A new approach to probe neutrino non-standard interactions in atmospheric neutrino experiments

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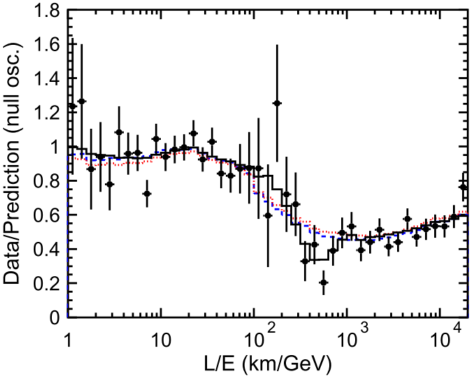
Oscillation dip in neutrino survival probability

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2 \left(1.27 \cdot |\Delta m^2_{32}| \, (\text{eV}^2) \cdot \frac{L_\nu \, (\text{km})}{E_\nu \, (\text{GeV})} \right)$$

- Super-K experiment dip, L/E = 500 km/GeV
- Neutrino decay and neutrino decoherence models were disfavored



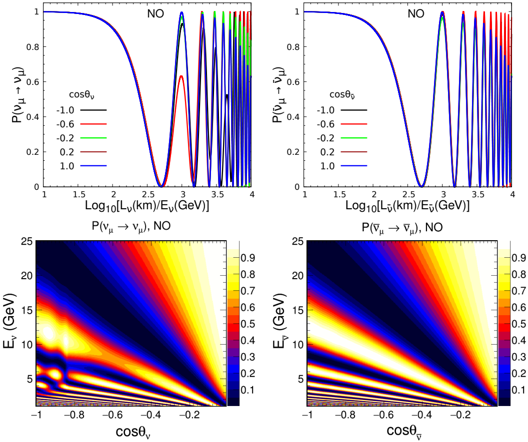
Phys.Rev.Lett. 93 (2004) 101801

Oscillation dip and oscillation valley in neutrino

Three-flavor oscillation framework in the presence of matter (PREM profile)

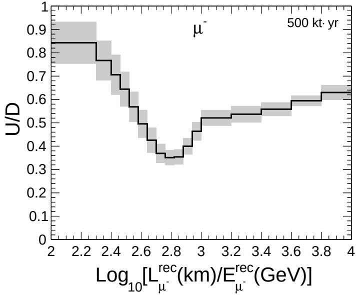
Expectation for ν and $\bar{\nu}$

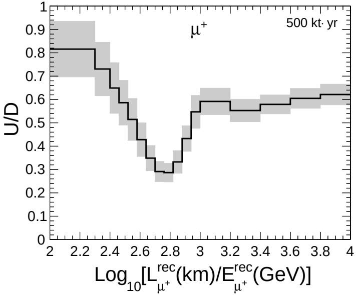
- **Oscillation dip** can be observed around $\log_{10}(L_\nu/E_\nu) = 2.7$
- Matter effect in $P(\nu_\mu \to \nu_\mu)$ for the case of neutrino (due to normal ordering) can be observed around $\log_{10}(L_\nu/E_\nu) = 3.0$
- The **oscillation valley** can be seen as dark blue diagonal band.



Oscillation dip in reconstructed muon observables at ICAL

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

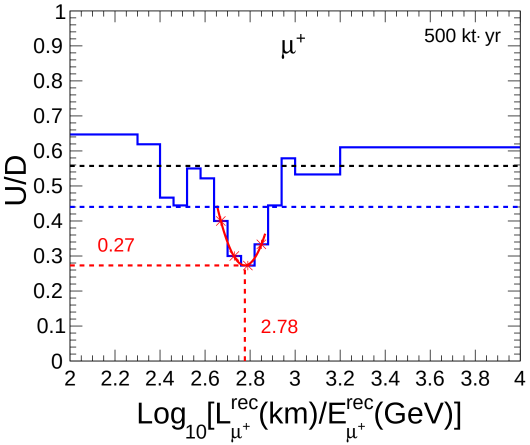




- The U/D ratio automatically cancels most of the systematic uncertainties.
- Statistical uncertainty calculated using 100 simulated sets of 10-year data.

Anil Kumar et. al. arXiv:2006.14529

Identifying the dip

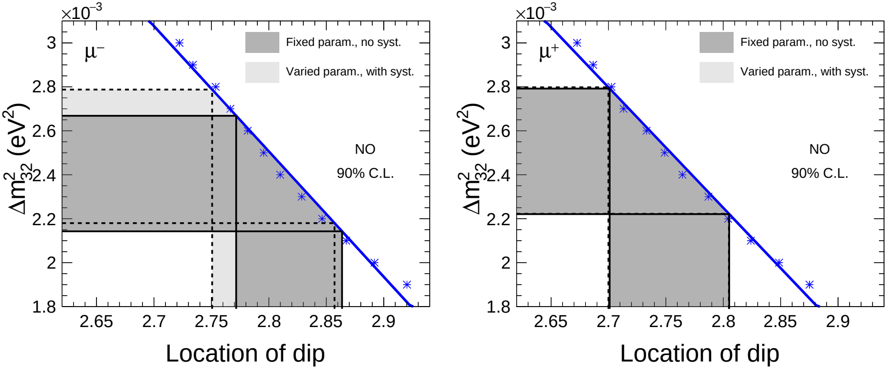


Dip identification algorithm[2] identifies single lowest dip

[2] Anil Kumar et. al. arXiv:2006.14529

Estimating Δm^2_{32} using location of dip

- We calibrate Δm^2_{32} with respect to the location of dip using 1000 yr MC.
- The 90% C.L. are obtained using multiple simulated sets of 10-year data.

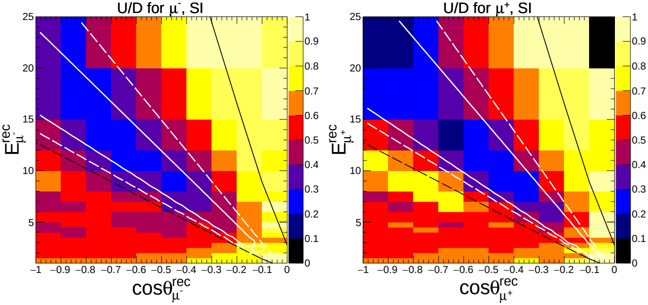


	Δm^2_{32} (in 10^{-3} eV^2) at 90% C.L.			
	μ^-		μ^+	
Fixed param., no syst.	-2.14	-2.67	-2.22	-2.79
Varied param., with syst.	-2.18	-2.79	-2.22	-2.80

Anil Kumar et. al. arXiv:2006.14529

Oscillation valley in reconstructed muon observables

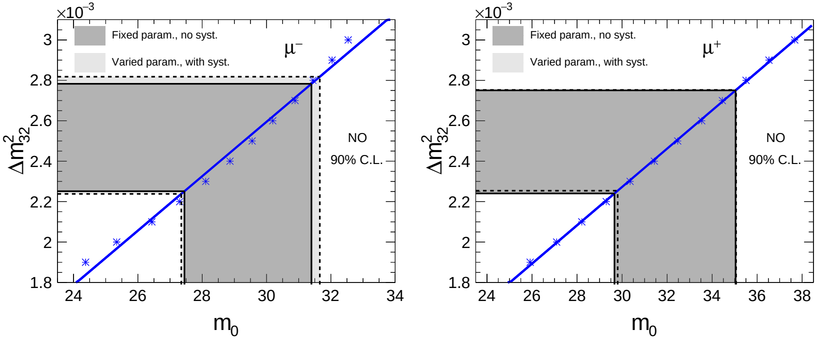
$$f(x,y) = z_0 + N_0 \cos^2\left(m_0 \frac{x}{y}\right)$$



- Mean of 100 U/D distribution for 10 year data.
- Solid black and dashed black lines show conical cut of $\log_{10} L/E = 2.2$ and $\log_{10} L/E = 3.0$ 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.

Constraints on Δm^2_{32} using alignment of oscillation valley

- We calibrate Δm^2_{32} with respect to m_0 using 1000 yr MC.
- The 90% C.L. are obtained using multiple simulated sets of 10-year data.



	Δm^2_{32} (in 10^{-3} eV^2) at 90% C.L.			
	μ^-		μ^+	
Fixed param., no syst.	-2.25	-2.78	-2.24	-2.75
Varied param., with syst.	-2.24	-2.82	-2.25	-2.75

arXiv: under progress

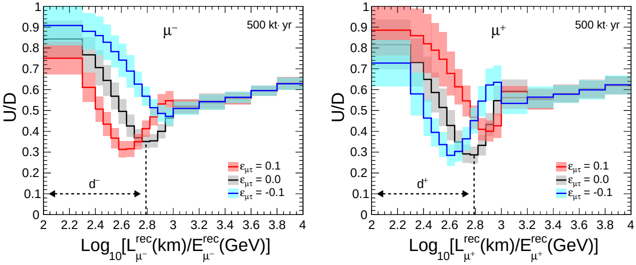
Neutral current Non-Standard Interactions (NSI)

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)

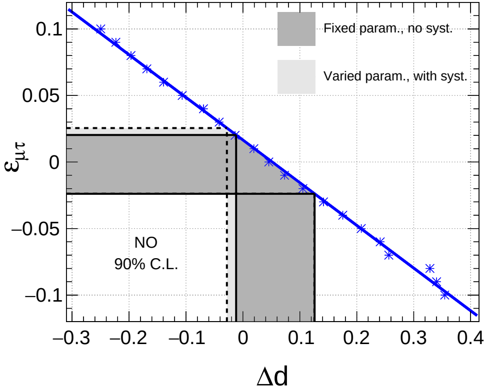
Shift in dip location in reconstructed muon observables



- 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).

arXiv: under progress

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



90% C.L.:

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

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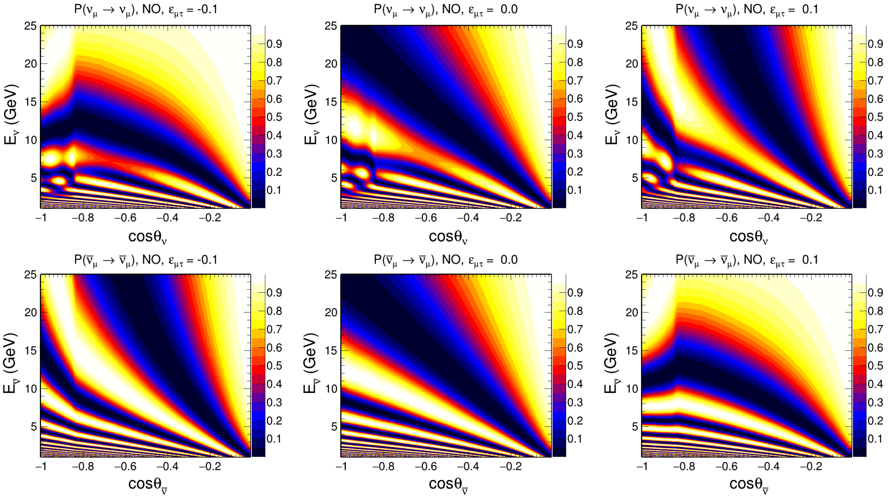
arXiv: under progress

Oscillation valley in neutrino survival probability



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

Identifying NSI through Oscillation Valley

For $\Delta^2_{21} L/4E \to 0$, $\theta_{13} = 0$, and $\theta_{23} = 45^\circ$, we have[7],

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

Modified fitting function for oscillation valley

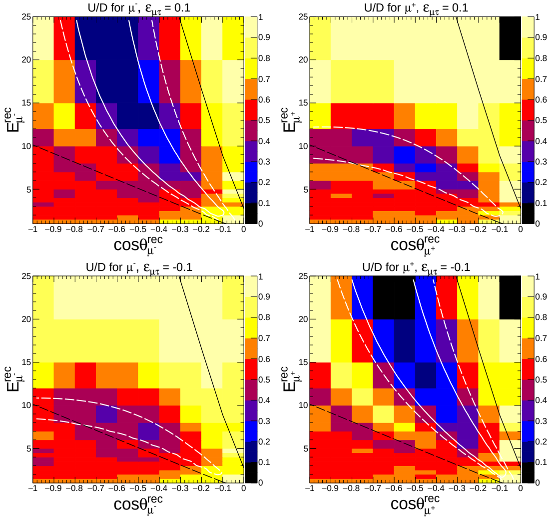
$$f(x, y) = z_0 + N_0 \cos^2 \left(m_\alpha \frac{x}{y} + \alpha x^2 \right)$$

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

[7] Irina Mocioiu et. al. arXiv:1410.6193

Curvature of oscillation valley in reconstructed muon observables

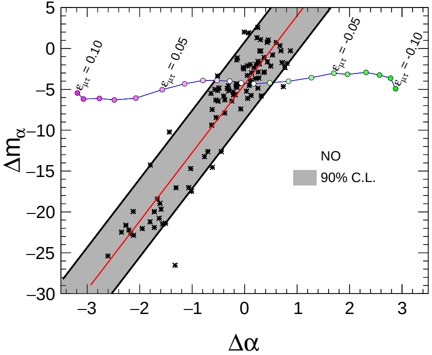
- Mean of 100 U/D distribution for 10 year data in presence of NSI ($\varepsilon_{\mu\tau} = -0.1$ and 0.1).
- Solid black and dashed black lines show conical cut of $\log_{10} L/E = 2.2$ and $\log_{10} L/E = 3.1$ respectively which includes bins used for fitting.
- Solid white and dashed white lines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



arXiv: under progress

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.: $-0.024 < \varepsilon_{\mu\tau} < 0.020$

arXiv: under progress

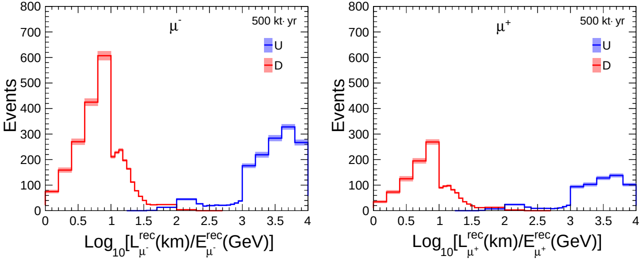
Conclusion

- 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 oscillations in three flavor framework and beyond.
- The location of dip is used to measure $|\Delta m^2_{32}|$.
- The alignment of valley is used to measure $|\Delta m^2_{32}|$.
- $|\Delta m^2_{32}|$ can be measured independently using μ^- and μ^+.
- A new variable representing shift in location of dip is used to constrain NSI parameter $\varepsilon_{\mu\tau}$.
- The curvature of valley is used to constrain NSI parameter $\varepsilon_{\mu\tau}$.

Thank you

Backup: Events at ICAL

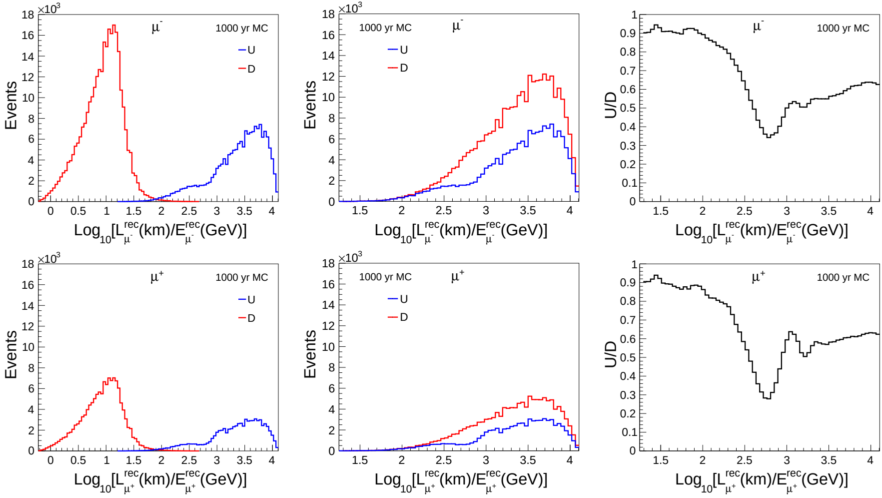
- Our aim is to probe these features in terms of reconstructed observable of ICAL detector at INO and put contraints on $|\Delta m^2_{32}|$ and $\varepsilon_{\mu\tau}$.
- In this study, we generate[10] the charged-current interactions of ν_μ and $\bar{\nu}_\mu$ using neutrino and antineutrino fluxes calculated in Theni site by Honda et.al[11] and the neutrino generator NUANCE.



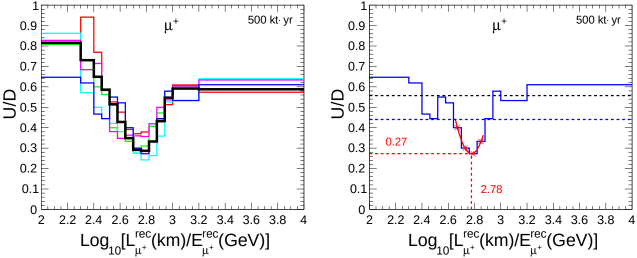
[10] arXiv:2006.14529

[11] arXiv:1210.5154 and arXiv:1502.03916

Backup: Events and U/D Ratio Using 1000-year MC Simulation



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.

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.

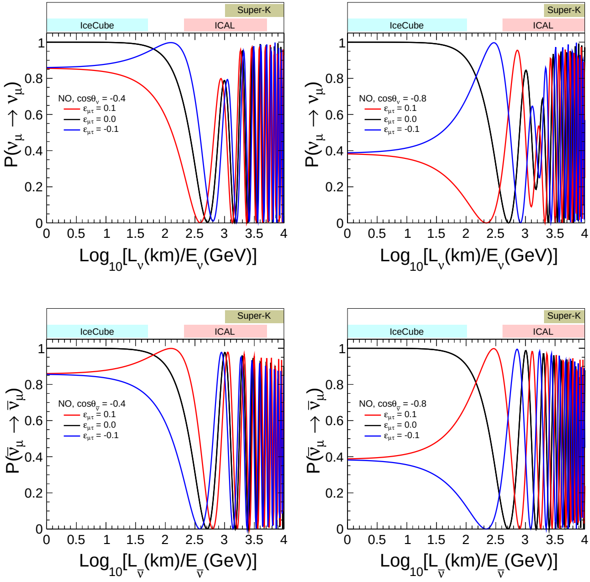
Systematics uncertainties

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 $(20\%, 10\%, 5\%, 5\%, 5\%)$.

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



Location of dip shits in the presence of NSI

Backup: Event distribution in presence of NSI