From oscillation dip to oscillation valley in atmospheric neutrino experiments

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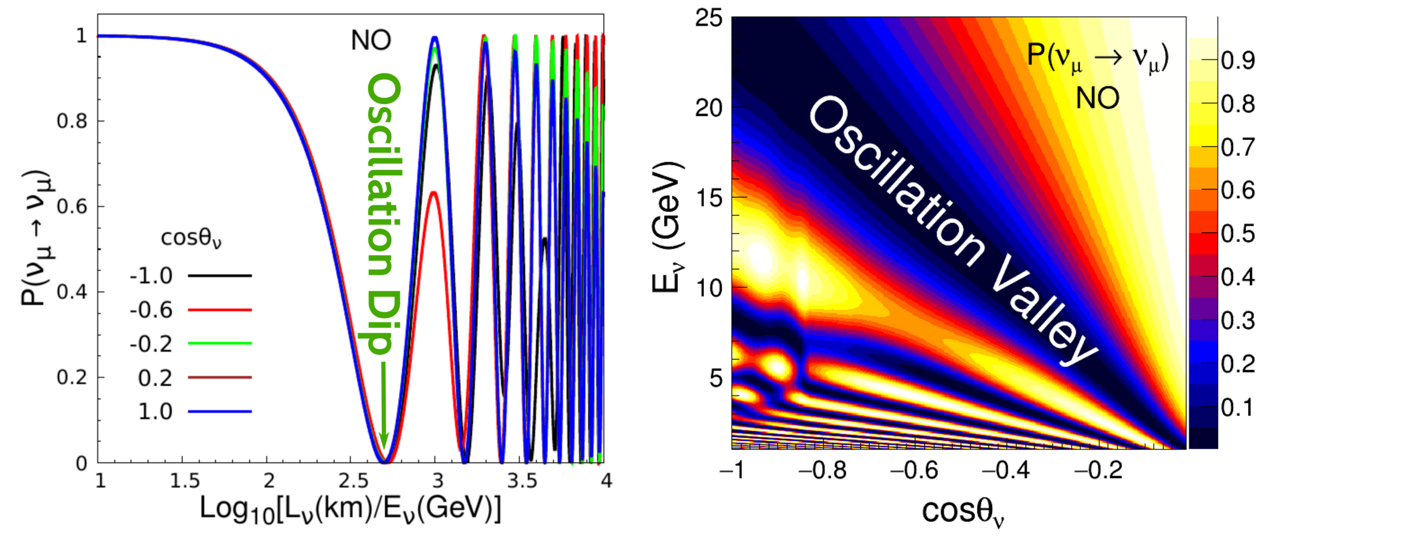
Iron Calorimeter (ICAL) Detector at INO [1] can play a key role in establishing three flavor neutrino oscillation over a wide range of energy.

- **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:** ∼ 10%
- **Baselines:** 15 – 12000 km, **Muon zenith angle resolution:** ∼ 1°

Oscillation Dip and Valley



ν_μ survival proabability

Methodology

Super-K Analysis [2]	Our Analysis [3]
Used the ratio of data and unoscillated Monte Carlo (MC)	Uses the ratio of upward-going (U) and downward-going (D) events
Used inferred neutrino observables L_ν and E_ν	Uses reconstructed muon observables $L_\mu^{\rm rec}$ and $E_\mu^{\rm rec}$

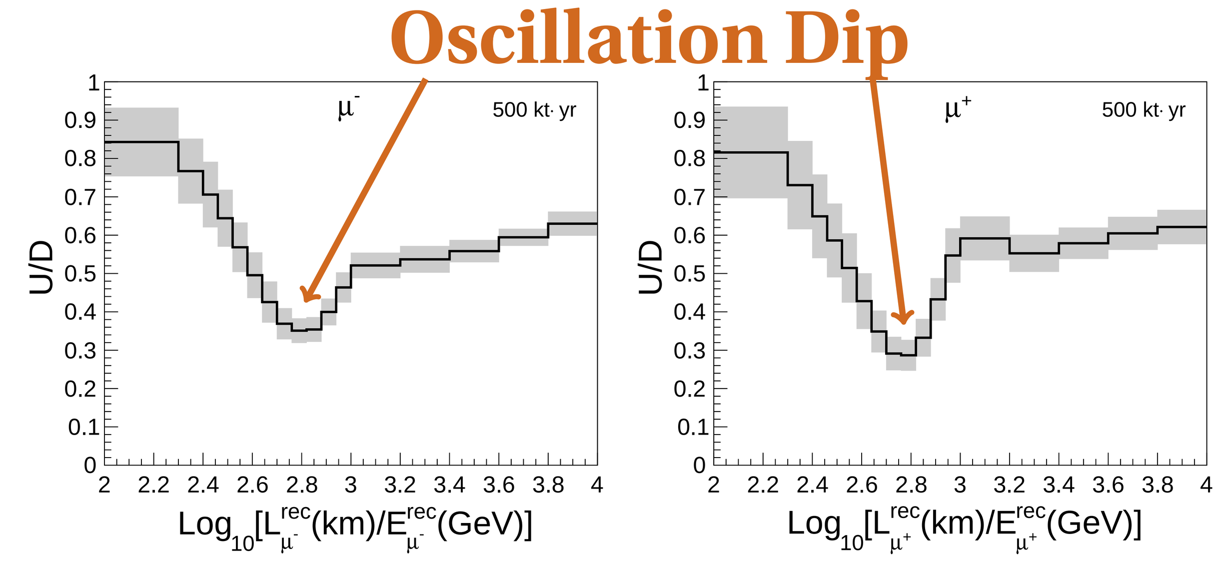
U/D ratio (defined for $\cos\theta_\mu^{\rm rec} < 0$)

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

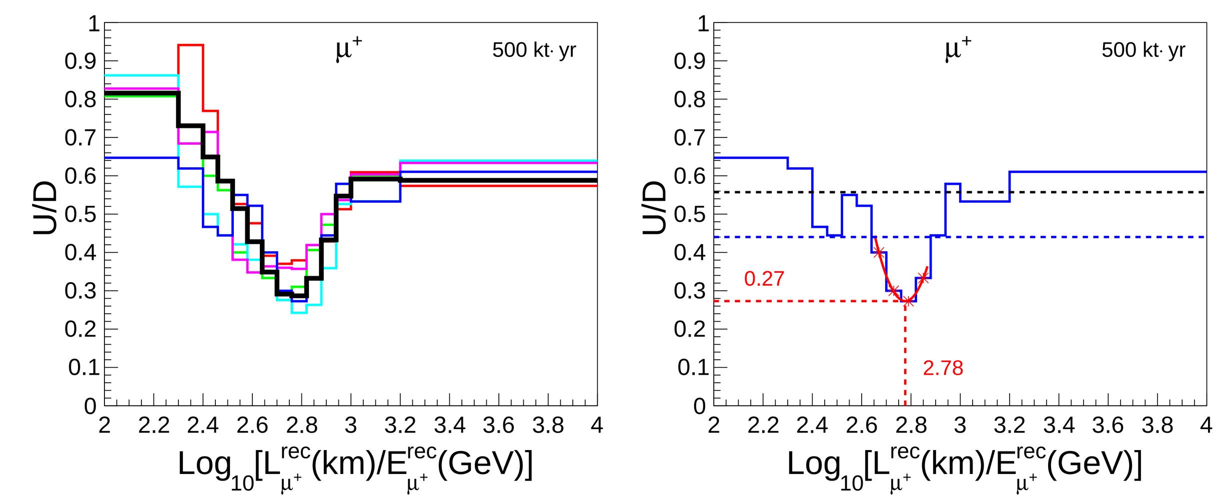
where $N(E_\mu^{\rm rec}, \cos\theta_\mu^{\rm rec})$ is the number of events with energy $E_\mu^{\rm rec}$ and zenith angle $\theta_\mu^{\rm rec}$.

The efficient reconstruction of both $\cos\theta_\mu^{\rm rec}$ and $E_\mu^{\rm rec}$ by ICAL enable us to go a step ahead and look at the distribution of the U/D ratio in the ($E_\mu^{\rm rec}$, $\cos\theta_\mu^{\rm rec}$) plane to reconstruct "oscillation valley".

Reconstructed Oscillation Dip

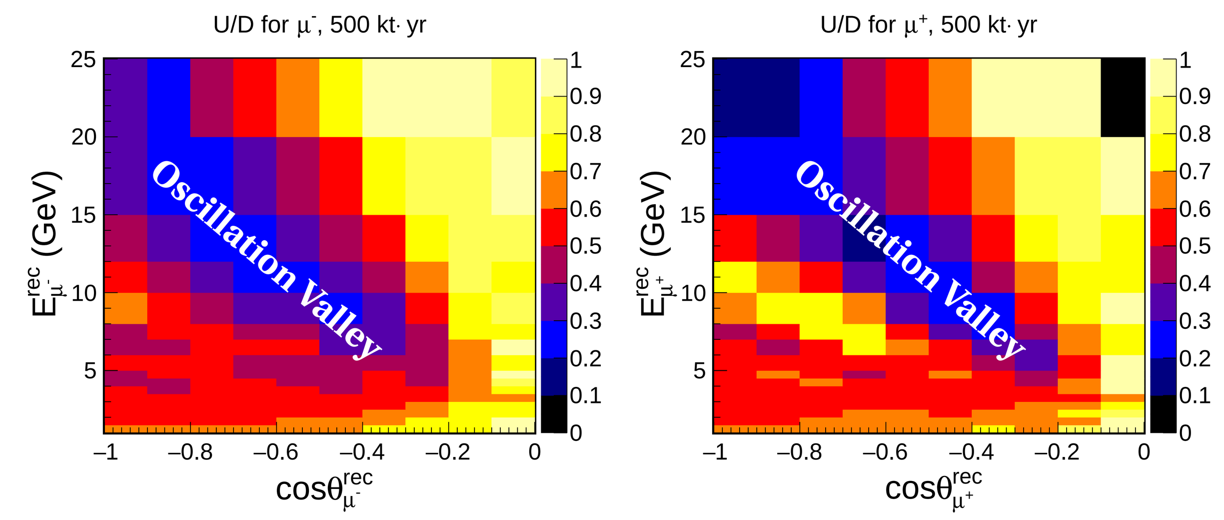


U/D distribution as a function of $L_\mu^{\rm rec}/E_\mu^{\rm rec}$

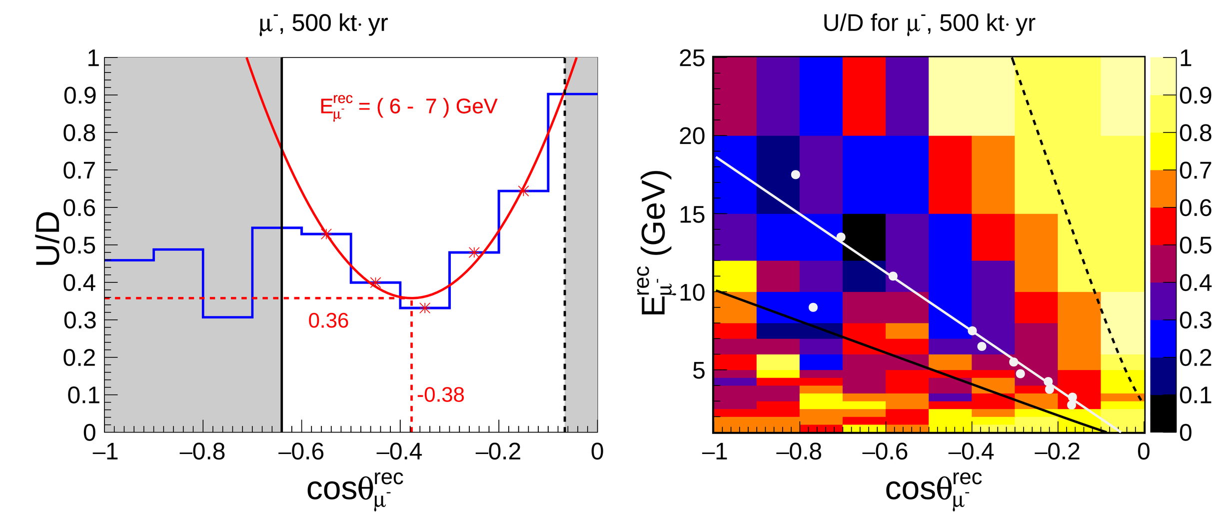


Dip identification algorithm to calculate location of dip

Reconstructed Oscillation Valley

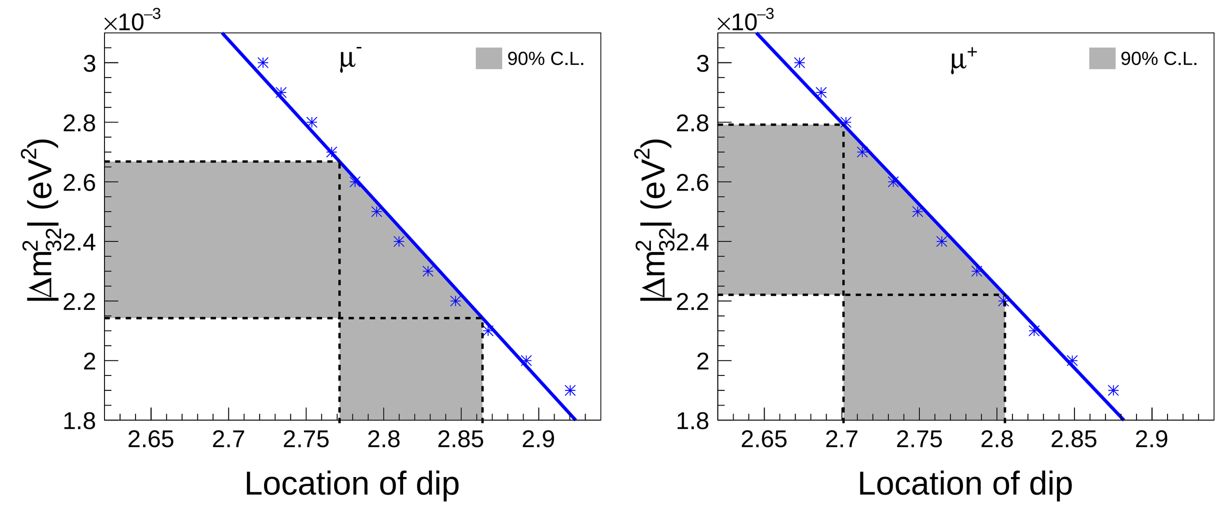


2D distribution of U/D

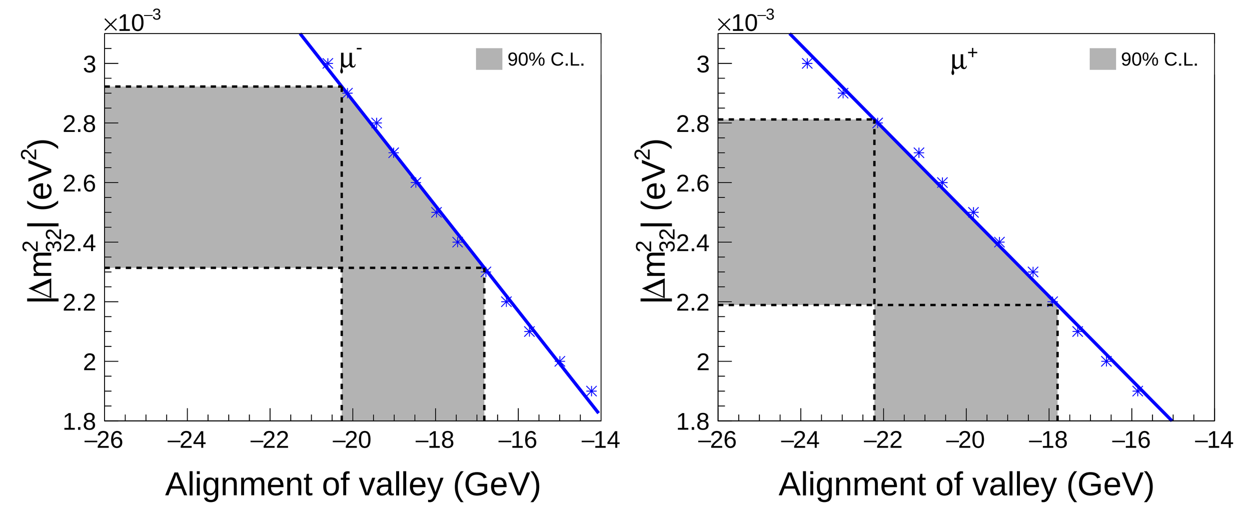


Identification of oscillation valley to calculate its alignment

$|\Delta m^2_{32}|$ from Oscillation Dip & Valley



90% C.L. for $|\Delta m^2_{32}|$ using location of dip



90% C.L. for $|\Delta m^2_{32}|$ using alignment of valley

The 90% C.L. (gray band) is obtained from 100 simulated data sets of 500 kt·yr whereas calibration (blue line) is done using 1000 yr MC.

Summary and Conclusion

- The U/D ratio of muon events can reconstuct oscillation dip at ICAL as a function of $L_\mu^{\rm rec}/E_\mu^{\rm rec}$ for μ^- and μ^+ separately.
- An "oscillation valley" can be reconstructed in ($E_\mu^{\rm rec}$, $\cos\theta_\mu^{\rm rec}$) plane for μ^- and μ^+ separately.
- Oscillation valley reconstruction needs access to higher energy, and enough bins in $E_\mu^{\rm rec}$ and $\cos\theta_\mu^{\rm rec}$, both possible with ICAL.
- This approach can be adopted by other atmospheric neutrino experiments to establish neutrino oscillations over a wide range of energy and direction.

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] Y. Ashie et al. "Evidence for an Oscillatory Signature in Atmospheric Neutrino Oscillations". In: *Physical Review Letters* 93.10 (2004).

[3] Anil Kumar et al. "From oscillation dip to oscillation valley in atmospheric neutrino experiments". In: *IP/BBSR/2020-3* (2020).

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