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

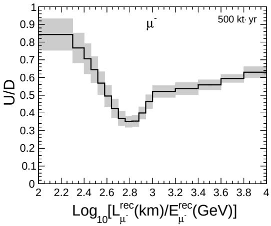
Anil Kumar
Research Scholar, India-based Neutrino Observatory (INO)
(Institute of Physics, Bhubaneswar, India)

Collaborators: Amina Khatun, Sanjib Kumar Agarwalla, Amol Dighe

February 23, 2021
XIX International Workshop on Neutrino Telescopes

Iron Calorimeter Detector (ICAL) at INO[2]

- **ICAL@INO:** 50 kton magnetized iron detector
- **Uniqueness:** CID for muons, distinguishes ν_μ and $\bar{\nu}_\mu$
- **Muon energy range:** 1 – 25 GeV, **Muon energy resolution:** $\sim 10\%$
- **Baselines:** 15 – 12000 km, **Muon zenith angle resolution:** $\sim 1^\circ$



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

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

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

- The U/D ratio of the reconstructed muon events is a good proxy for ν_μ survival probability which has **oscillation dip and valley**[1] features.
- The U/D ratio automatically cancels most of the systematic uncertainties.

[1] Anil Kumar et al., arXiv: 2006.14529

[2] Pramana - J Phys (2017) 88 : 79, arXiv:1505.07380

Neutral current Non-Standard Interactions (NSI)

Neutral current NSI in propagation through matter.

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

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

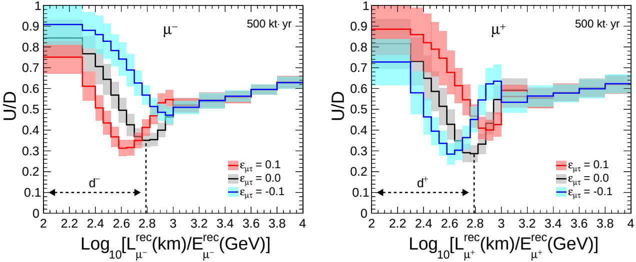
In this analysis, we use:

- Three flavor matter oscillation with PREM profile
- NUANCE neutrino event generator
- Neutrino Flux at INO site (Theni)
- Migration matrices[3] for muon from GEANT4 simulation of ICAL

$\sin^2 2\theta_{12}$	$\sin^2 \theta_{23}$	$\sin^2 2\theta_{13}$	$\lvert\Delta m^2_{32}\rvert$ (eV^2)	Δm^2_{21} (eV^2)	δ_{CP}	Mass Ordering
0.855	0.5	0.0875	2.46×10^{-3}	7.4×10^{-5}	0	Normal (NO)

[3] Animesh Chatterjee et al. 2014 JINST 9 P07001, arXiv:1405.7243

Shift in dip location in reconstructed muon observables



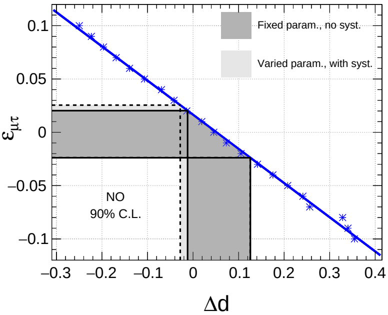
- Statistical uncertainty calculated using 100 simulated sets of 10-year data.
- The location of dip d^- or d^+ depends on magnitude as well as sign of $\varepsilon_{\mu\tau}$.
- d^- and d^+ shift in the opposite direction due to $\varepsilon_{\mu\tau}$.
- d^- and d^+ shift in the same direction due to change in Δm^2_{32}.
- New variable $\Delta d = d^- - d^+$ depends on $\varepsilon_{\mu\tau}$ but independent of Δm^2_{32}(true).

Anil Kumar et al., arXiv: 2101.02607

Constraints on $\varepsilon_{\mu\tau}$ from measurement of Δd

- We calibrate $\varepsilon_{\mu\tau}$ with respect to Δd using 1000 yr Monte Carlo.
- The 90% C.L. are obtained using multiple simulated sets of 10-year data.

- **Variation over oscillation parameters:** 20 random choices of oscillation parameters for each 10-year simulated data set, according to the Gaussian distribution using σ from current global fit.
- **Systematics errors with Gaussian distributions**: overall flux normalization (20%), cross sections (10%), energy dependence (5%), zenith angle dependence (5%), and overall systematics (5%).

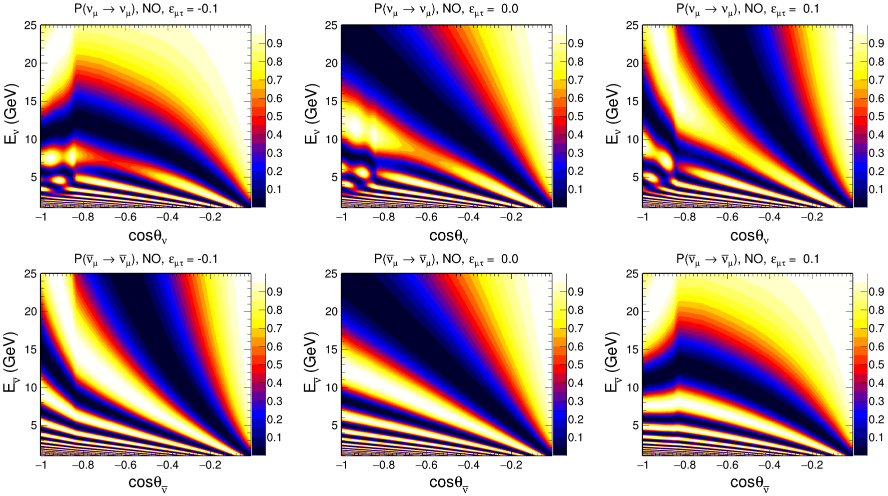


90% C.L.:

- Fixed param., no syst: $-0.024 < \varepsilon_{\mu\tau} < 0.020$
- Varied param., with syst.: $-0.025 < \varepsilon_{\mu\tau} < 0.024$

Anil Kumar et al., arXiv: 2101.02607

Oscillation valley in neutrino survival probability



The presence of NSI results in the curvature of oscillation valley (dark blue diagonal band).

Anil Kumar et al., arXiv: 2101.02607

Identifying NSI through Oscillation Valley

For $\Delta^2_{21} L/4E \to 0$, $\theta_{13} = 0$, and $\theta_{23} = 45^\circ$, we have[6],

$$P(\nu_\mu \to \nu_\mu) = cos^2 \left[L \left(\frac{\Delta m^2_{32}}{4E} + \varepsilon_{\mu\tau} V_{CC} \right) \right]$$

Fitting function for oscillation valley

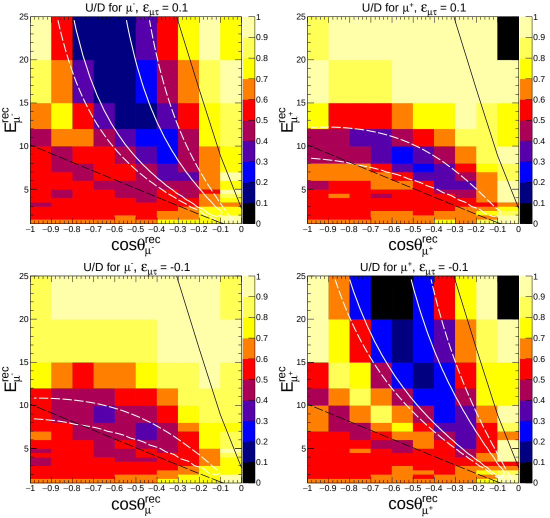
$$f(x, y) = z_0 + N_0 \cos^2 \left(m_\alpha \frac{x}{y} + \alpha x^2 \right)$$

The parameter α is the measure of the curvature of oscillation valley.

[6] Irina Mocioiu et al., Nuclear Physics B 893 (2015) 376–390, arXiv:1410.6193

Curvature of oscillation valley in reconstructed muon observables

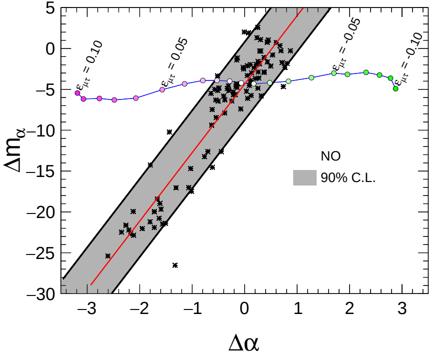
- Mean of 100 U/D distribution for 10 year data in presence of NSI ($\varepsilon_{\mu\tau} = -0.1$ and 0.1).
- Solid black and dashed black lines show conical cut of $\log_{10} L/E = 2.2$ and $\log_{10} L/E = 3.1$ respectively which includes bins used for fitting.
- Solid white and dashed white lines show contours with U/D ratio of 0.4 and 0.5 respectively for fitted function $f(x, y) = z_0 + N_0 \cos^2\left(m_\alpha \frac{x}{y} + \alpha x^2\right)$.



Anil Kumar et al., arXiv: 2101.02607

Constraints on $\varepsilon_{\mu\tau}$ using curvature of oscillation valley

$\Delta m_\alpha = m_{\alpha^-} - m_{\alpha^+}$ and $\Delta\alpha = \alpha^- - \alpha^+$



90% C.L.:

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

Anil Kumar et al., arXiv: 2101.02607

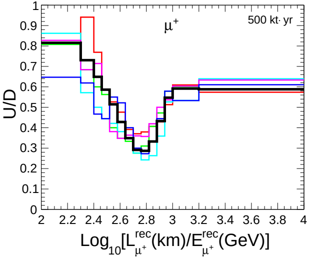
Conclusion

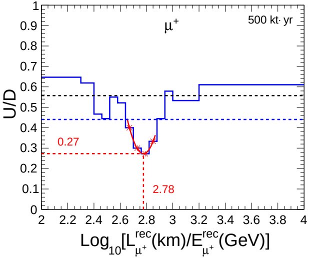
- ICAL has good reconstruction efficiency for μ^- and μ^+ over a wide range of energy and direction.
- Oscillation dip and oscillation valley can be observed in reconstructed muon observables at ICAL.
- We propose a new approach to utilize oscillation dip and oscillation valley to probe neutral-current NSI parameter $\varepsilon_{\mu\tau}$.
- A new variable representing shift in location of dip for μ^- and μ^+ is used to constrain NSI parameter $\varepsilon_{\mu\tau}$.
- The contrast in curvature of valley for μ^- and μ^+ is used to constrain NSI parameter $\varepsilon_{\mu\tau}$.

Acknowledgement: We acknowledge financial support from the Department of Atomic Energy (DAE), Department of Science and Technology (DST), Govt. of India, and the Indian National Science Academy (INSA).

Thank you

Backup: Identifying the dip





- The left panel shows 5 representative set of 10-year simulated data and thick black line shows mean of 100 simulated sets of 10-year data.
- The right panel shows dip identification algorithm where we start with initial ratio threshold which is shown as dashed black line.
- If ratio threshold passes through more than one dip then we decrease the ratio threshold.
- The blue dashed line shows the final ratio threshold which passes through only single oscillation dip.
- The bins with U/D ratio less than final ratio threshold are fitted with parabola to obtain location of dip.

Backup: Variation of oscillation parameters

We first simulated 100 statistically independent unoscillated data sets. Then for each of these data sets, we take 20 random choices of oscillation parameters, according to the gaussian distributions
$\Delta m^2_{21} = (7.4 \pm 0.2) \times 10^{-5}$ eV^2 , $\Delta m^2_{32} = (2.46 \pm 0.03) \times 10^{-5}$ eV^2 ,
$\sin^2 2\theta_{12} = 0.855 \pm 0.020$, $\sin^2 2\theta_{13} = 0.0875 \pm 0.0026$, $\sin^2 \theta_{23} = 0.50 \pm 0.03$,
guided by the present global fit. We keep $\delta_{\rm CP} = 0$, since its effect on ν_μ survival probability is known to be highly suppressed in the multi-GeV energy range. This procedure effectively enables us to consider the variation of our results over 2000 different combinations of oscillation parameters, to take into account the effect of their uncertainties.

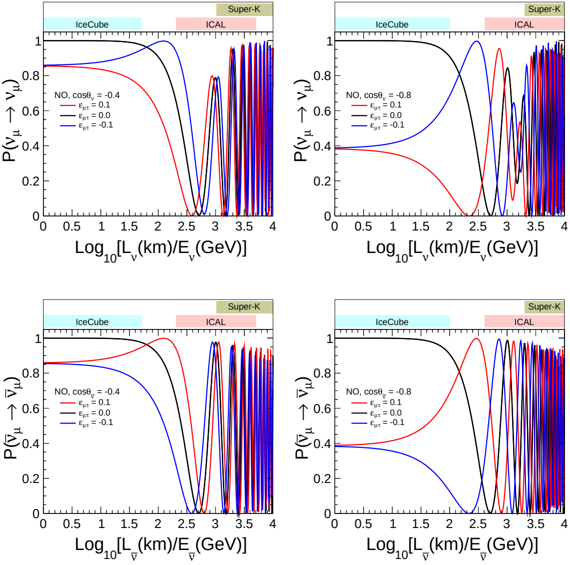
Backup: Systematics uncertainties

The five uncertainties are (i) 20% in overall flux normalization, (ii) 10% in cross sections, (iii) 5% in the energy dependence, (iv) 5% in the zenith angle dependence, and (iii) 5% in overall systematics.
For each of the 2000 simulated data sets, we modify the number of events in each $(E_\mu^{\rm rec}, \cos\theta_\mu^{\rm rec})$ bin as

$$N = N^{(0)}(1+\delta_1)(1+\delta_2)(E_\mu^{\rm rec}/E_0)^{\delta_3}(1+\delta_4\cos\theta_\mu^{\rm rec})(1+\delta_5)\ ,$$

where $N^{(0)}$ is the theoretically predicted number of events, and $E_0 = 2$ GeV. Here $(\delta_1, \delta_2, \delta_3, \delta_4, \delta_5)$ is an ordered set of random numbers, generated separately for each simulated data set, with the gaussian distributions centred around zero and the 1σ widths given by $(20\%, 10\%, 5\%, 5\%, 5\%)$.

Backup: Survival probability $P(\nu_\mu \to \nu_\mu)$ in presence of NSI



Backup: Event distribution in presence of NSI