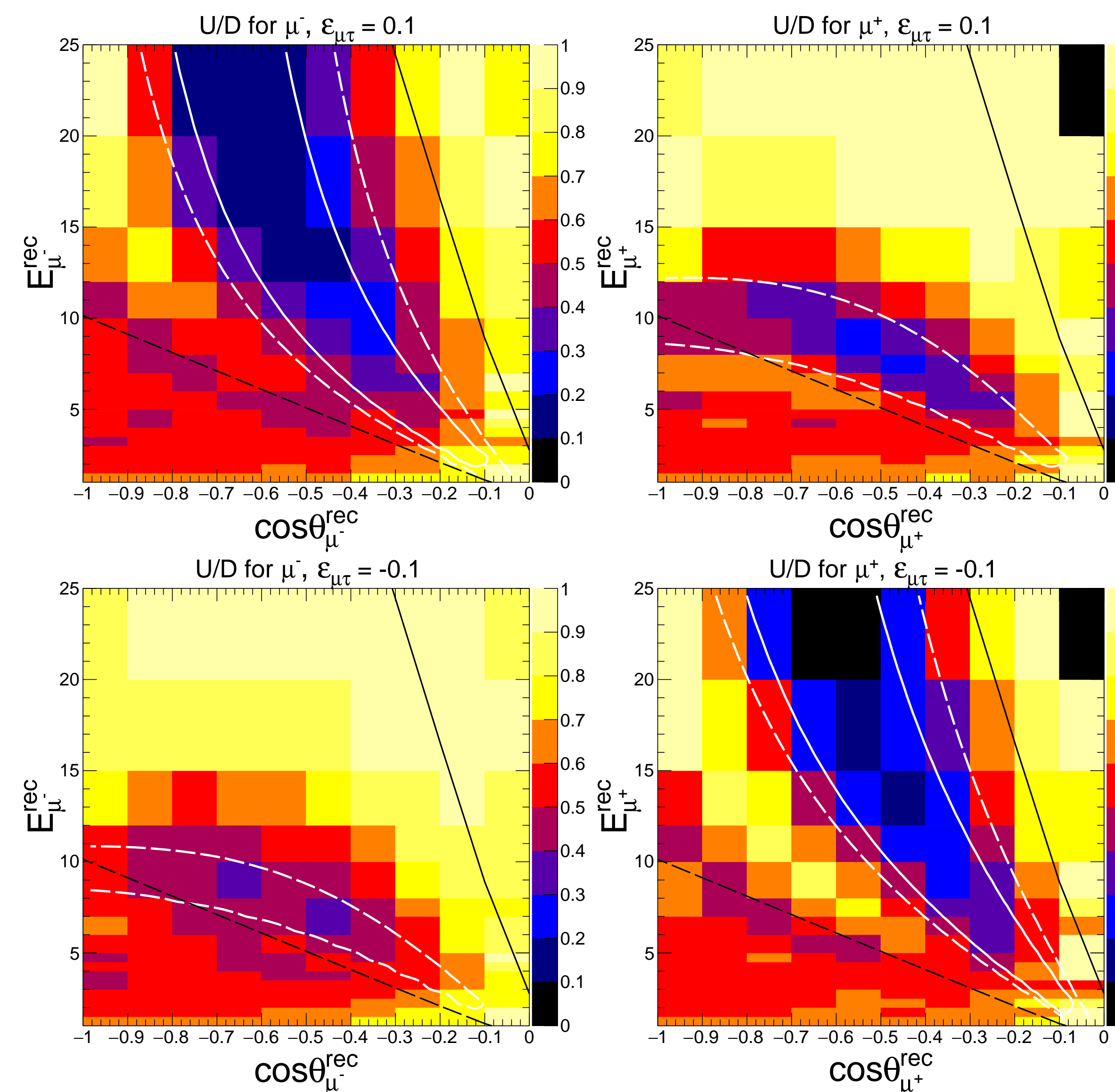


Oscillation dip [3] shifts in the opposite directions for  $\mu^-$  and  $\mu^+$  in the presence of NSI parameter  $\epsilon_{\mu\tau}$  [2]

## Curvature in Reconstructed Oscillation Valley

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

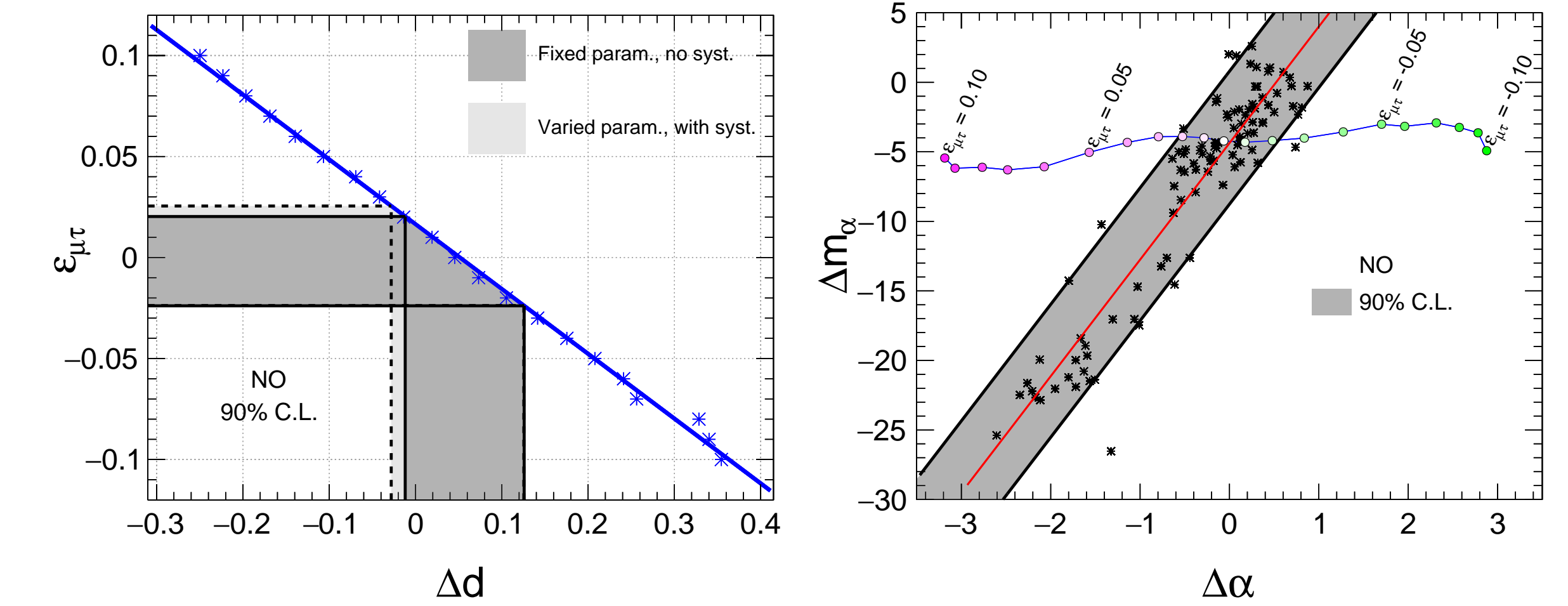
$$f(x, y) = z_0 + N_0 \cos^2\left(m_\alpha \frac{x}{y} + \alpha x^2\right)$$



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

## Constraining $\epsilon_{\mu\tau}$ 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  $\epsilon_{\mu\tau}$  at 90% C. L. with 500 kt-yr exposure:

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

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

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

## 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 contrasts in the curvature of valleys for  $\mu^-$  and  $\mu^+$  is used to constrain NSI parameter  $\epsilon_{\mu\tau}$ .

## References:

- [1] Shakeel Ahmed et al. "Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO)". In: *Pramana* 88.5 (2017), p. 79. arXiv: 1505.07380 [physics.ins-det].
- [2] Anil Kumar et al. "A New Approach to Probe Non-Standard Interactions in Atmospheric Neutrino Experiments". In: *JHEP* 04 (2021), p. 159. DOI: 10.1007/JHEP04(2021)159. arXiv: 2101.02607 [hep-ph].
- [3] 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].