Muons at the ICAL at INO

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Pinning down neutrino oscillation parameters in the 2-3 sector with a magnetised atmospheric neutrino detector: a new study,
Lakshmi S. Mohan, D. Indumathi, arXiv:1605.04185 [hep-ph] and Thesis
Oscillation Studies with Upward-Going Muons Using INO-ICAL,
R. Kanishka, Vipin Bhatnagar, D. Indumathi, Proc.Phys. 174 (2016) 299-304 and Thesis
Atmospheric Muon Charge Ratio using the ICAL detector,
Meghna K.K., D. Indumathi, Nita Sinha, to be published and Thesis.

Outline of Talk

- Brief description of neutrino oscillations
- Muon resolutions at ICAL; in brief
- Physics potential 1: measurement of neutrino oscillation parameters with neutrinos at ICAL
- Physics potential 2: measurement of neutrino oscillation parameters with rock muons at ICAL
- Physics potential 3: measurement of cosmic ray background with muons at ICAL

Parameters of 3ν framework

- The flavour eigenstates ν_α, $\alpha = e, \mu, \tau$, are expressed as superpositions of the mass eigenstates ν_i:

  $$\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i \ .$$

  where at least two of the masses m_1, m_2 and m_3 are non-zero.

- $U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$ is the mixing matrix.

- Matter effects involve the participation of all three (active) flavours; the main effect is to enhance the across-generation mixing:

  (1) $$(\sin\ 2\theta_{13})_m = \frac{(\sin\ 2\theta_{13})}{\sqrt{[\cos 2\theta_{13} - (A/\Delta m^2_{32})]^2 + (\sin 2\theta_{13})^2}}$$

  where $A = 7.6 \times 10^{-5}\ \rho\ E\ eV^2 \quad \Delta m^2_{32} = m^2_3 - m^2_2$,

  ρ = earth density (gms/cc); E = neutrino energy in GeV.

A Schematic of Neutrino Properties

Oscillation studies only determine the mass-squared differences: $\Delta m_{ij}^2 = m_i^2 - m_j^2$ and the mixing angles θ_{ij}. Currently, $\theta_{12} \sim 34^\circ$ (solar); $\theta_{23} \sim 45^\circ$ (atmospheric); $\theta_{13} \sim 9^\circ$ (reactor); Phase(s) unknown.

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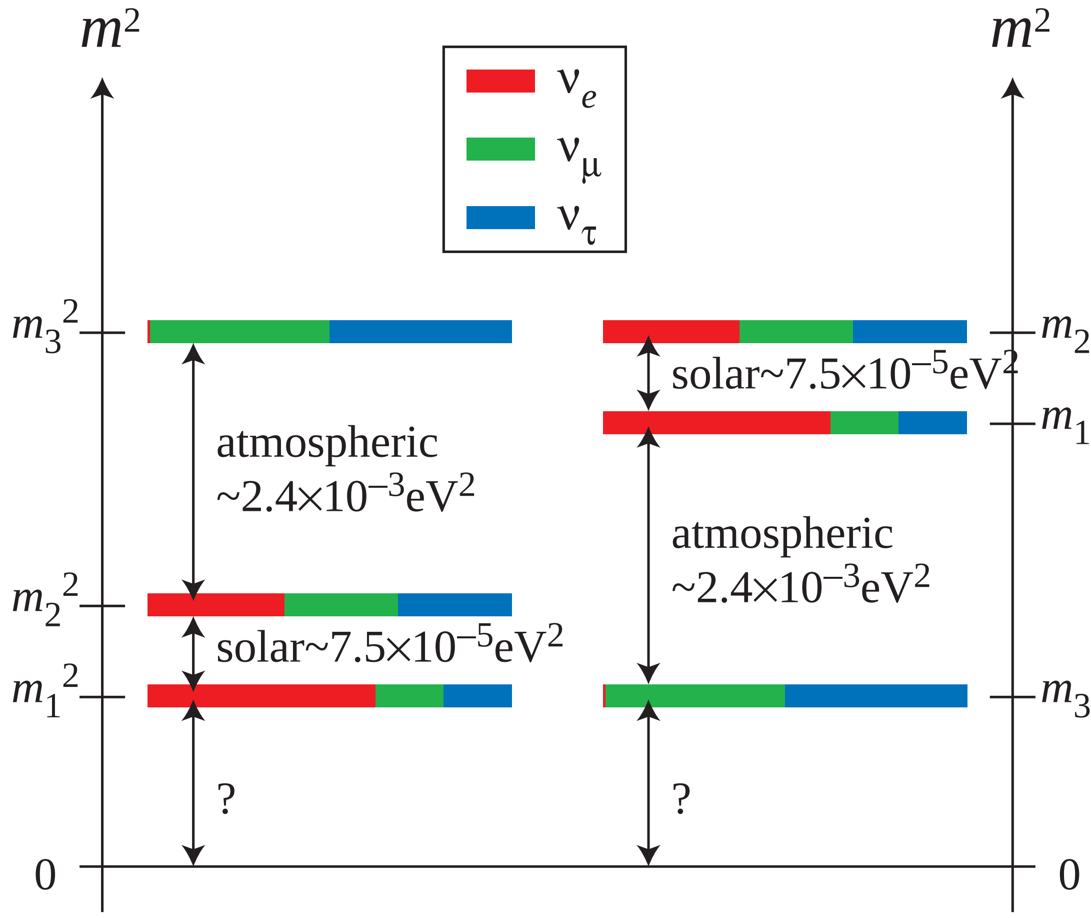

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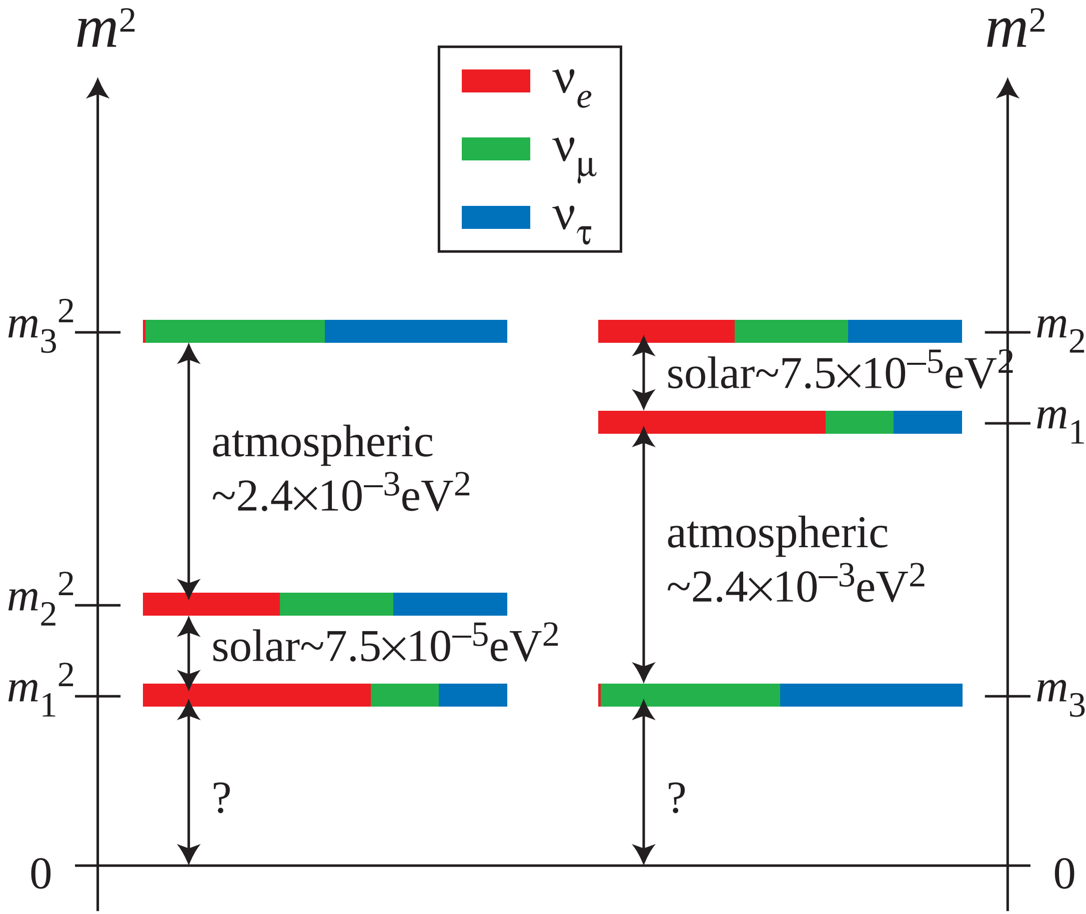
$\Delta m_{21}^2 \sim 7.6 \times 10^{-5}$ eV^2 ;

$|\Delta m_{32}^2| \sim 2.4 \times 10^{-3}$ eV^2 ;

$\sum_i m_i < 0.7$–2 eV.



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- $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV

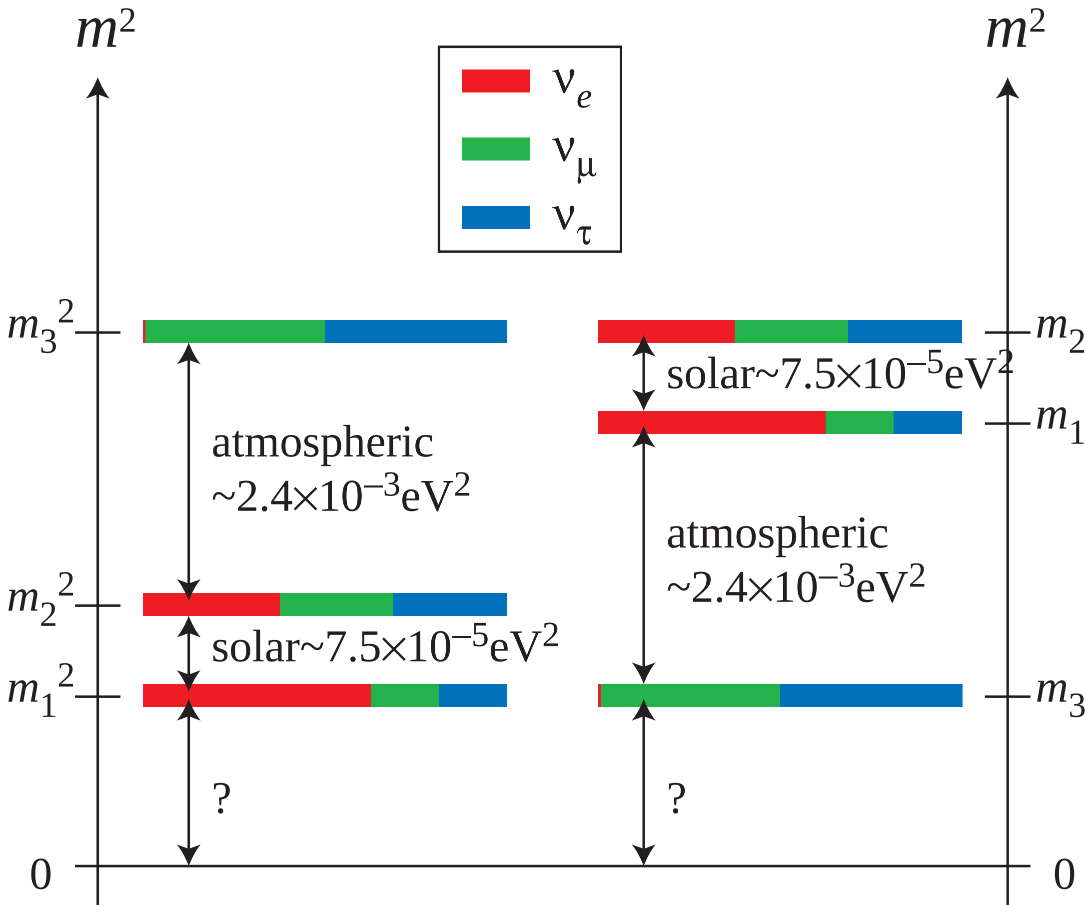
(Degenerate hierarchy)

- $m_1 < m_2 \ll m_3$

(Normal hierarchy)

- $m_3 \ll m_1 < m_2$

Inverted hierarchy



(APS multi-divisional neutrino study, physics/0411216)

Probabilities in matter

- Hierarchy discriminator: Earth matter, difference in interactions between ν and $\overline{\nu}$.

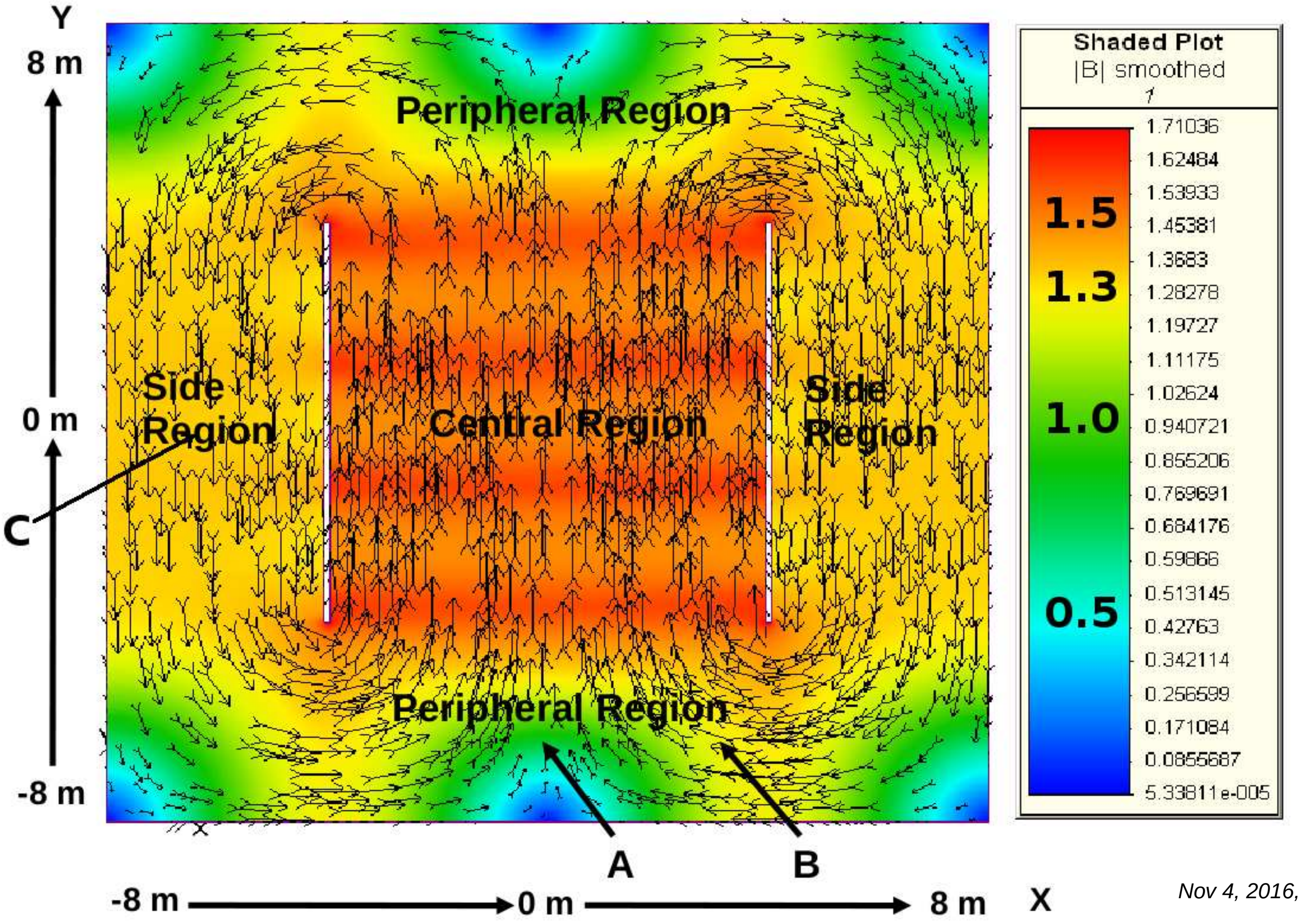
$$
\begin{aligned}
P^m_{\mu\mu} &\approx P^{(2)}_{\mu\mu} - \sin^2\theta_{13} \times \\
& \left[\frac{A}{\Delta m^2 - A} T_1 + \left(\frac{\Delta m^2}{\Delta m^2 - A} \right)^2 \left(T_2 \sin^2[(\Delta m^2 - A)x] + T_3 \right) \right] \\
\overline{P}^m_{\mu\mu} &\approx P^{(2)}_{\mu\mu} - \sin^2\theta_{13} \times \\
& \left[\frac{-A}{\Delta m^2 + A} T_1 + \left(\frac{\Delta m^2}{\Delta m^2 + A} \right)^2 \left(T_2 \sin^2[(\Delta m^2 + A)x] + T_3 \right) \right]
\end{aligned}
$$

- $A \propto \rho E$. **Changes sign between neutrinos and anti-neutrinos.**
- To distinguish the effect of matter, therefore, need to separate ν_μ and $\overline{\nu}_\mu$ events: need charge identification:

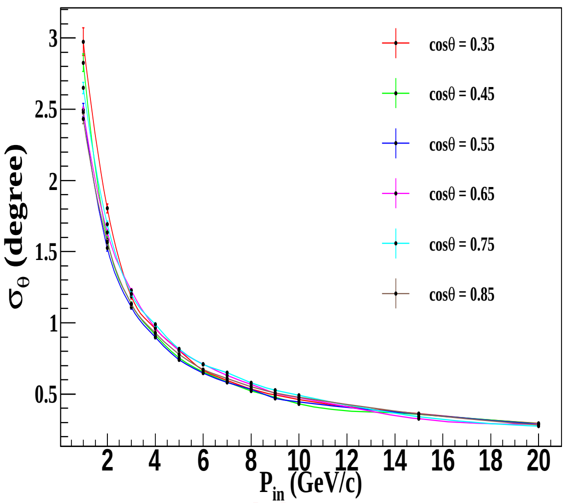
$$\nu_\mu N \longrightarrow \mu^- X \; ; \; \overline{\nu}_\mu N \longrightarrow \mu^+ X \; .$$

The iron calorimeter (ICAL) detector

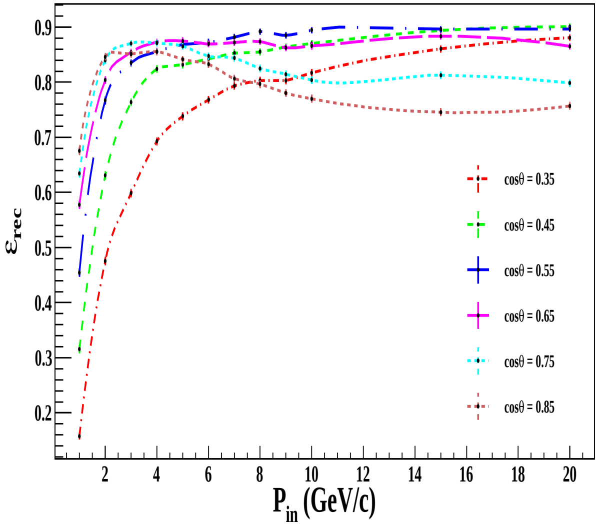
- 50 kTon magnetised iron detector; RPCs as active detector elements.
- Good tracking and energy resolution;
- $\sim ns$ time resolution for up/down discrimination; good directionality;
- Good charge resolution; magnetic field ~ 1.5 Tesla.



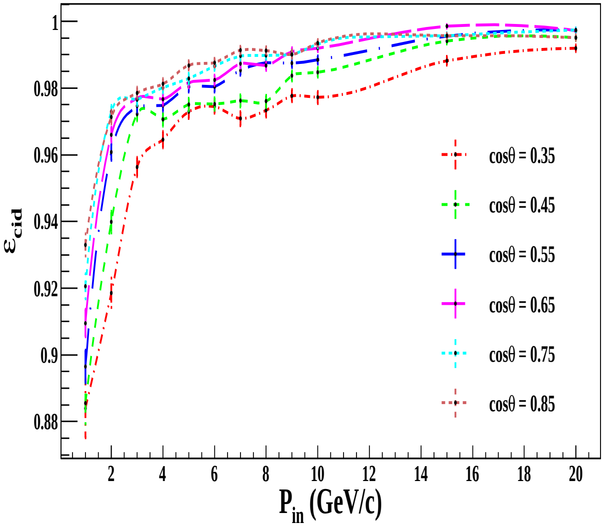
Simulations response of ICAL to muons



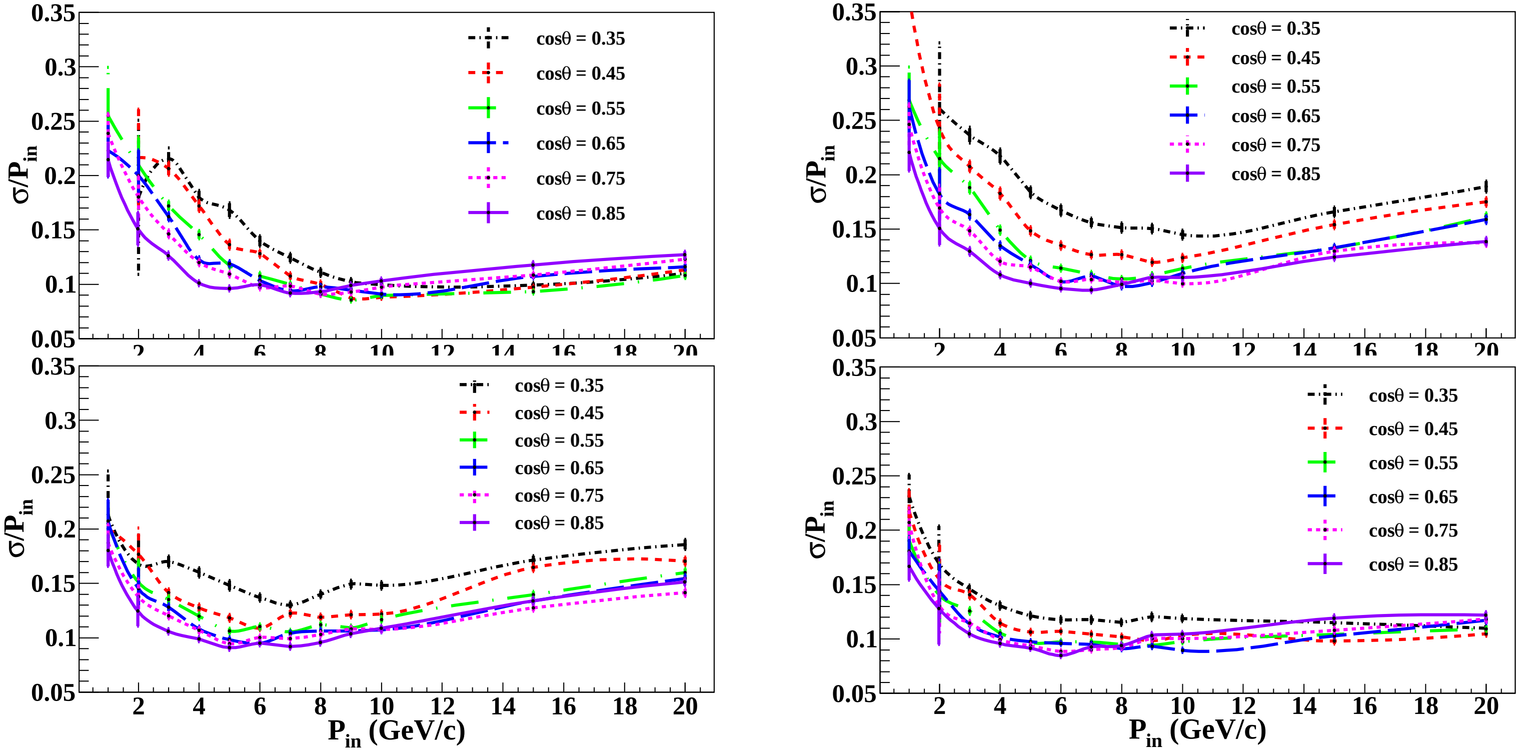
Zenith Angle



Reco eff



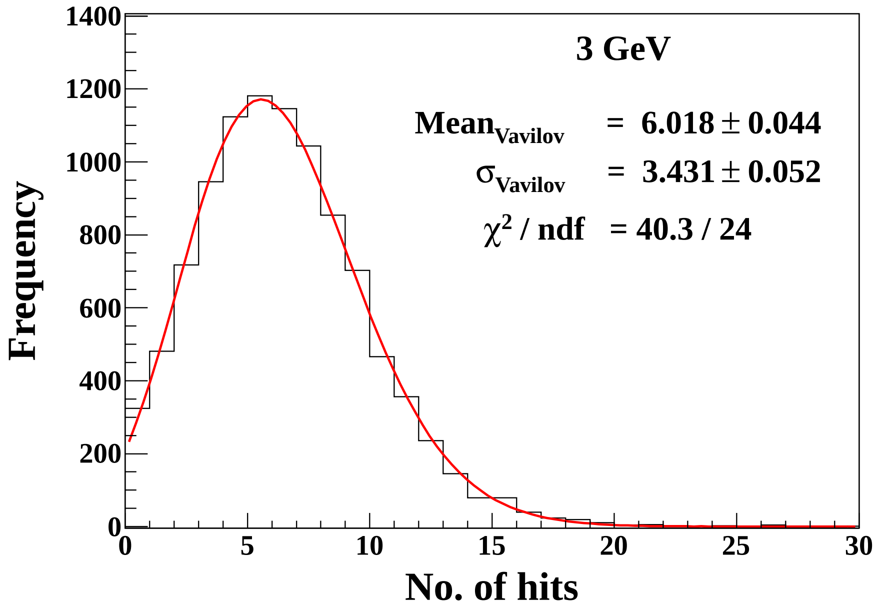
CID eff

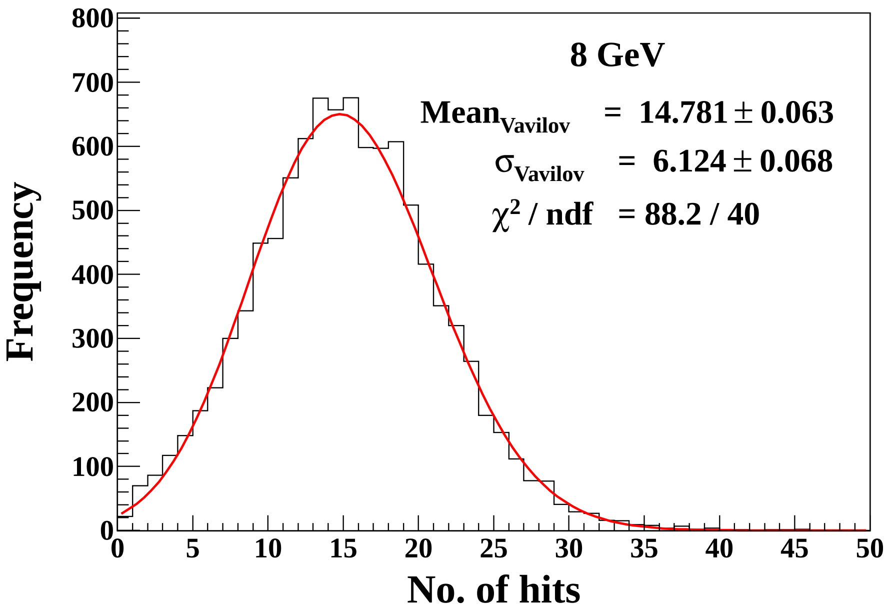


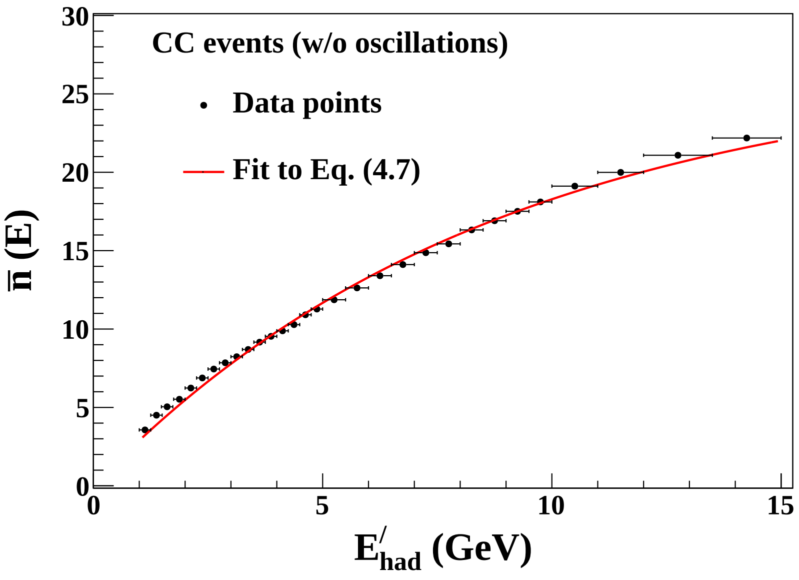
Energy Resolution as a function of energy in different (θ, ϕ) bins.

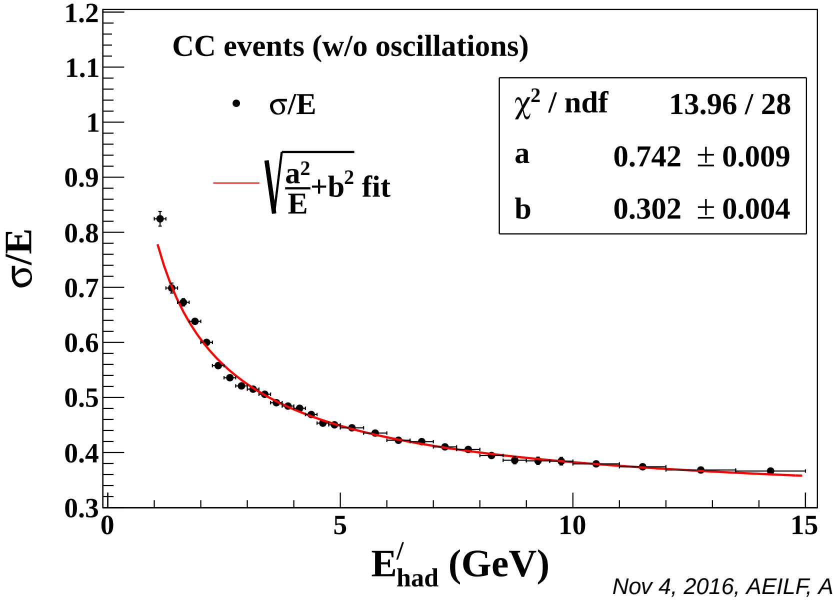
Simulations Response of ICAL to hadrons

Inputs: Single pions, Honda-3D Atmospheric Neutrino Fluxes; NUANCE Neutrino Generator; GEANT4 ICAL@INO simulation.









Precision “measurements” at ICAL

- Generate CC μ events (1000 years) with NUANCE 3.504 neutrino generator: $\nu_\mu N \to \mu X$ using both Φ_μ and Φ_e fluxes:

  $$\text{Muon Events} \propto \left[P_{\mu\mu}\Phi_\mu + P_{e\mu}\Phi_e\right]\ \sigma(\nu_\mu N \to \mu X)\ .$$

- “Data”: Oscillate events using central values of the oscillation parameters; include detector response (for muons and hadrons); scale to get 10 years “data”; bin them in variables such as muon momentum and direction $(E_\mu^{obs}, \cos\theta_\mu^{obs})$, hadron energy (E'_{had}), etc.

- “Theory”: Repeat, with different sets of oscillation parameters, to generate “theories”; test against “data” by minimising χ^2:

$$\chi^2_{11} = \min_{\xi_l^{\pm}, \xi_6} \sum_{ij(k)} 2\left[\left(T^{+}_{ij(k)} - D^{+}_{ij(k)}\right) - D^{+}_{ij(k)} \ln\left(\frac{T^{+}_{ij(k)}}{D^{+}_{ij(k)}}\right)\right] + \sum_{l^{+}=1}^{5} \xi^2_{l^{+}} +$$

$$2\left[\left(T^{-}_{ij(k)} - D^{-}_{ij(k)}\right) - D^{-}_{ij(k)} \ln\left(\frac{T^{-}_{ij(k)}}{D^{-}_{ij(k)}}\right)\right] + \sum_{l^{-}=1}^{5} \xi^2_{l^{-}} + \xi_6^2\ .$$

The systematics

- A set of systematic uncertainties are included to account for:
  1. $\pi_1 = 20\%$ flux normalisation error,
  2. $\pi_2 = 10\%$ cross section error,
  3. $\pi_3 = 5\%$ tilt error,
  4. $\pi_4 = 5\%$ zenith angle error,
  5. $\pi_5 = 5\%$ overall systematics.
  6. $\pi_6 = 2.5\%$ μ^-/μ^+ flux ratio.

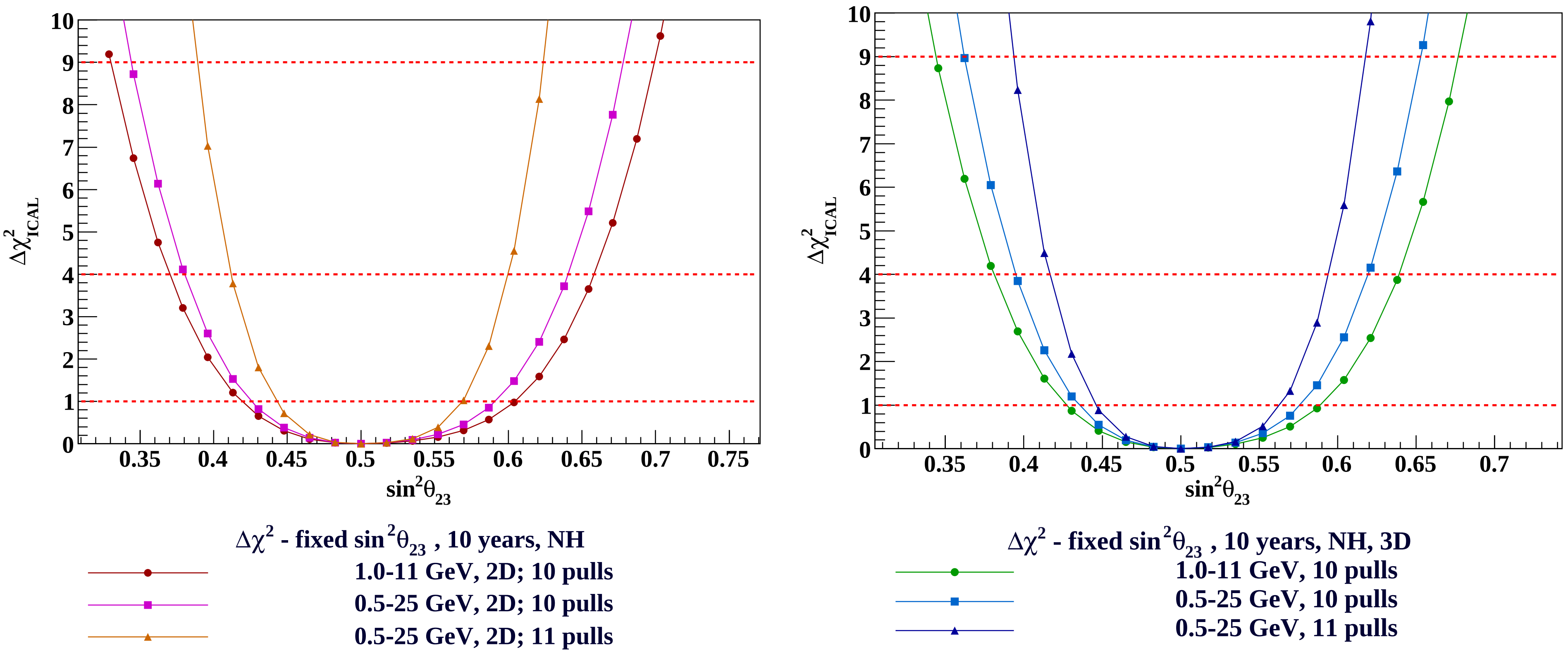
$$T^+_{ij(k)} = T^{0+}_{ij(k)} \left(1 + \sum_{l^+=1}^{5} \pi^{l^+}_{ij(k)} \xi_{l^+} + \pi_6 \xi_6 \right) ,$$

$$T^-_{ij(k)} = T^{0-}_{ij(k)} \left(1 + \sum_{l^-=1}^{5} \pi^{l^-}_{ij(k)} \xi_{l^-} - \pi_6 \xi_6 \right) .$$

- An additional 8% prior on $\sin^2 2\theta_{13}$ since it is well-known
- 1–2 sector ignored; δ_{CP} set to zero since irrelevant; marginalise over 3σ ranges of relevant parameters: $\sin^2 2\theta_{13}$, δm^2_{31} (actually Δm^2_{eff}) and its sign (the mass ordering), and θ_{23}.

Precision "measurements": $\sin^2\theta_{23}$

Left: 2D–Observables: $(E_\mu^{obs}, \cos\theta_\mu^{obs})$; Right: 3D–also (E'_{had})



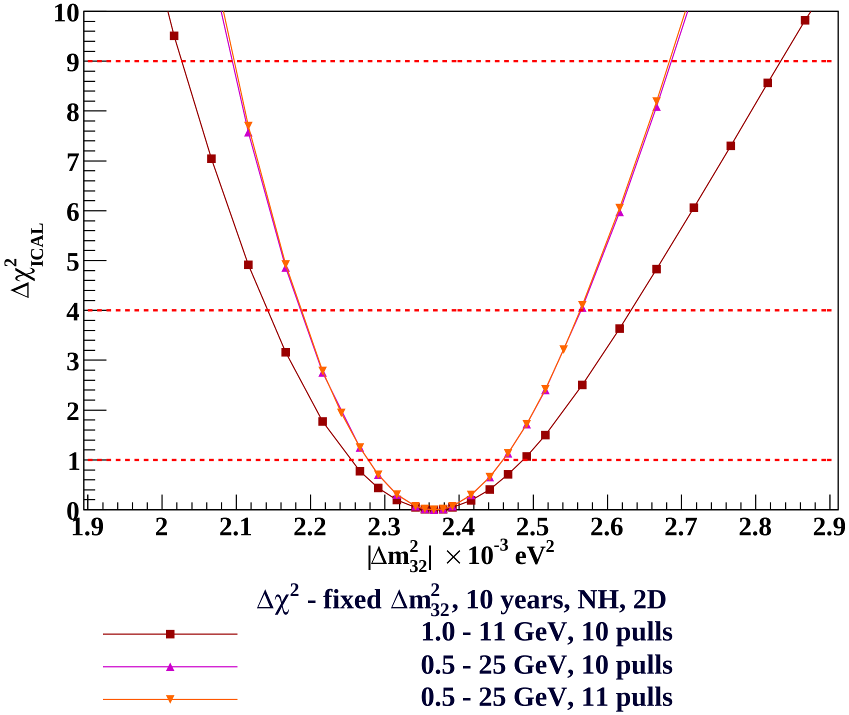
Earlier best results from M. M. Devi *et al.*, JHEP **10** (2014) 189.

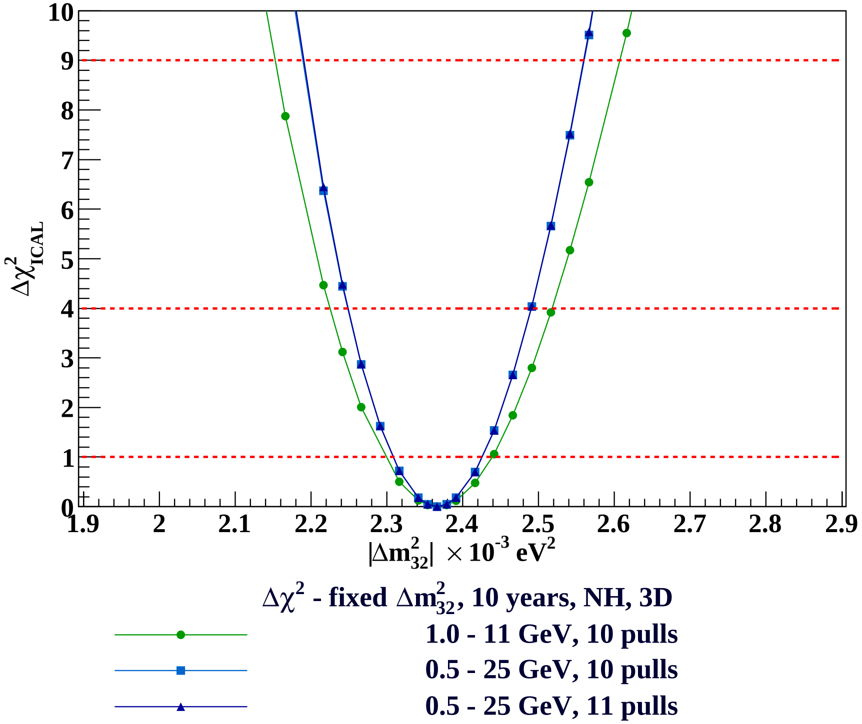
Earlier best 2D result: bins in ($\cos\theta_\mu^{obs}$ and E_μ^{obs} from 1–11 GeV);

Earlier best 3D result: bins in ($\cos\theta_\mu^{obs}$ and E_μ^{obs} from 1–11 GeV) with E'_{had}

bins as well.

Precision “measurements”: Δm^2_{31}





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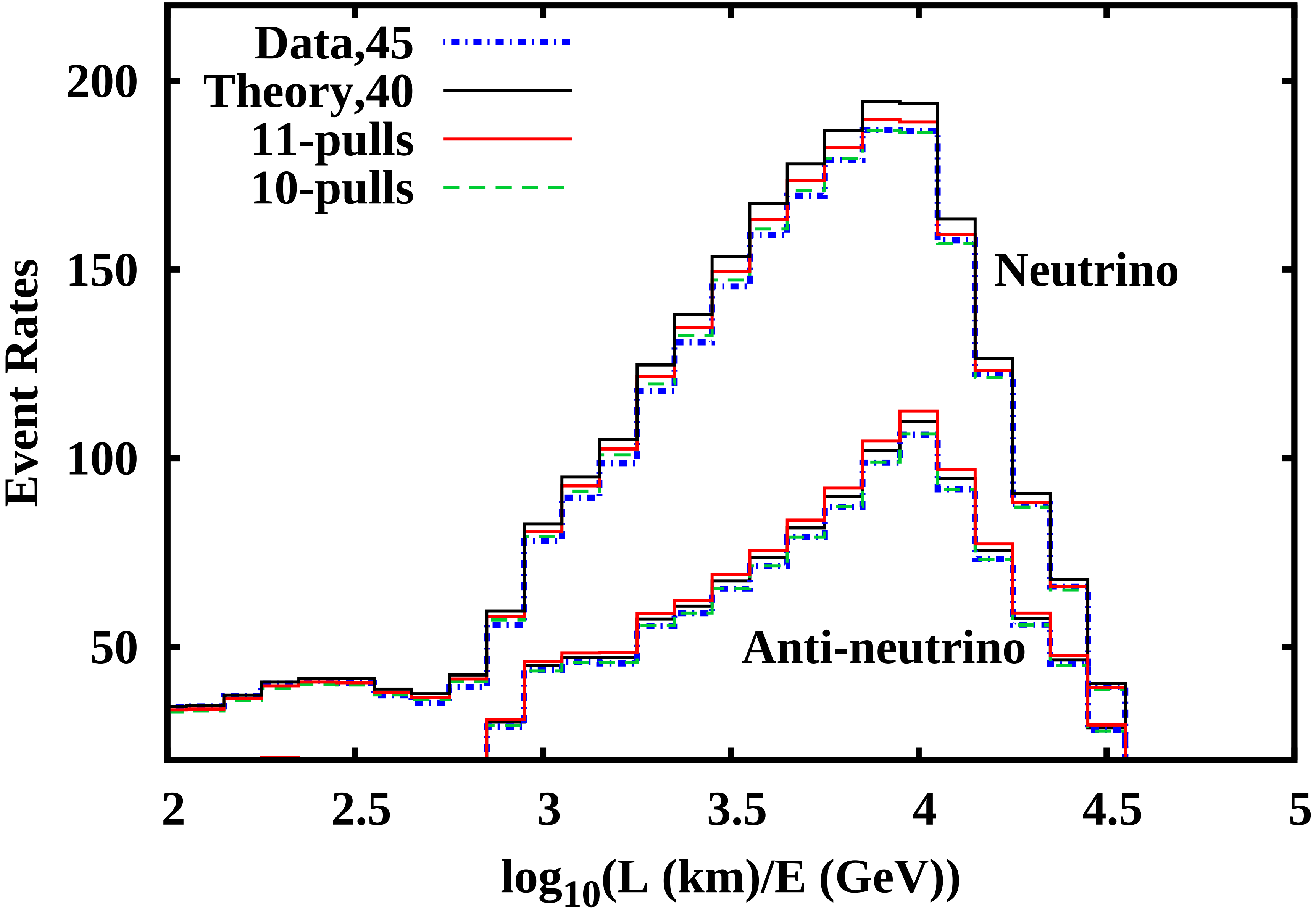
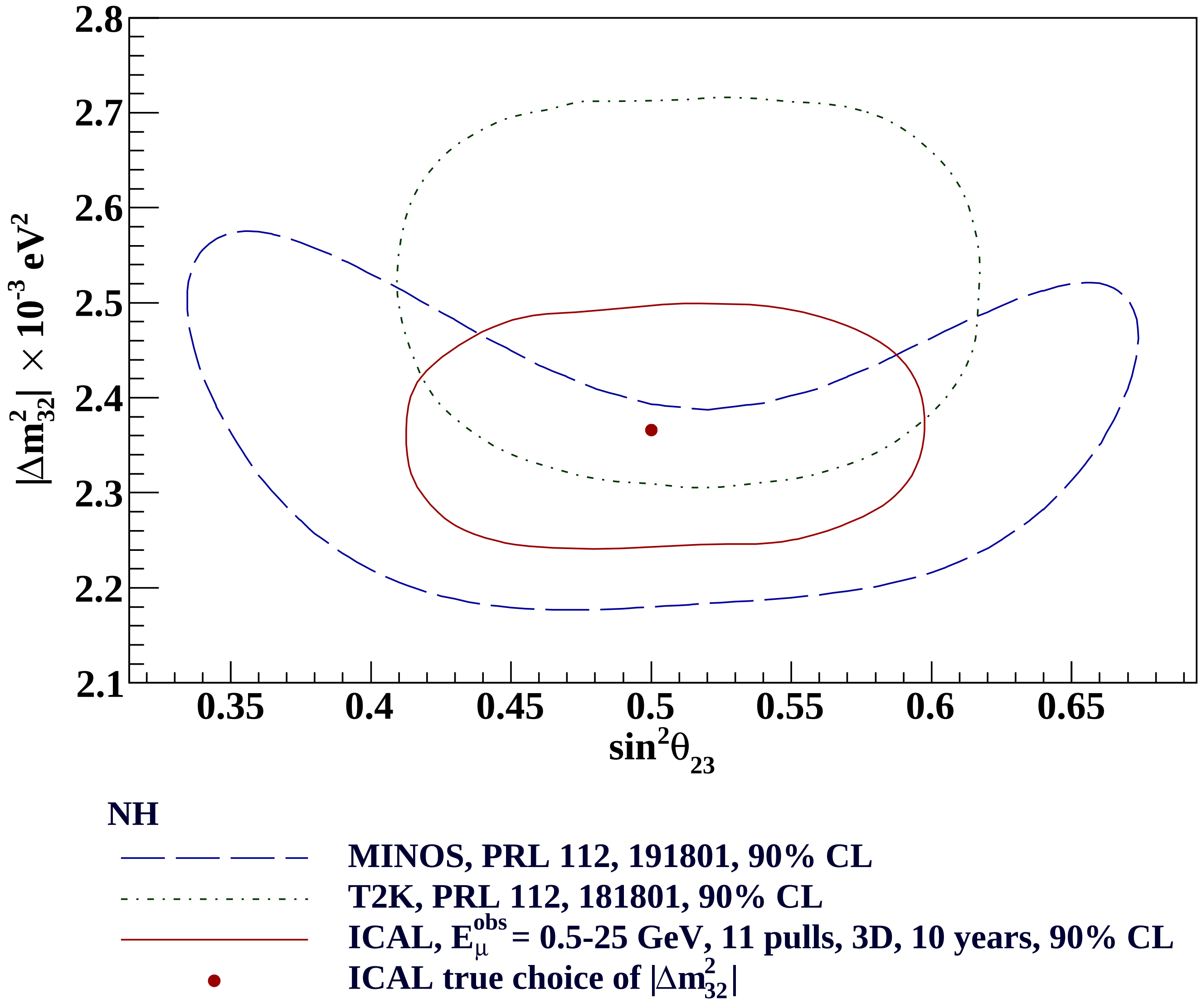
Earlier best 3D result: bins in ($\cos\theta_\mu^{obs}$ and E_μ^{obs} from 1–11 GeV) with E'_{had} bins as well.

Note: quality of new 2D results: Δm^2_{31} sensitive to inclusion of high energy spectrum.

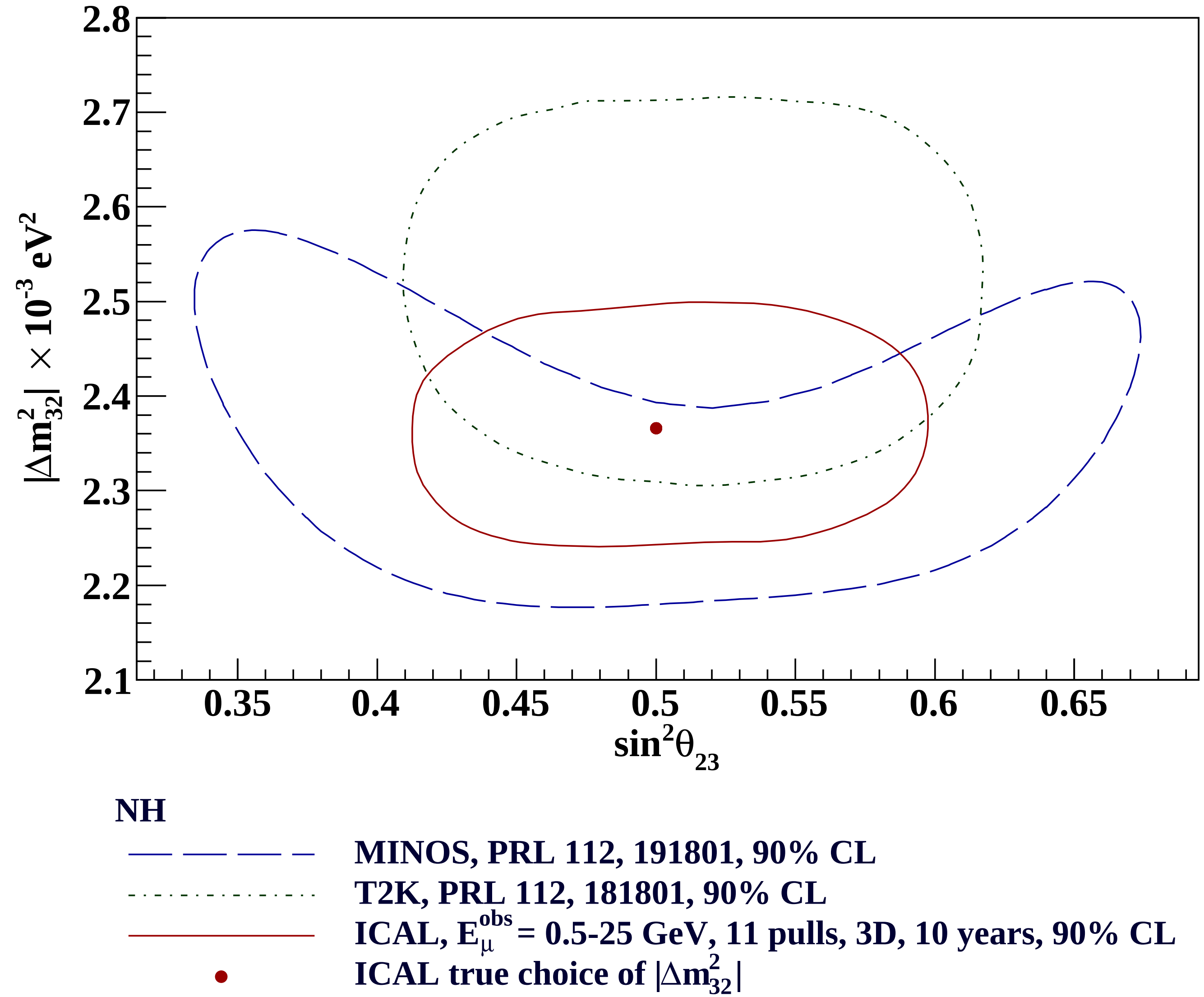
The effect of the 11th pull



The $(\Delta m^2_{31}, \sin^2\theta_{23})$ parameter space

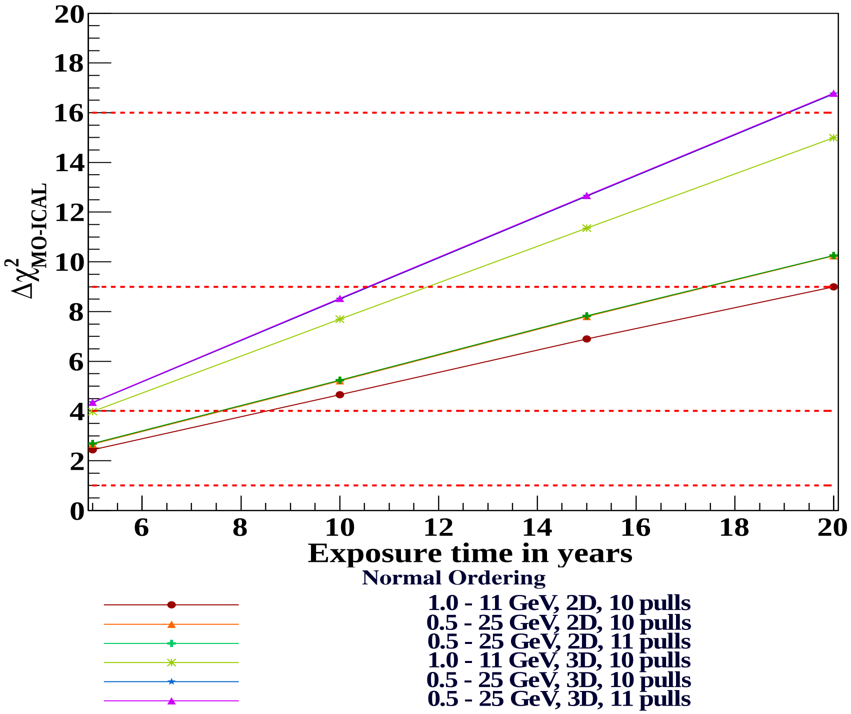


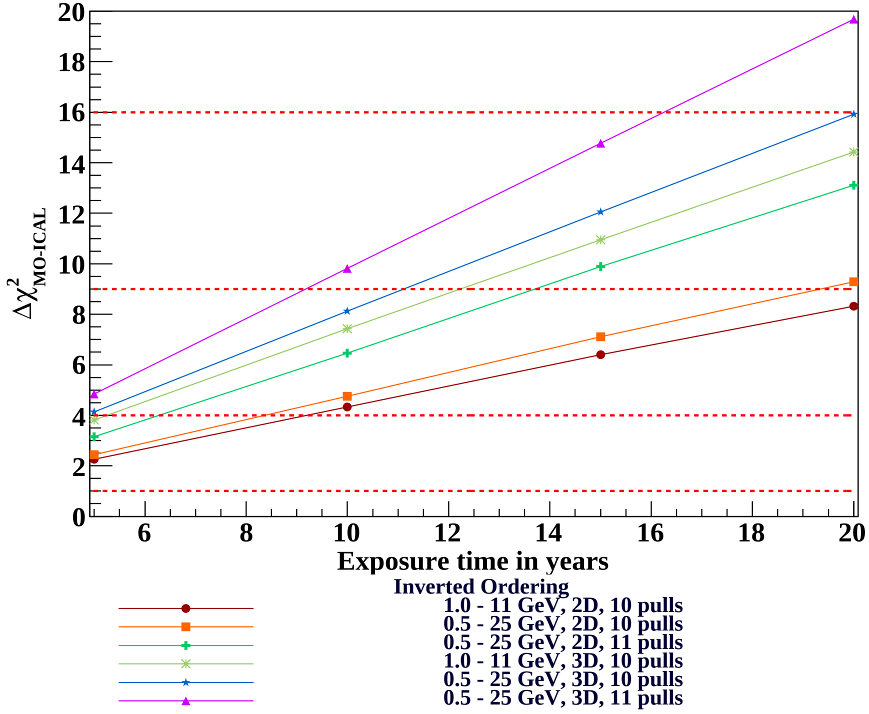
The $(\Delta m^2_{31}, \sin^2\theta_{23})$ parameter space



To our sorrow, it must be remembered, though, that these experiments are already taking data while ICAL is yet to be constructed!

The hierarchy/mass ordering

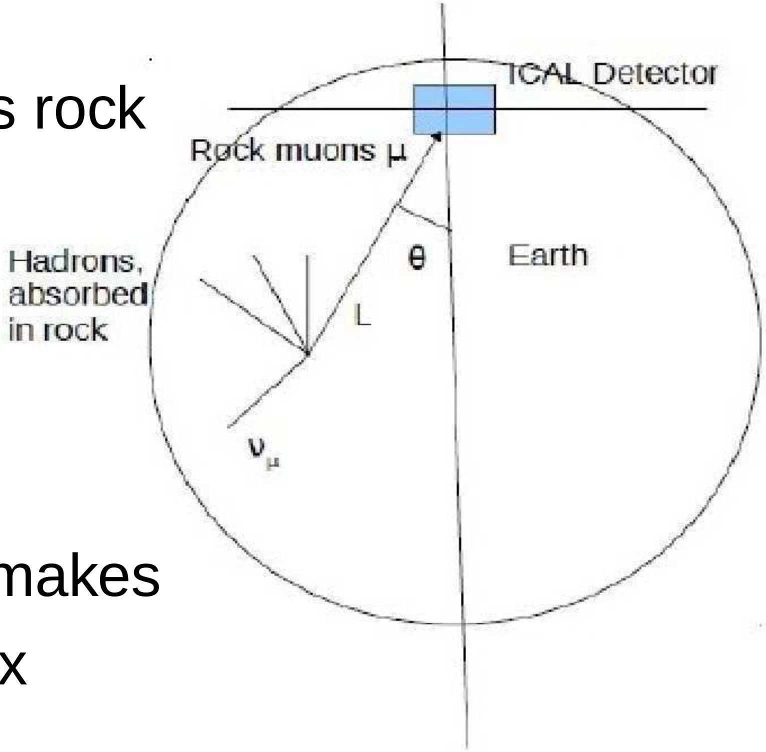




Note that 2σ result can be reached in 5 years' exposure at ICAL.

Rock Muons at ICAL

- Upward-going muons, also known as rock muons provide an independent measurement of the oscillation parameters.
- The signature is clean, although the energy loss of the muon in the rock makes it less sensitive than contained vertex muons.
- Also, the sample contains higher proportion of high energy muons than contained vertex events.



Poster: Kanishka Rawat, in this meeting.

ltimate background: Cosmic Ray Muons

- Primary cosmic rays (protons, neutrons and nuclei) interact with atmospheric nuclei and produce hadron showers containing mainly πs and Ks.

- Out of the secondary particles πs are the most abundant due to its lower mass. The secondaries decay:

$$
\begin{aligned}
\pi^+ &\to \mu^+\nu_\mu \ , \\
\pi^- &\to \mu^-\overline{\nu}_\mu \ , \\
K^+ &\to \mu^+\nu_\mu \ , \\
K^- &\to \mu^-\overline{\nu}_\mu \ .
\end{aligned}
$$

- These muons have energies MeVs–TeVs; mean energy at sea level ~ 4 GeV. The low energy muons decay into electrons and neutrinos: atmospheric neutrinos.

- The vertical muon intensity at the sea level is about $1 cm^{-2} min^{-1} sr^{-1}$ for horizontal detectors.

The cosmic ray muon charge ratio

- Since the primary cosmic rays mainly contain positively charged particles (protons), there are more positive πs and Ks.
- The π^+/π^- charge ratio ~ 1.27.
- The K^+/K^- charge ratio is also expected to be larger than 1.
- However, there is a crucial difference between the two in their interactions with air nuclei:

$$p + A \to K^+ + \Lambda + X \ ,$$

$$n + A \to K^0 + \Lambda + X \ ,$$

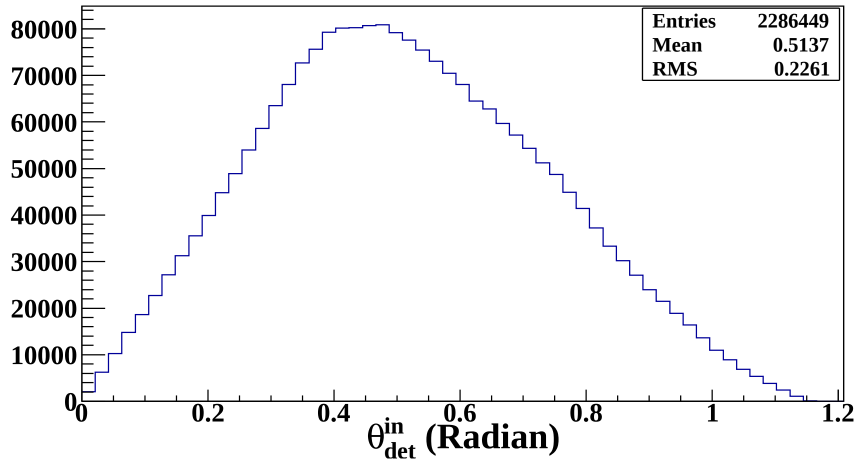
i.e., $(uud) \to (u\bar{s}) + (uds)$,
but $(udd) \to (d\bar{s}) + (uds)$.

- This leads to a rise in the charge ratio at high energies where K decay is significant.

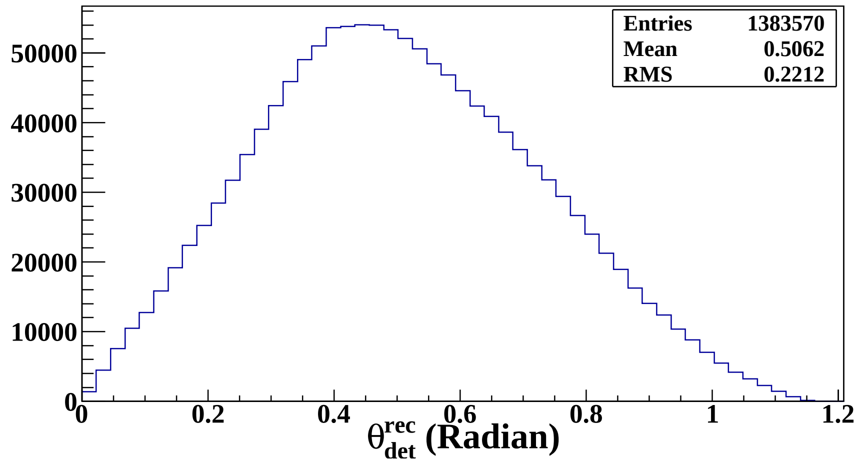
Simulations of Cosmic muons at Theni

- Generated cosmic ray muons for 1 year at the surface above ICAL, using actual geography of Theni.
- Propagated muons to detector underground; muons lose energy in rock.
- Reconstructed events in GEANT4-simulated ICAL, studied events with $E_\mu^{reco;ICAL} < 100$ GeV.
- Used the reconstructed energy and angle (θ, ϕ) information to propagate the muon back to the surface
- Compare with original flux distribution to understand sensitivity to cosmic ray muon charge ratio.

Reconstruction of Zenith Angle

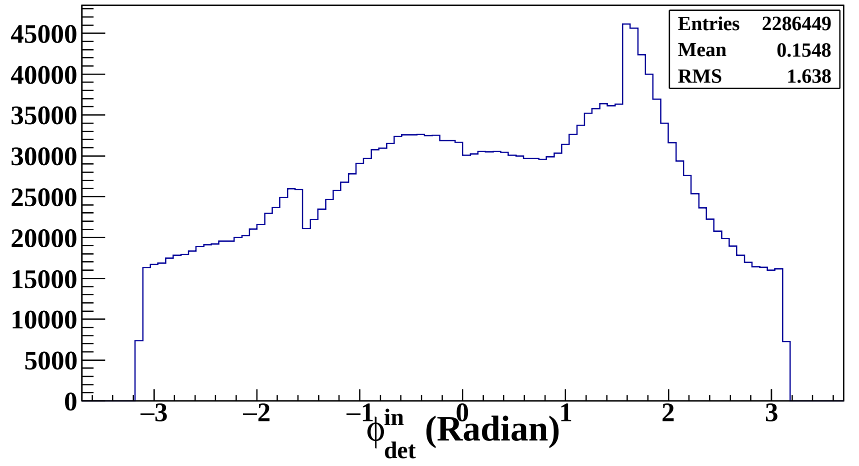


Original

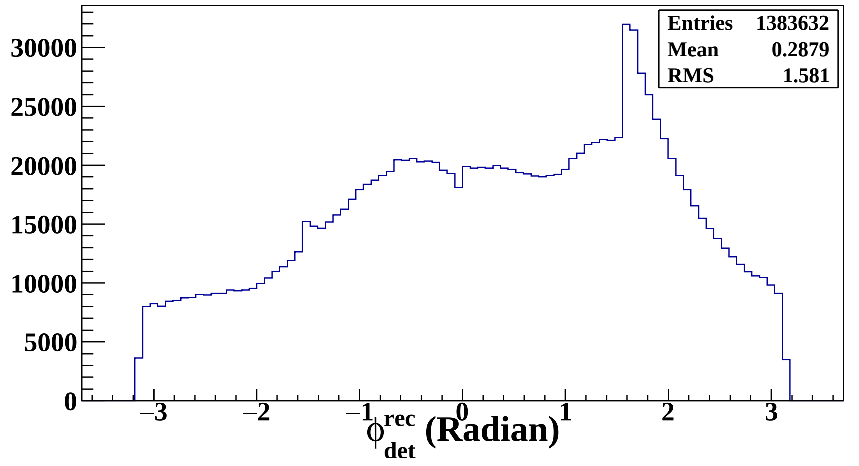


Reconstructed

- The zenith angle (↑) and azimuthal (↓) distribution of muons.

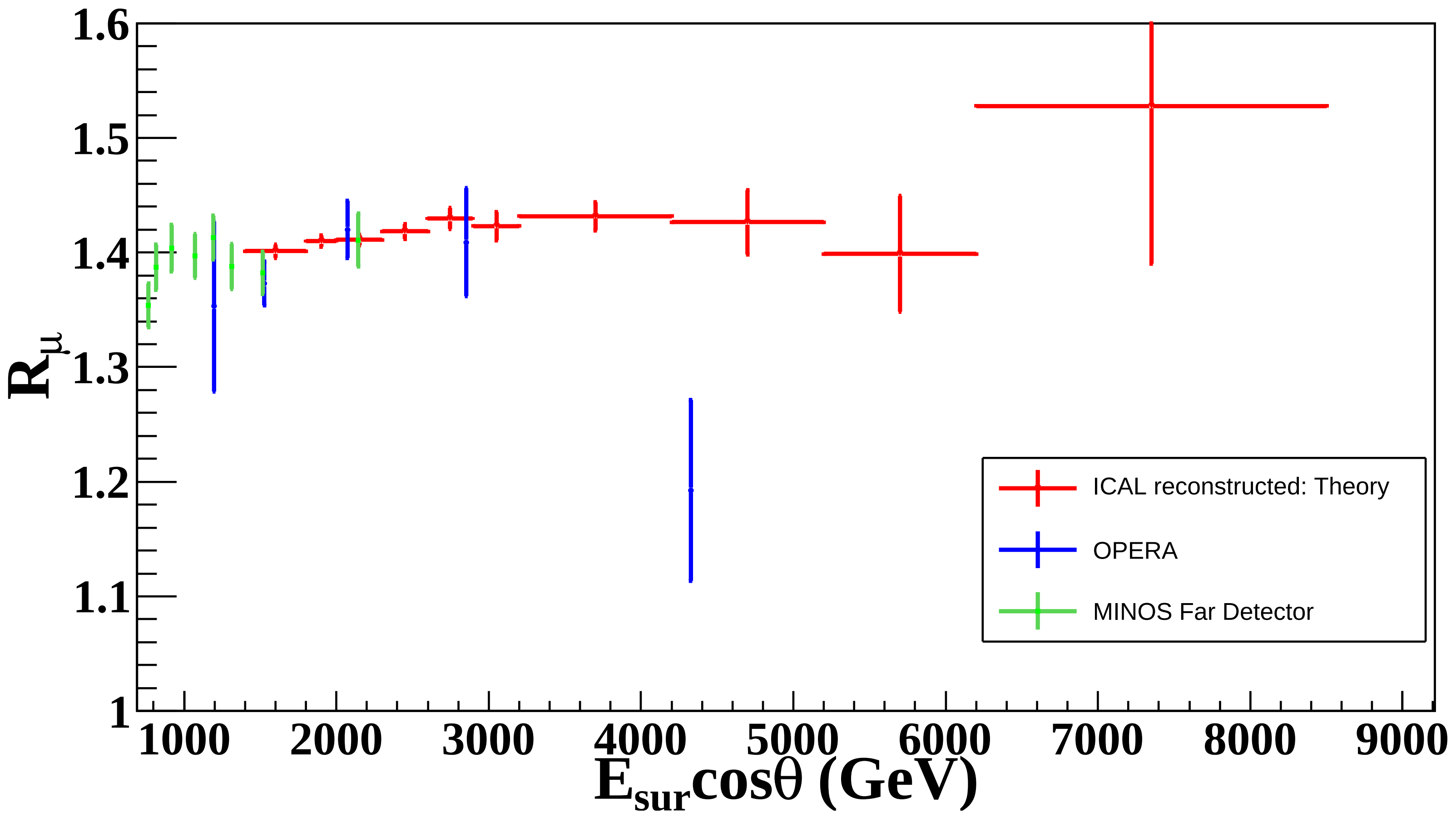


Original



Reconstructed

Results of the simulations



- Charge ratio expected to be measured over 1 year at ICAL as a function of $(E_\mu^{surface}\cos\theta)$ in comparison with other experiments.
- Caveat: energy loss mechanism of muons through the Earth has been modeled here to be charge-independent.

Summary and Conclusions

- ICAL has been designed to be maximally sensitive to the momentum, direction and charge sign of muons.
- The physics potential of such a detector is very strong with respect to standard oscillation physics of atmospheric neutrinos in the 2–3 sector: both with contained-vertex neutrino events as well as so-called rock muon events. This reach depends on two facts:
  - Atmospheric neutrinos cover such a large range of path length (L) and energy (E) that their rates in ICAL are insensitive to the CP phase which is unknown.
  - The 1–3 across-generation mixing angle is already well-measured.
- The charge identification capability will make ICAL competitive with respect to measurement of the neutrino mass ordering.
- This will also help to determine the cosmic ray muon charge ratio which is an important input to understand its kaon component.