Neutrino Physics from ICAL:

Current status

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Outline of talk

- The context: physics of atmospheric neutrinos

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- Reach of INO/ICAL: “Standard physics" with a focus on three-flavour oscillations

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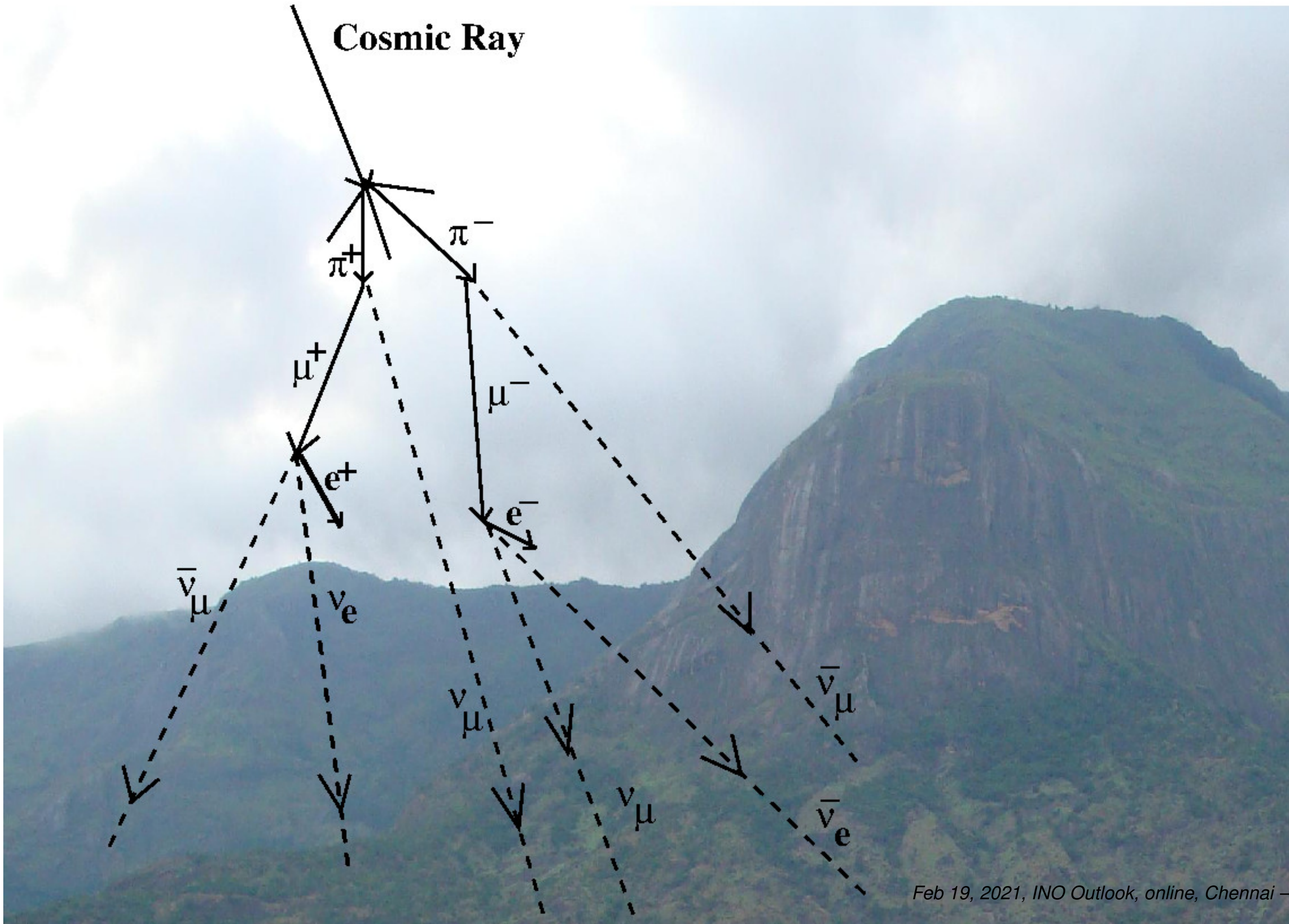
- Reach of INO/ICAL: “Standard physics" with a focus on three-flavour oscillations
- Mini-ICAL: Cosmic muon physics

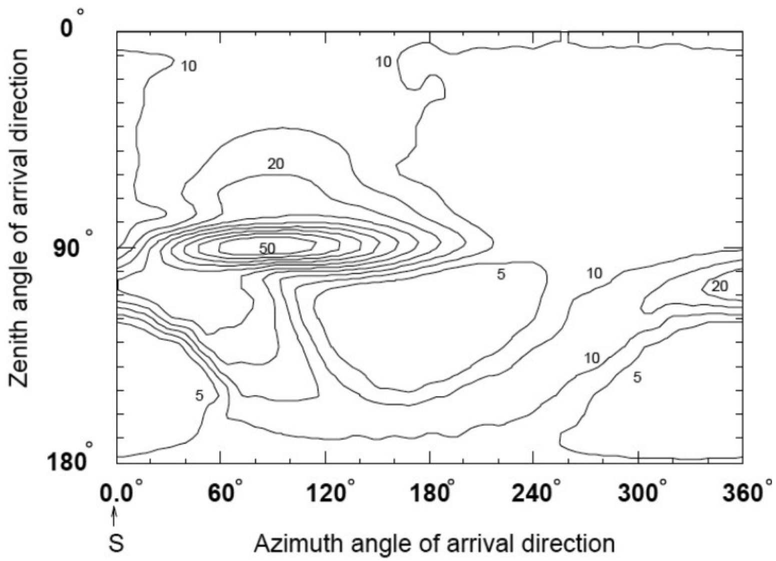
Atmospheric Neutrinos

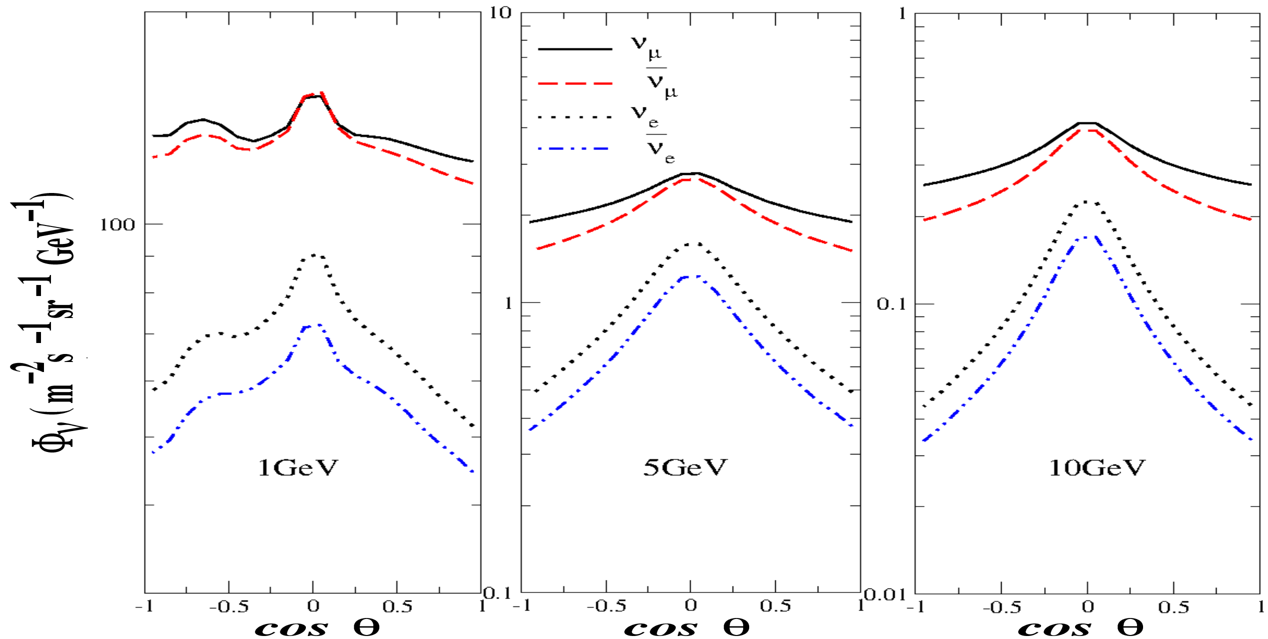
- Cosmic rays reach Earth's atmosphere and interact with C, O nuclei to give pions and kaons. These decay to muons and neutrinos.

$$\pi(K) \to \mu\,\nu_\mu; \qquad \mu \to \nu_\mu\, e\, \nu_e\ .$$



Atmospheric Neutrino Fluxes





Rigidity at SK

$\Phi_{\mu,e}(E_\nu, \cos\theta)$

- Rigidity latitude dependent; actually magnetic latitude; fluxes about 25% smaller at $E < 1$ GeV, and about 10% larger beyond, at Theni
- East-west asymmetry pronounced at low energies.
- Large contribution from up-going neutrinos.

Honda et al., Phys.Rev. D83 (2011) 123001, [arXiv:1102.2688]

Honda et al., Phys.Rev.D 92 (2015) 2, 023004, [arXiv:1502.03916]

Parameters of the 3 ν framework

- The ν_e, ν_μ and ν_τ flavours do not have definite masses:

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

where ν_1, ν_2 and ν_3 have well-defined masses: m_1, m_2 and m_3, some are non-zero. $U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$ is the mixing matrix.

- The Earth matter effect mainly occurs in the θ_{13} parameter:

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

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

$A \to -A$ for anti-neutrinos.

- Separation of neutrino and anti-neutrino events can probe the matter effect and hence the mass ordering.

A Schematic of Neutrino Properties

Neutrino masses are not well-known. Oscillation studies only determine the mass-squared differences: $\Delta m^2_{ij} = m^2_i - m^2_j$ and mixing angles θ_{ij}.

$\Delta m^2_{21} \sim 0.76 \times 10^{-4}$ eV^2 ;

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

$\sum_i m_i < 0.7$–2 eV.

$\theta_{12} \sim 34°$;

$\theta_{23} \sim 45°$;

$\theta_{13} \sim 8.5°$.

Phase(s) unknown.

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

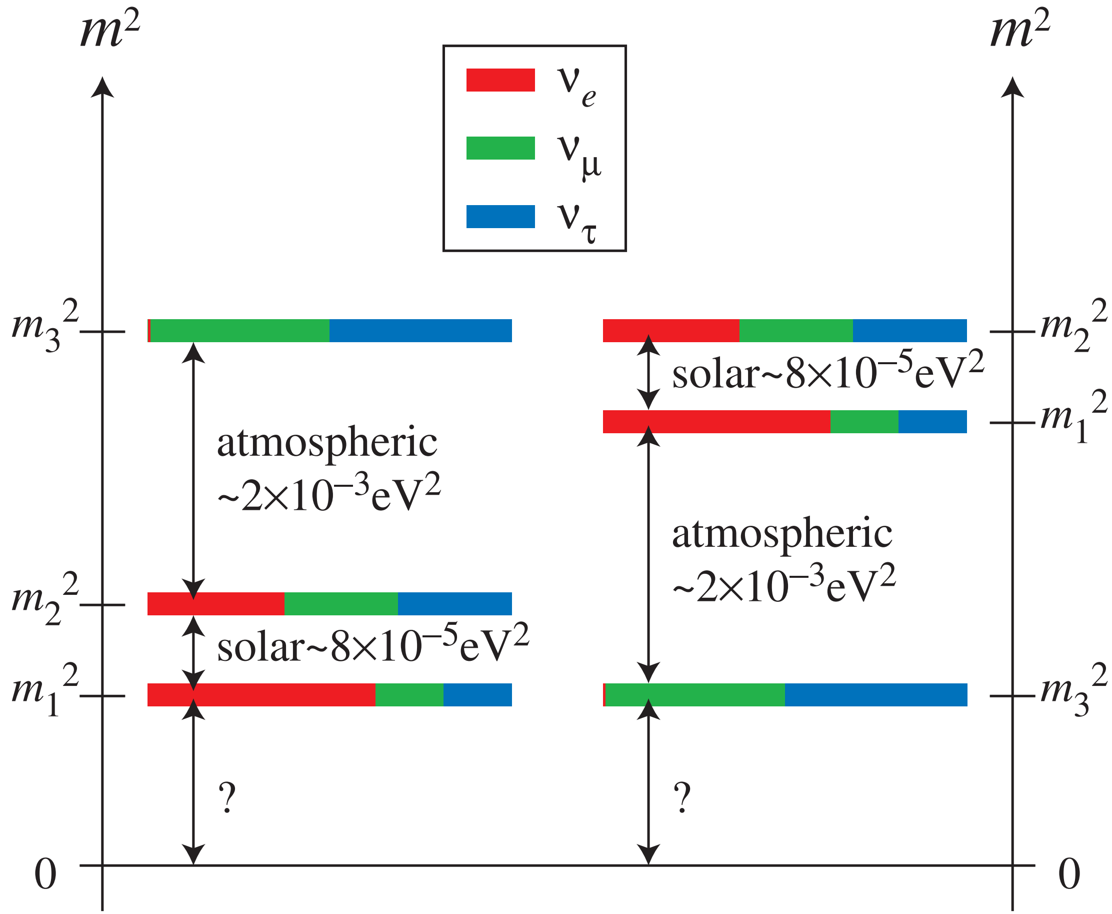
(Degenerate hierarchy)

- $m_1 < m_2 \ll m_3$

(Normal hierarchy)

- $m_3 \ll m_1 < m_2$

Inverted hierarchy



(Nu-Fit, JHEP 12 (2012) 123 [arXiv:1209.3023])

Events from atmospheric neutrinos

- $\nu_l N \to l^- X$ (CC), $\nu_l N \to \nu_l X$ (NC).

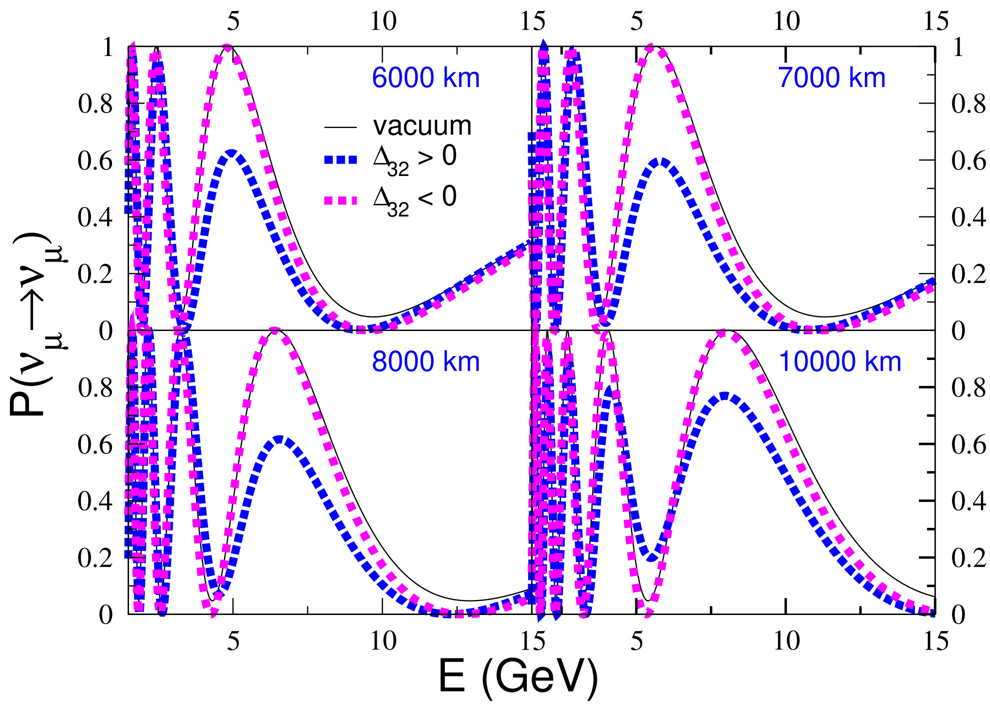
$$N_\mu^{CC} = \mathcal{N}\left[P_{\mu\mu}\Phi_\mu + P_{e\mu}\Phi_e\right] \times \sigma_\mu^{CC} \ .$$
$$N_e^{CC} = \mathcal{N}\left[P_{\mu e}\Phi_\mu + P_{ee}\Phi_e\right] \times \sigma_e^{CC} \ .$$
$$N_\tau^{CC} = \mathcal{N}\left[P_{\mu\tau}\Phi_\mu + P_{e\tau}\Phi_e\right] \times \sigma_\tau^{CC} \ .$$

- $\overline{\nu}_l N \to l^+ X$ (CC), $\overline{\nu}_l N \to \overline{\nu}_l X$ (NC).

- Main focus on muon neutrino ($\overline{\nu}$) events, including "rock events"

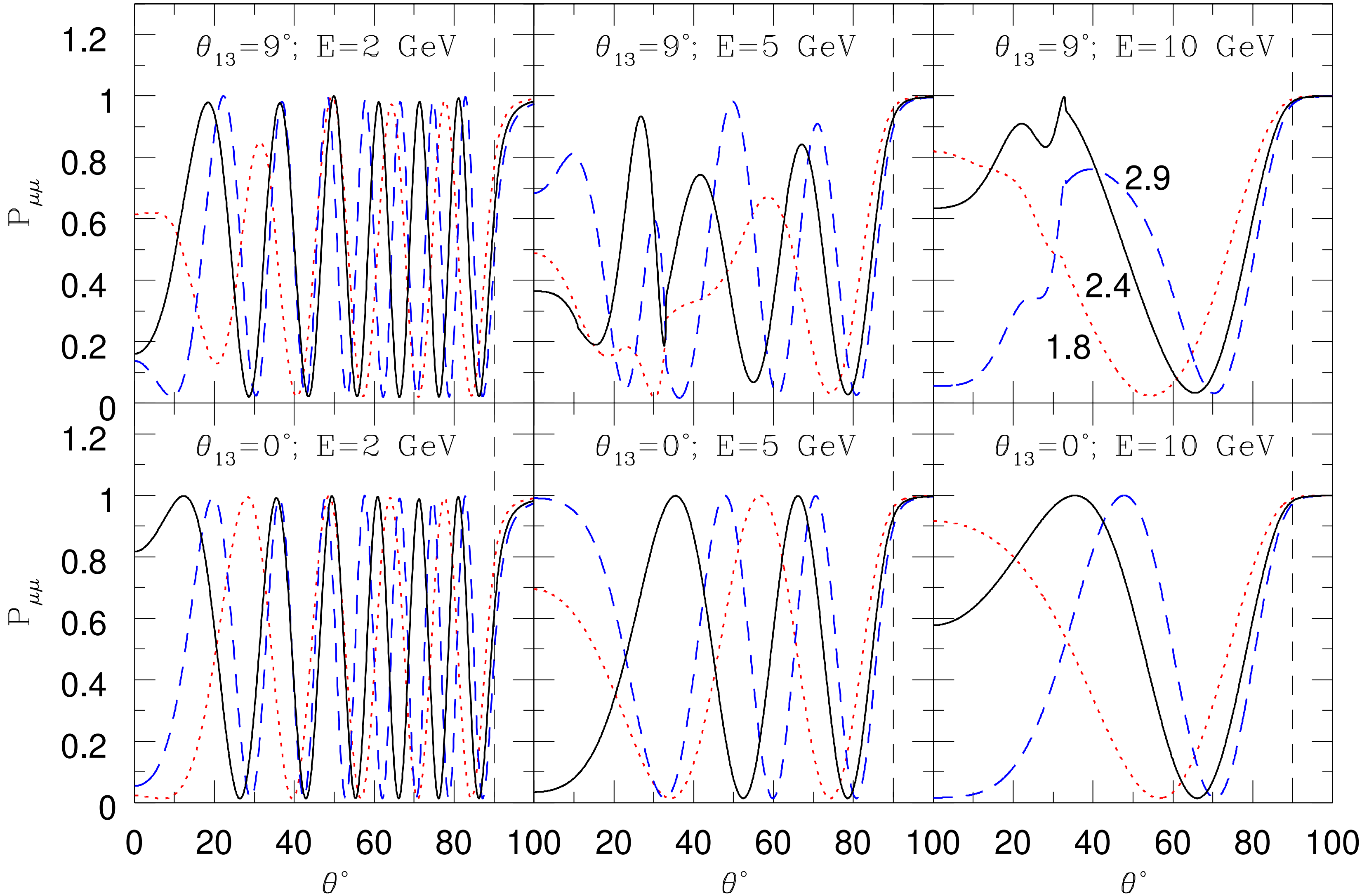
- Hence detector sensitivity to muons/hadrons important

- P_{ij} depend on both energy and path length traversed by neutrinos, apart from oscillation parameters.



R. Gandhi et al., PRL 94 (2005) 051801

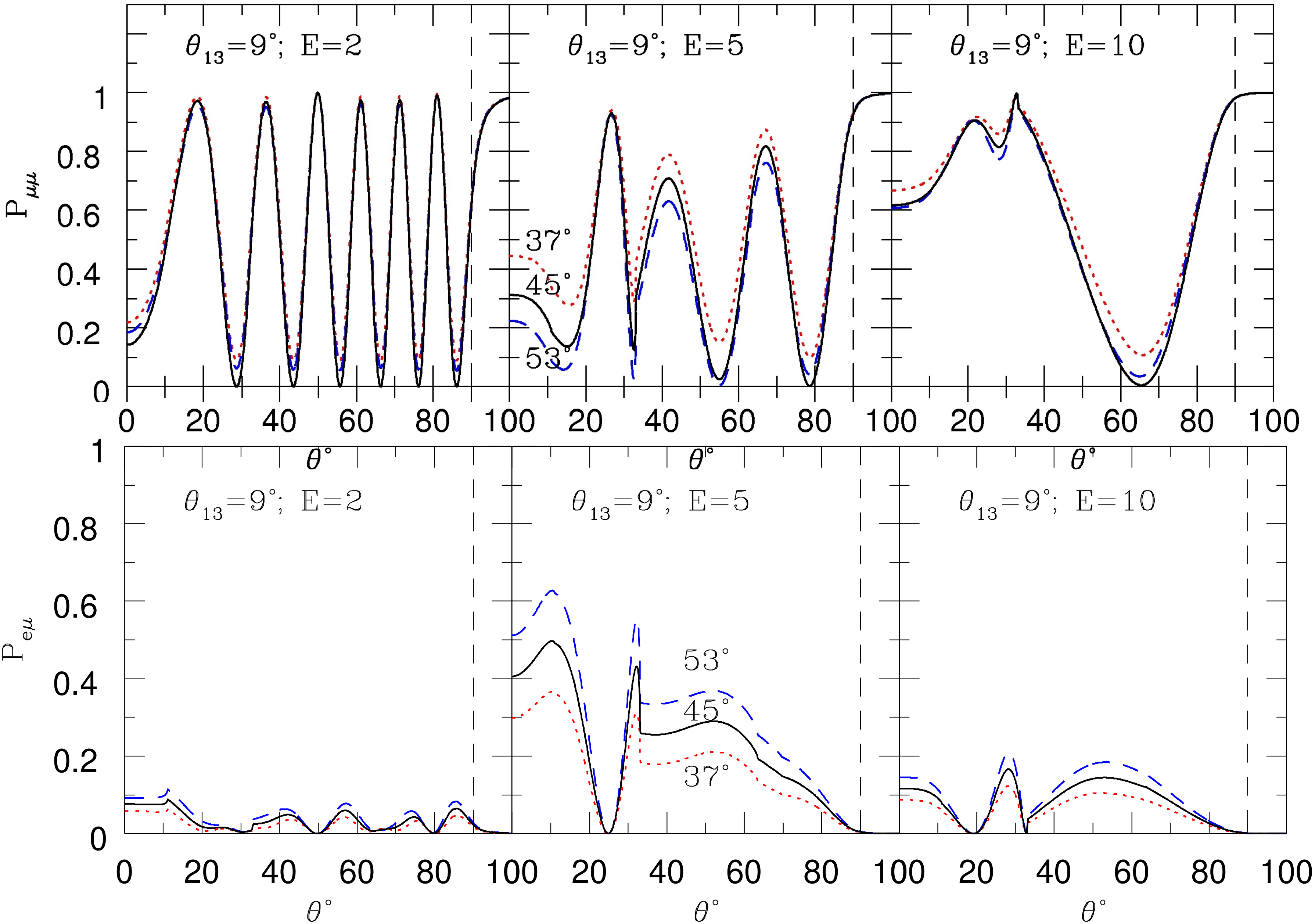
Sensitivity to $\Delta m^2_{\rm atm}$



- Sensitivity is hierarchy dependent. Shown here for NO.
- Reduced sensitivity in anti-neutrino sector ($A \to -A \equiv \theta_{13} = 0$)

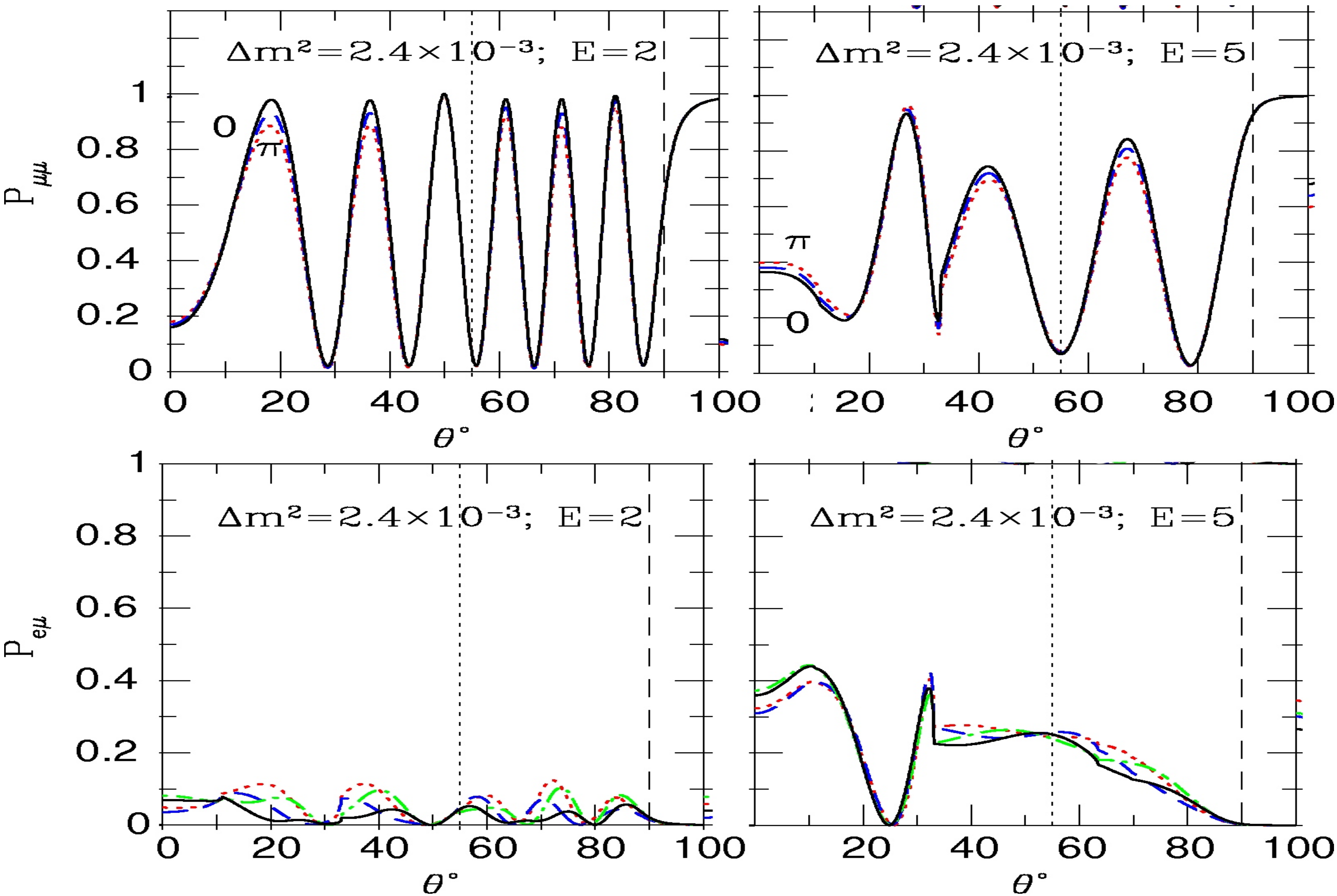
D. Indumathi et al., Phys.Rev.D 74 (2006) 053004, arXiv:hep-ph/0603264]

Sensitivity to octant of θ_{23}



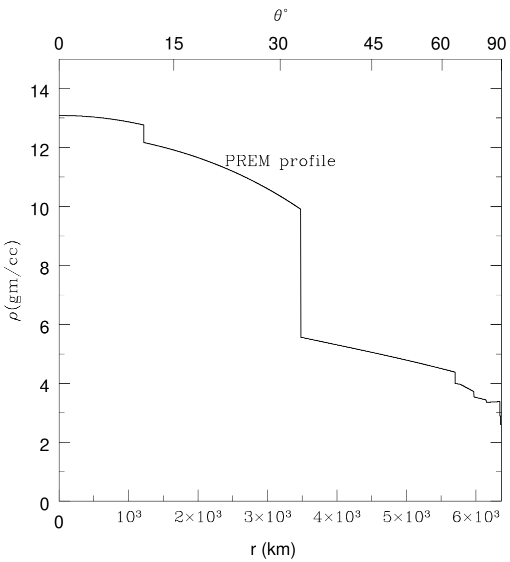
Only visible for non-zero θ_{13}

Sensitivity to the CP phase

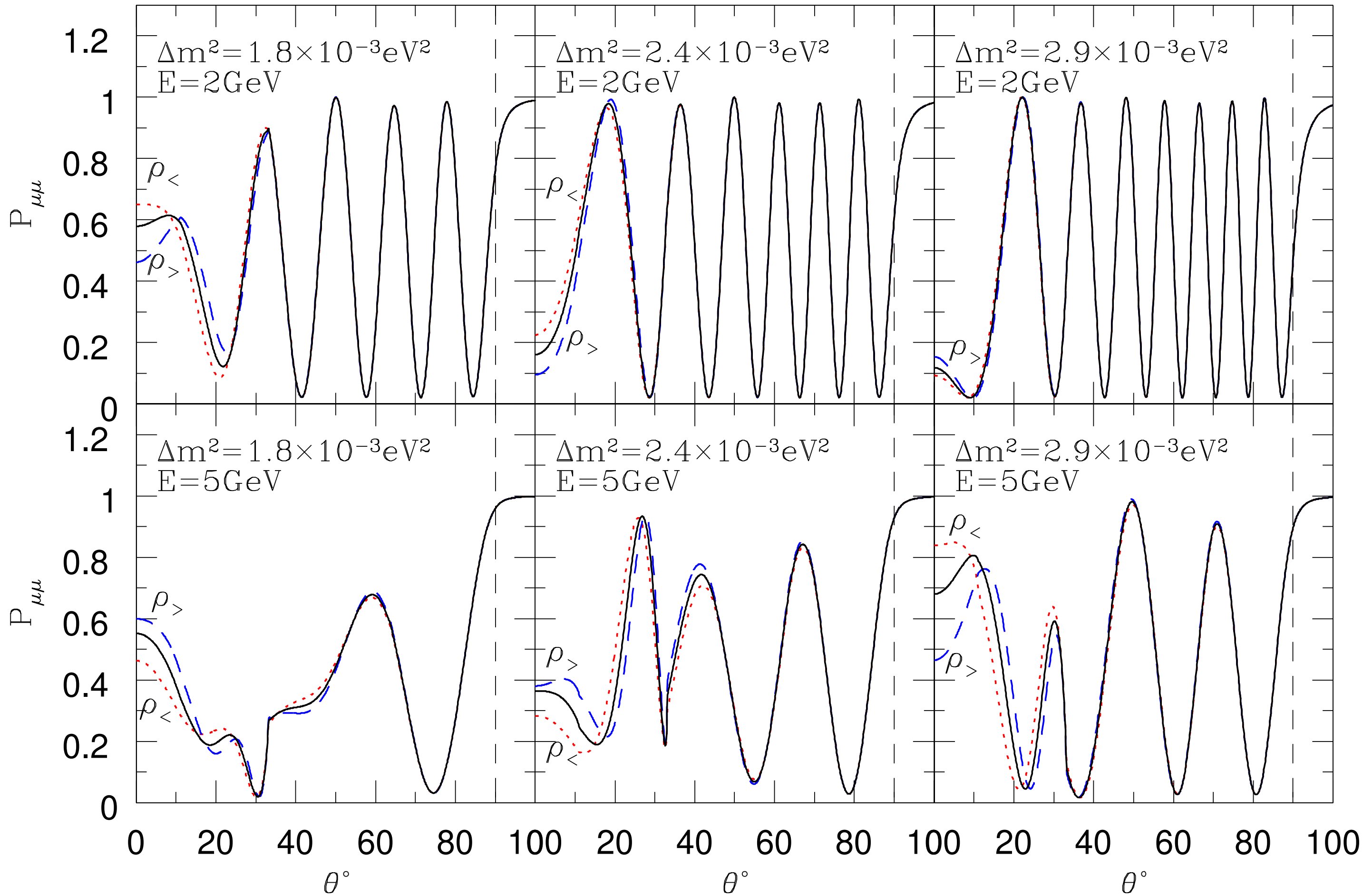


For energies of interest in ICAL, there is no sensitivity to δ_{CP}; visible only at $E \lesssim 1$ GeV.

Sensitivity to Earth density profile



PREM Profile



Core-crossing effect clearer at larger energies. May be statistics limited.

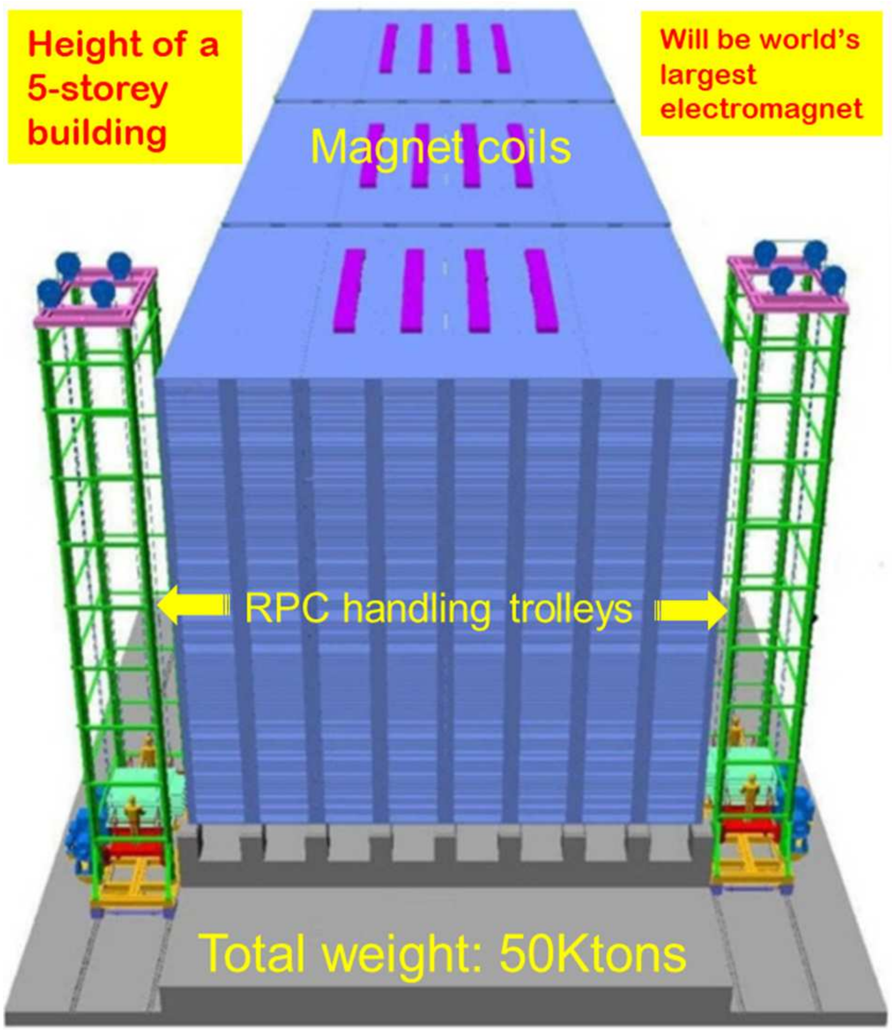
Characteristics of Atm. ν Detectors

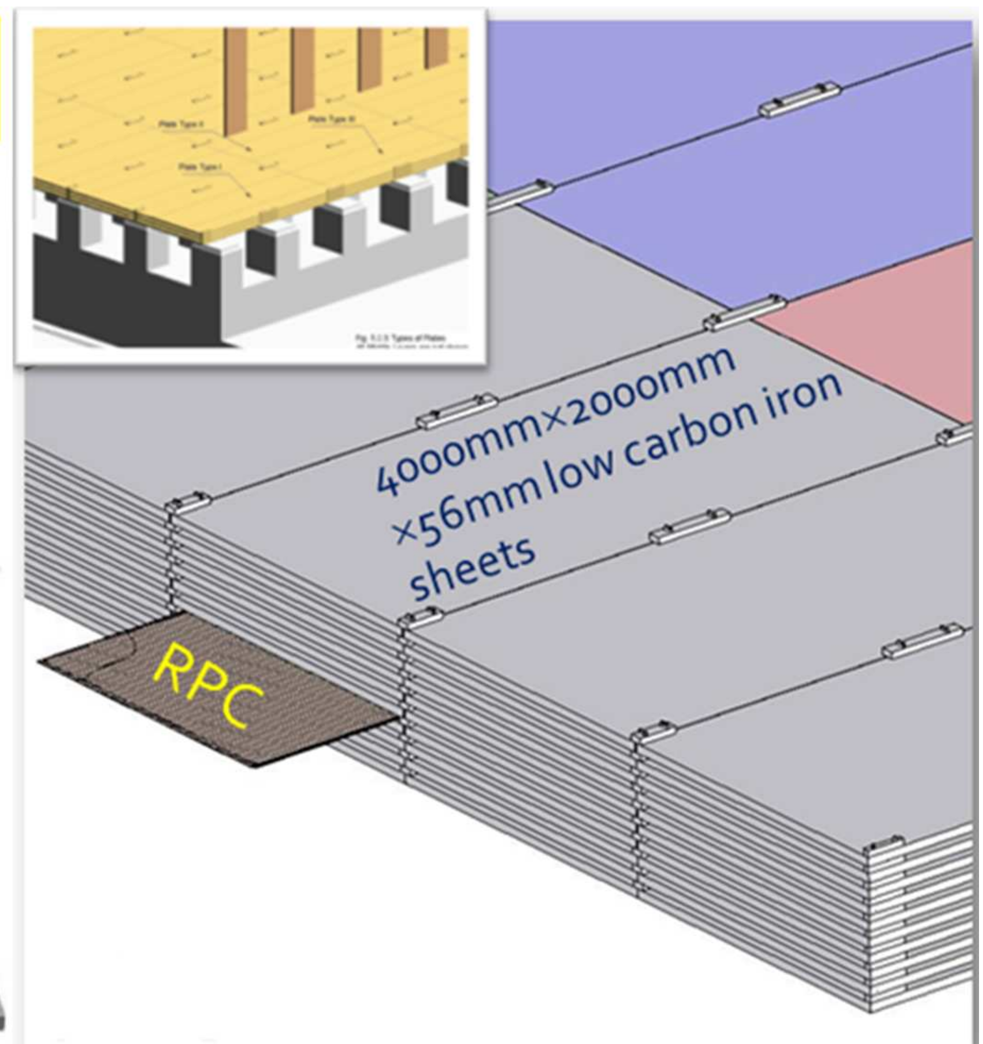
Atmospheric neutrinos have large L and E range. Some desirable features of atmospheric neutrino detectors are :

- Nearly 4π coverage in solid angle;
- Sensitivity to as low/high energies as possible; note that the most interesting region for observing matter effects in the 2–3 sector is 3–15 GeV;
- Sensitivity to direction, up/down discrimination; via timing (~ 1 ns)
- Desirable: Good charge resolution to distinguish neutrino and anti-neutrino events via separation of μ^- and μ^+ events.
- Sensitivity to electrons
- Desirable: sensitivity to hadrons and tau (indirect).

The ICAL detector

- 50 kton iron, magnetised to ~ 1.5 T with 150 layers of 5.6 cm plates in three modules ($16 \times 16 \times 14.4$ m^3)
- Interleaved by active detectors called Resistive Plate Chambers (RPCs)



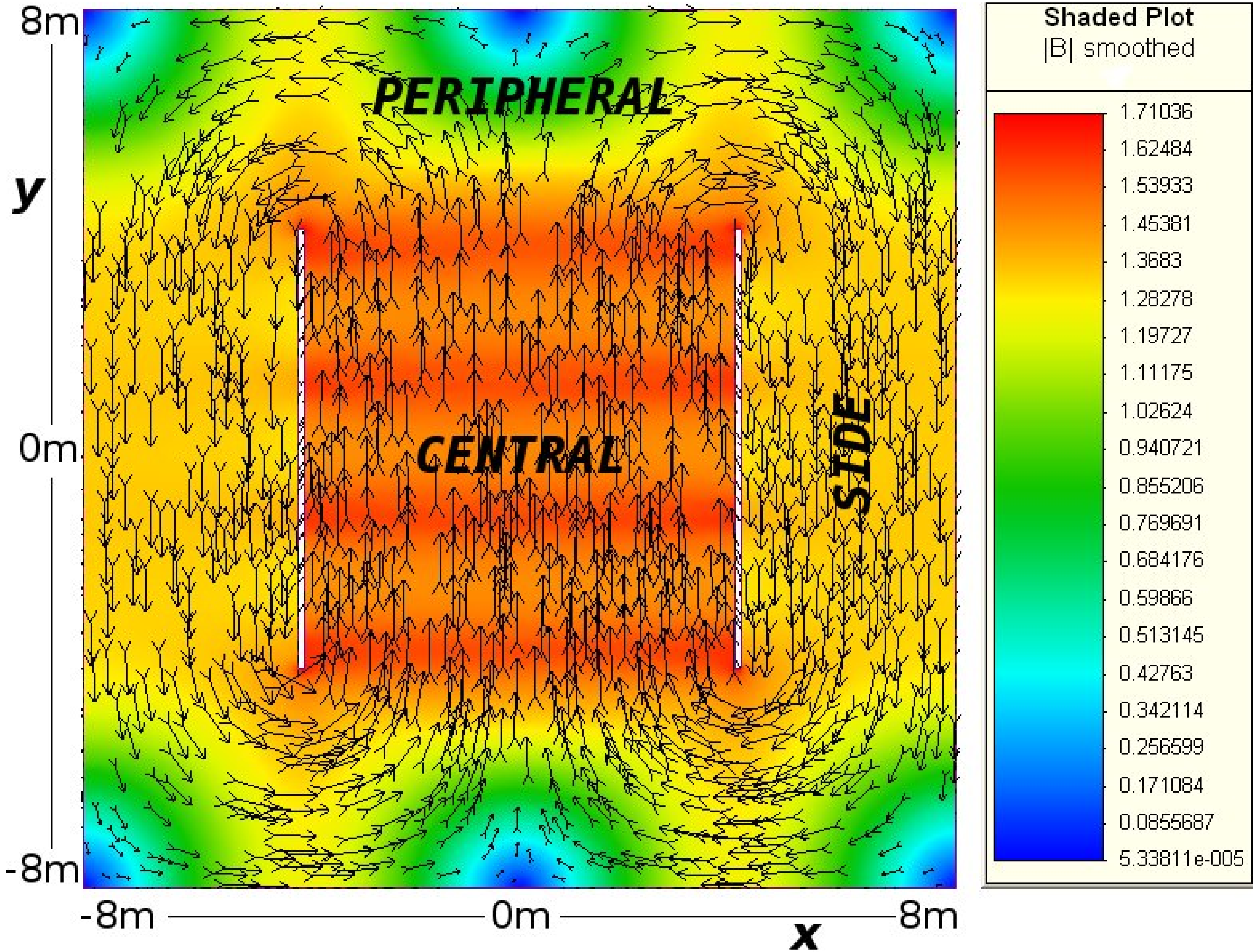


Specifications of the ICAL detector

ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 14.4 m
Detector dimension	48 m $\times$ 16 m $\times$ 14.4 m
No. of layers	150
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	$\sim$ 30,000
No. of electronic readout channels	3.9 $\times 10^6$

Completely indigenous. Needs large industry interface.

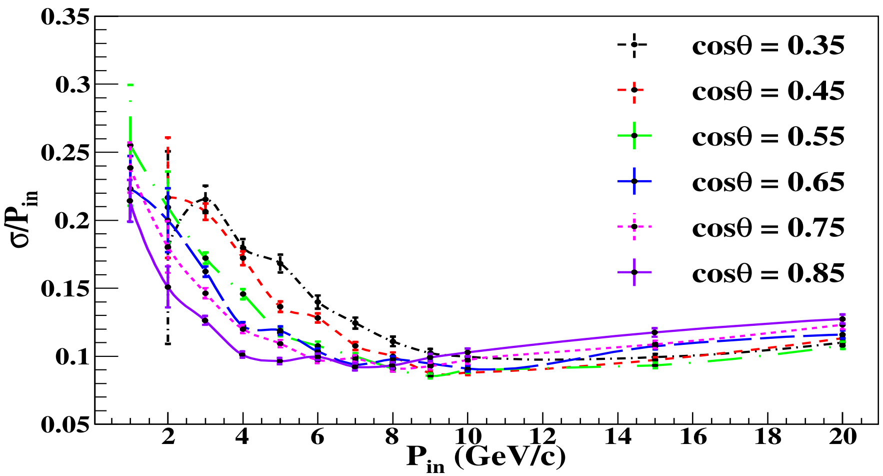
The magnetic field



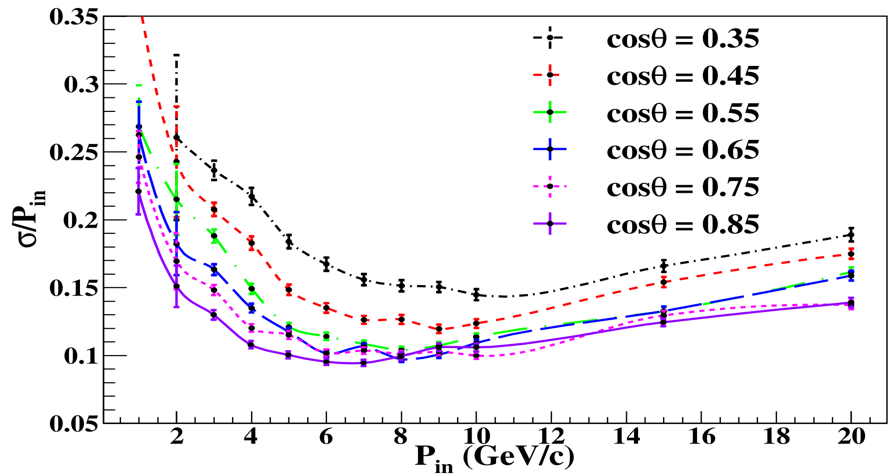
The magnetic field (magnitude and direction) at the centre of an iron plate in a single module of ICAL.

The detector resolutions: Muons

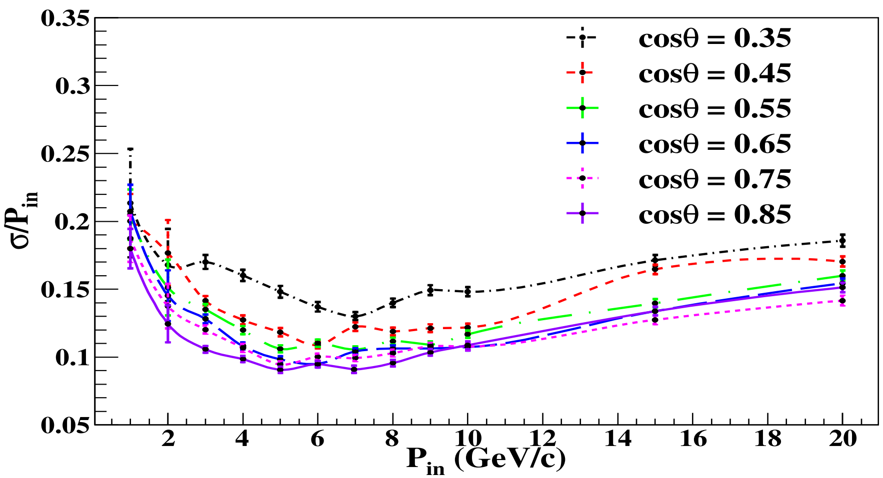
A. Chatterjee et al., JINST 9 (2014) P07001; arXiv: 1405.7243 [physics.ins-det]



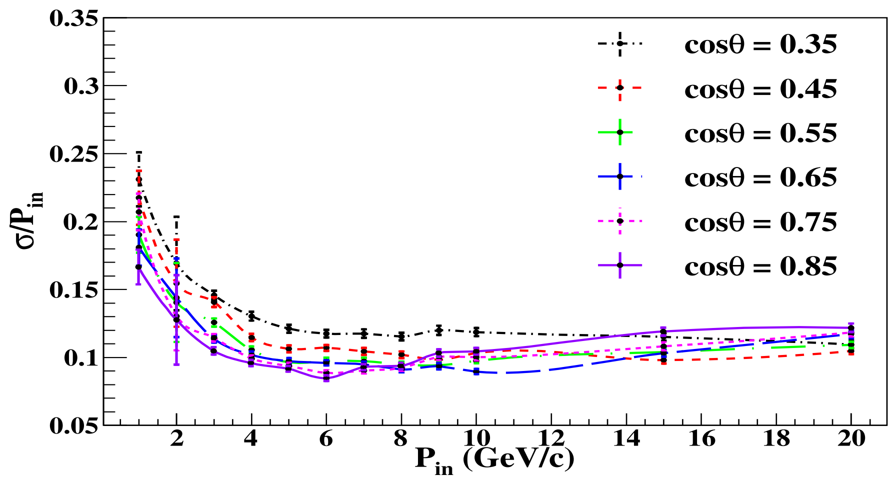
(a) $|\phi| \leq \pi/4$



(b) $\pi/4 < |\phi| \leq \pi/2$

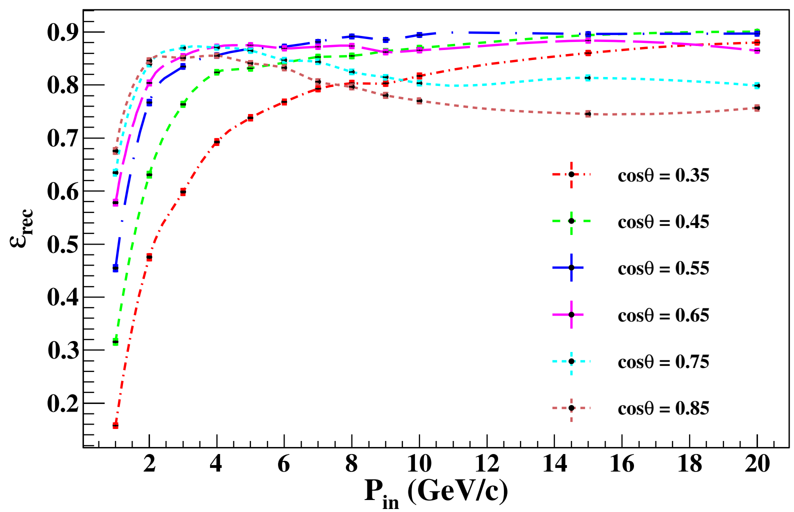


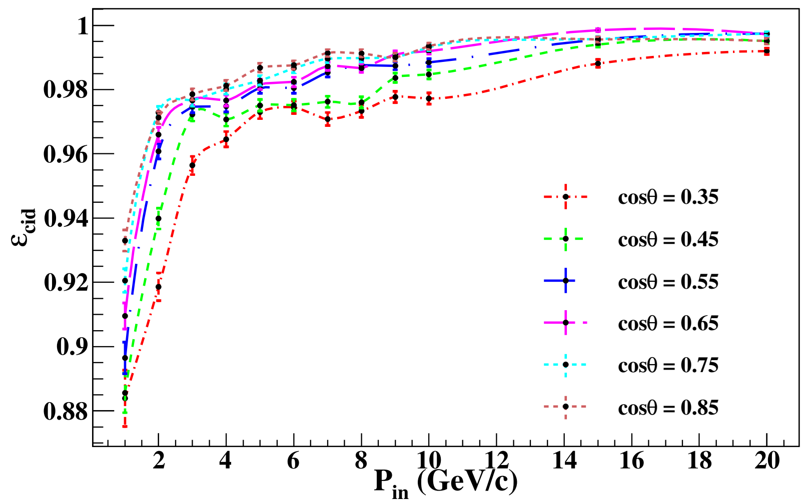
(c) $\pi/2 < |\phi| \leq 3\pi/4$



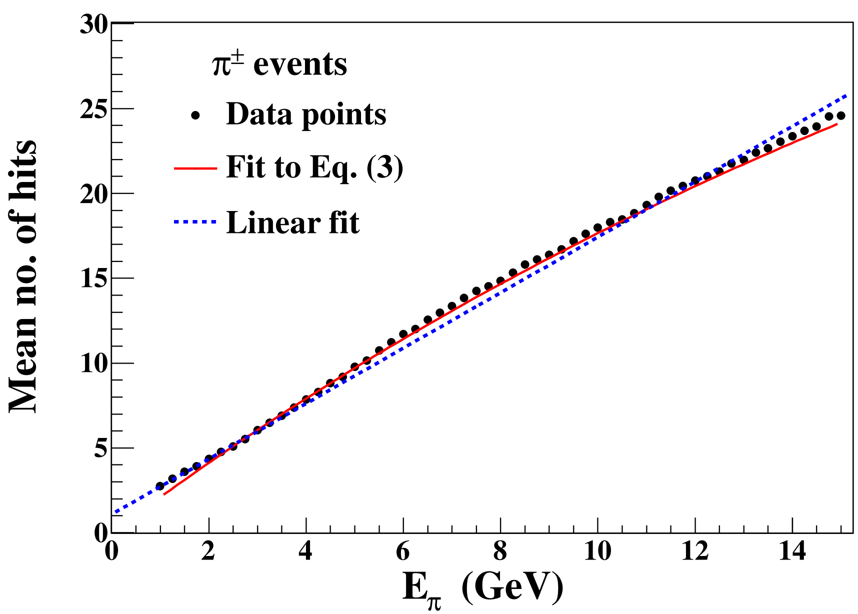
(d) $3\pi/4 < |\phi| \leq \pi$

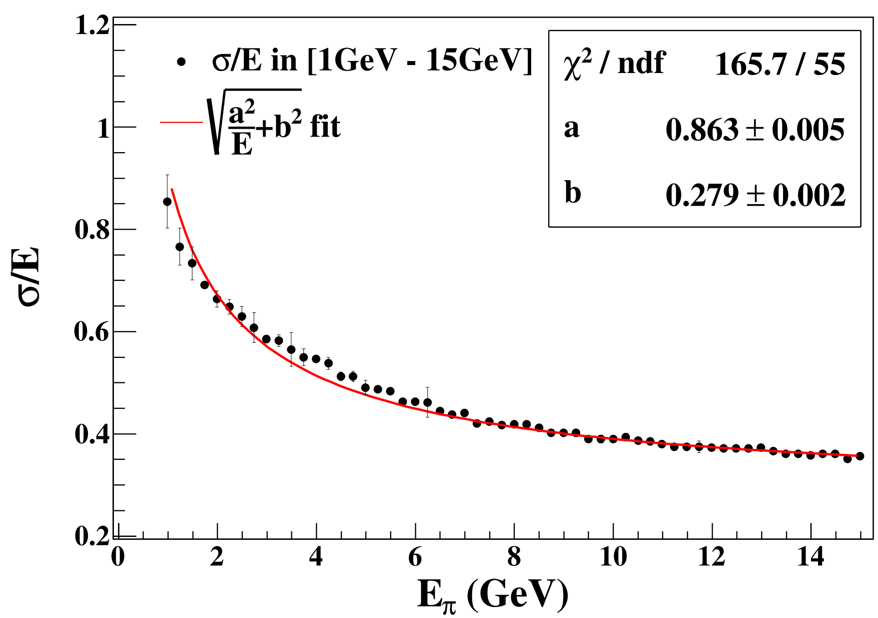
The reconstruction efficiencies: Muons





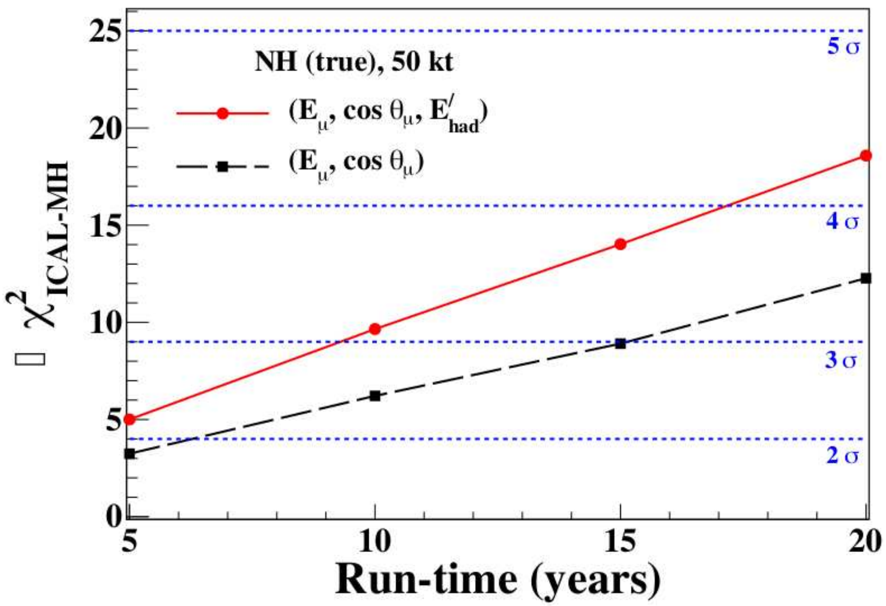
Hadron resolutions

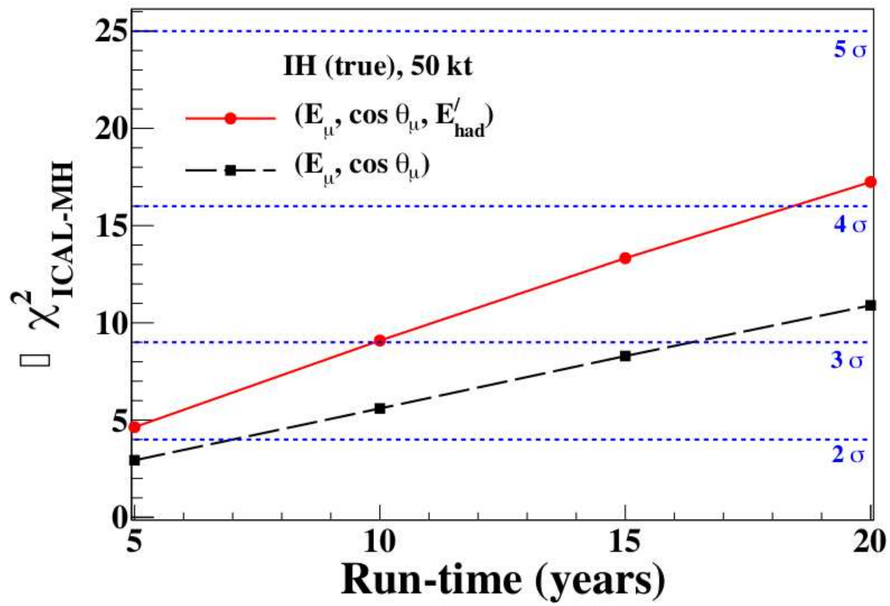




M.M. Devi et al., JINST 8 (2013) P11003; arXiv: 1304.5115 [physics.ins-det]

The hierarchy reach of ICAL

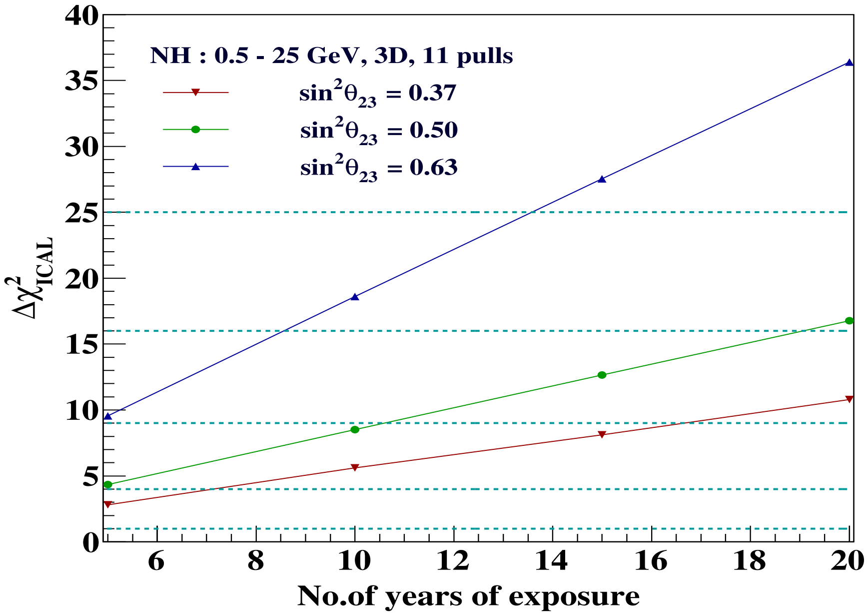


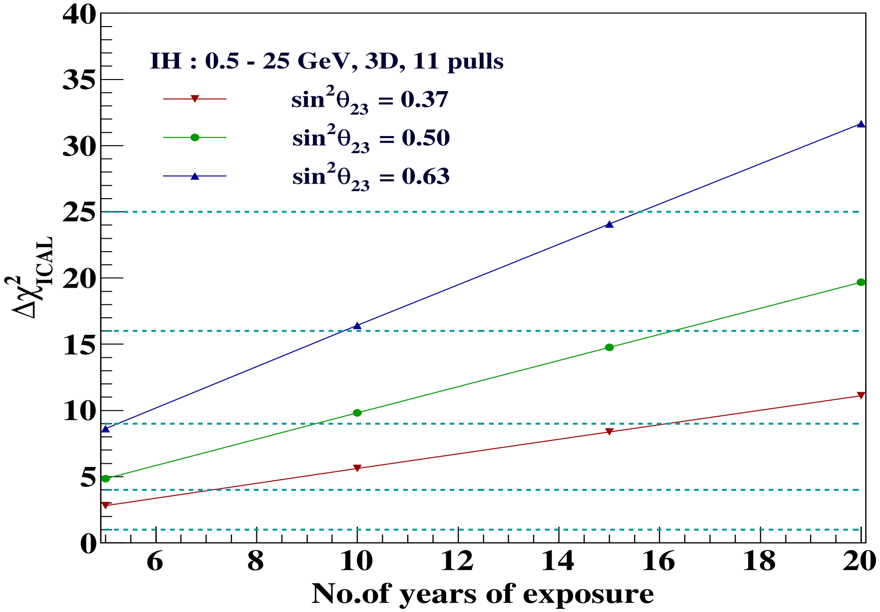


- Hierarchy sensitivity with NO (left) and IO (right).
- $|\Delta m^2_{\rm eff}|, \sin^2\theta_{23}, \sin^2\theta_{13}$ marginalised over their 3σ ranges.
- All results for 10 years running unless otherwise specified

M.M. Devi et al., 10.1007/JHEP10(2014)189, arXiv: 1406.3689

Hierarchy Dependence on θ_{23}

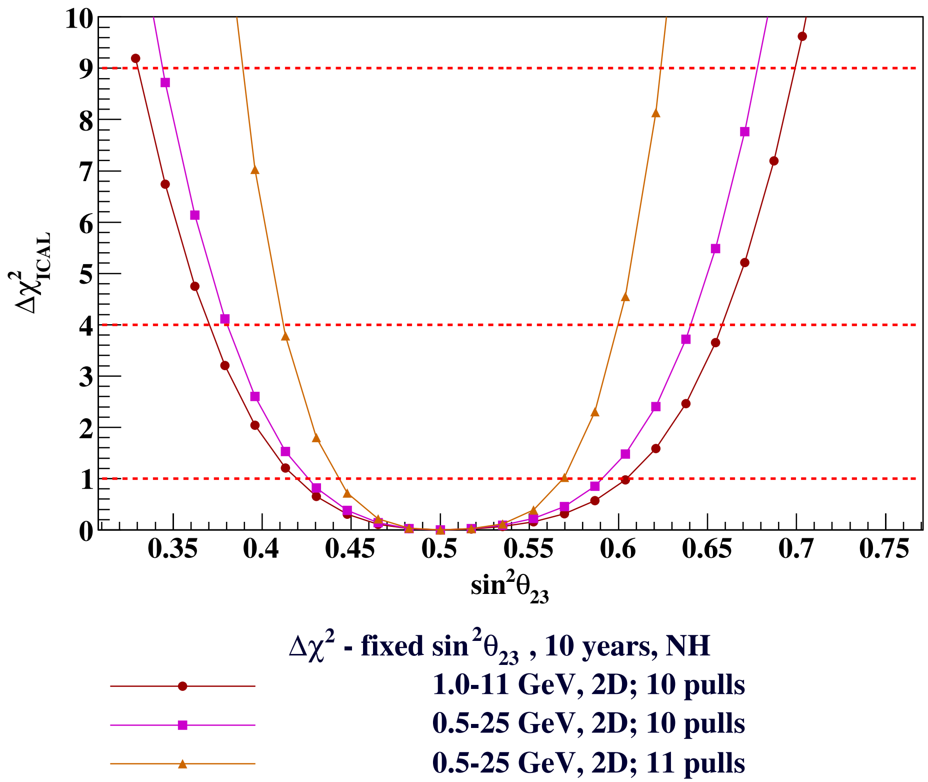


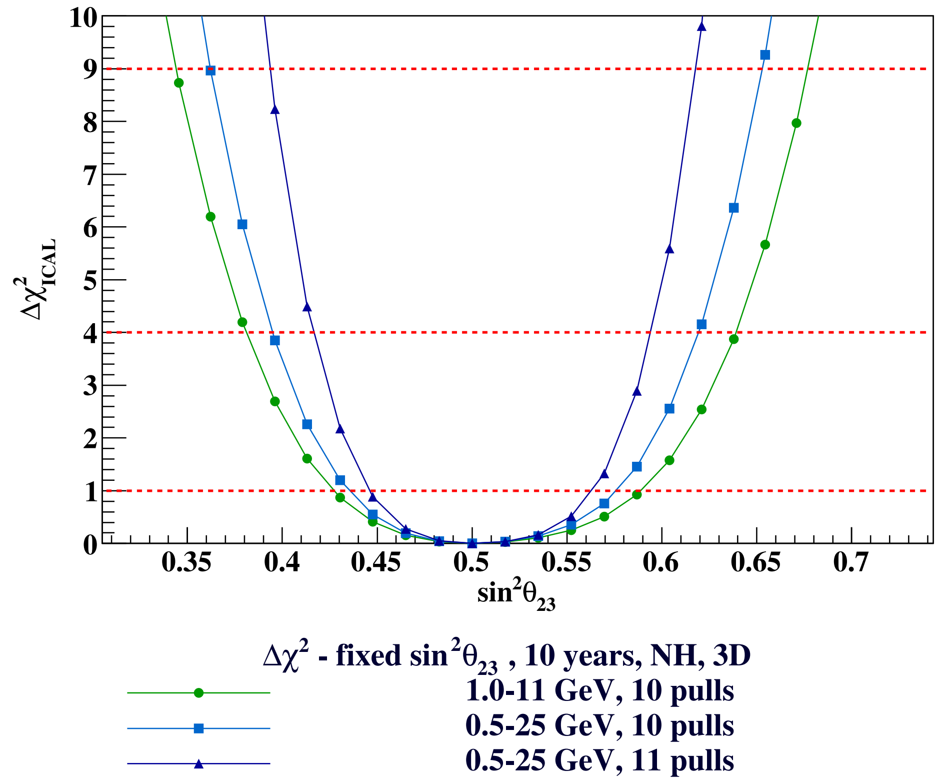


- Again, remaining parameters are marginalised over
- Sensitivity improves with θ_{23}

Lakshmi S Mohan et al., Eur.Phys.J.C 77 (2017) 1, 54, arXiv: 1605.04185 [hep-ph]

Sensitivity of ICAL to θ_{23}



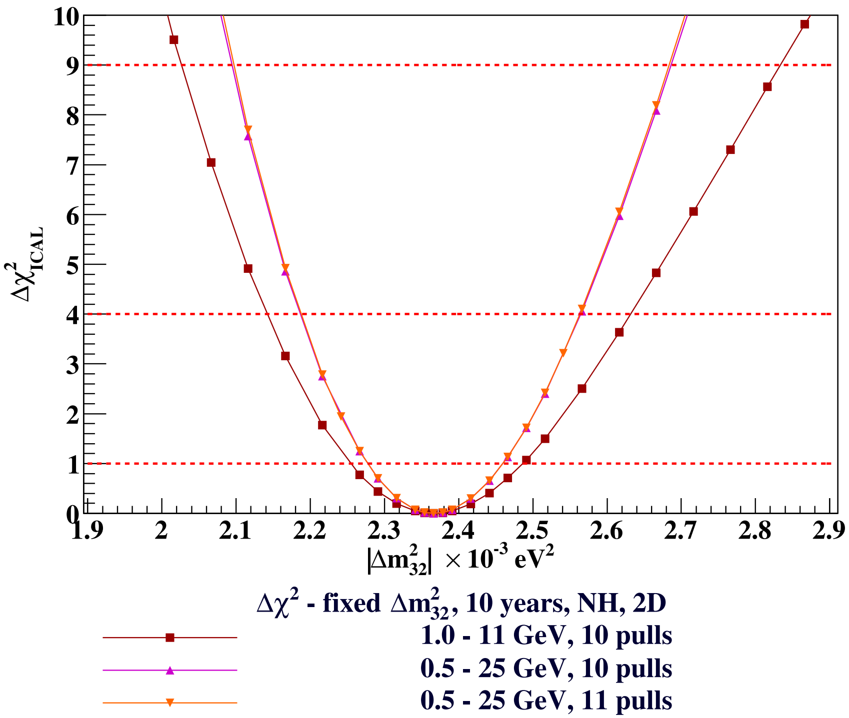


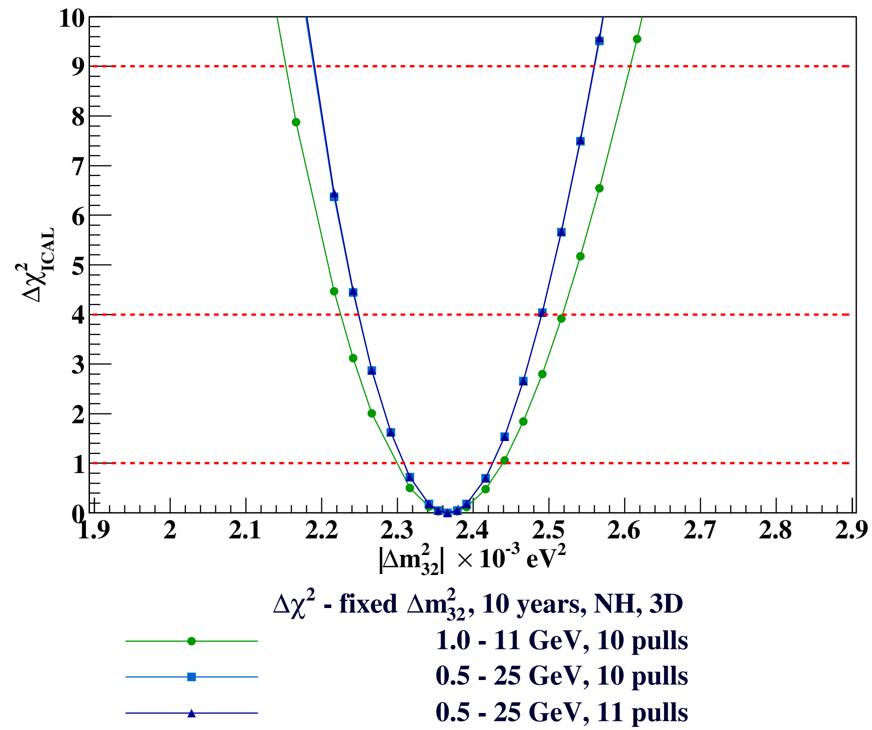
Lakshmi S Mohan et al., Eur.Phys.J.C 77 (2017) 1, 54, arXiv: 1605.04185 [hep-ph]

- Precision decreases by 4% when event by event reconstruction taken, rather than the resolution functions for muon energy and direction. This study was restricted to muon analysis alone, for 5 years data.

K. Rebin et al., Eur.Phys.J.C 79 (2019) 4, 295, arXiv: 1804.02138 [hep-ex]

Sensitivity of ICAL to Δm^2_{eff}

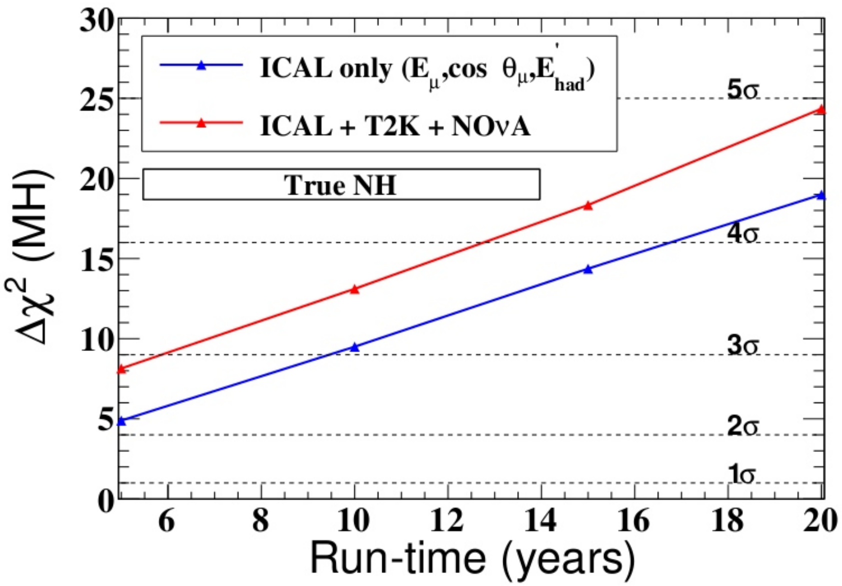


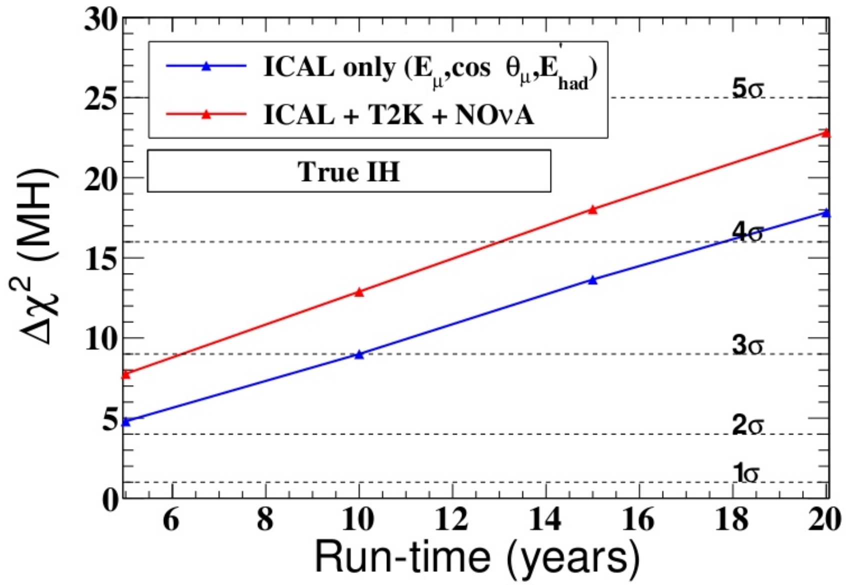


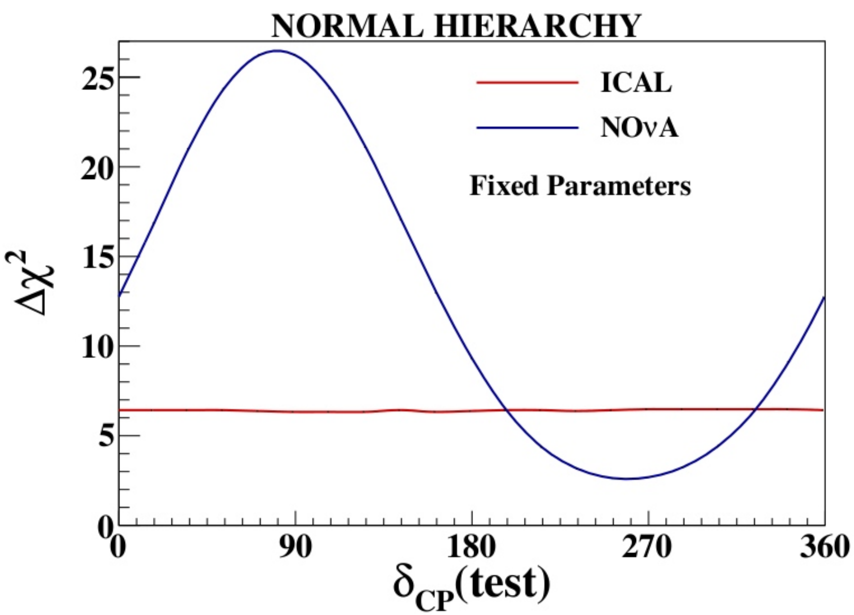
- Using the resolutions and efficiencies determined earlier
- Precision decreases by 7% when event by event reconstruction taken, rather than the resolution functions for muon energy and direction. This study was restricted to muon analysis alone, for 5 years data.

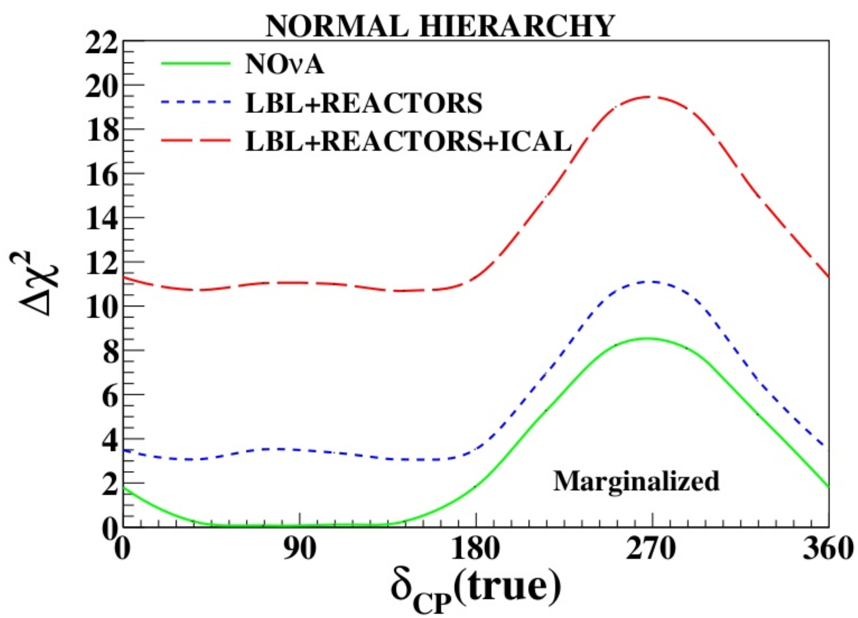
K. Rebin et al., Eur.Phys.J.C 79 (2019) 4, 295, arXiv: 1804.02138 [hep-ex]

Additional Synergies



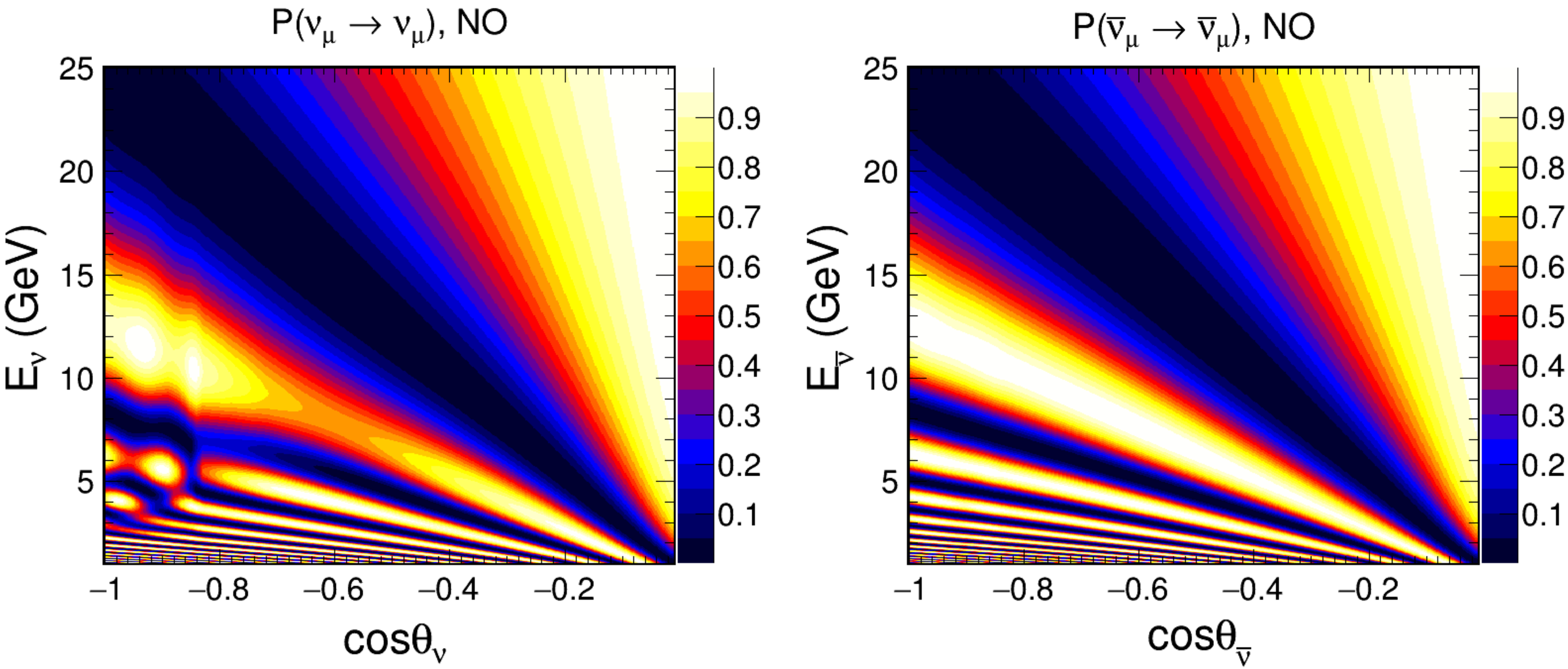






Shakeel Ahmed et al., Pramana 88 (2017) 5, 79; arXiv: 1505.07380 [physics.ins-det]; S. K. Agarwalla et al., ref. ibid.

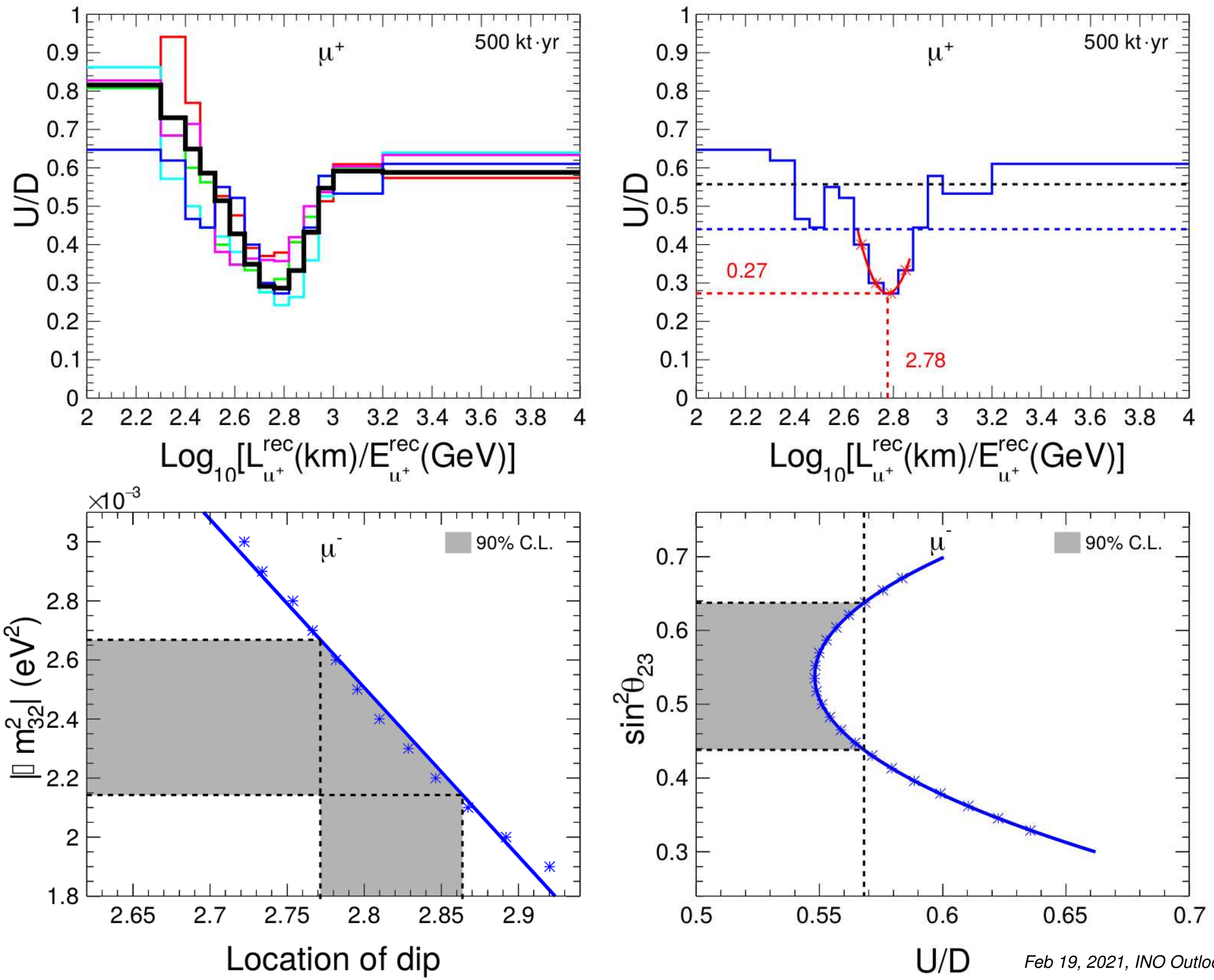
L/E analysis of atmospheric neutrinos



- MSW resonance at $(-0.6, 6$ GeV$)$ clearly visible
- Oscillation length resonance at 3-4 GeV and $\cos\theta < -0.8$ is also visible.
- Also note the “oscillation valley" in black.

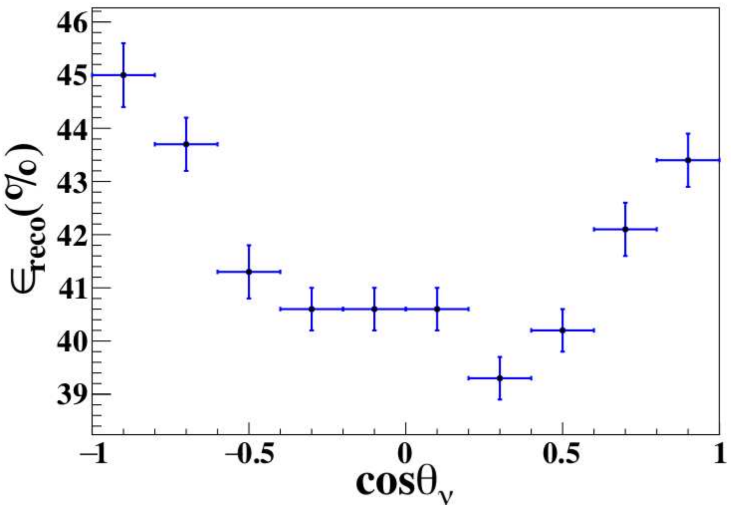
Parameter extraction from dip

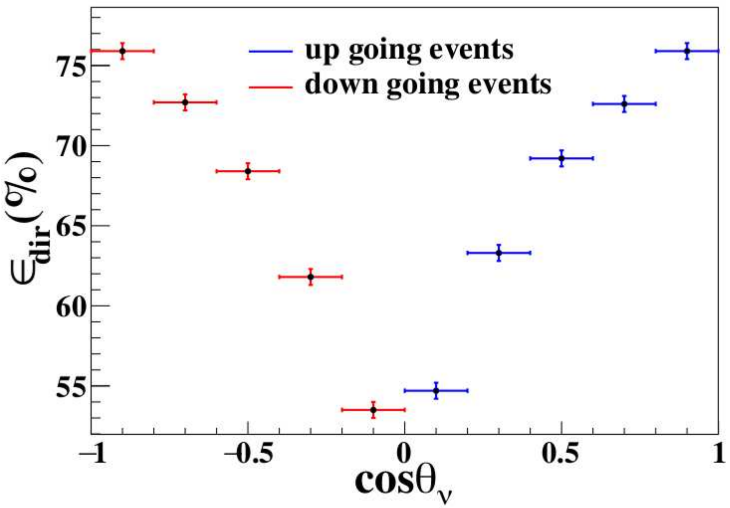
Anil Kumar et al., arXiv: 2006.14529 [hep-ph]

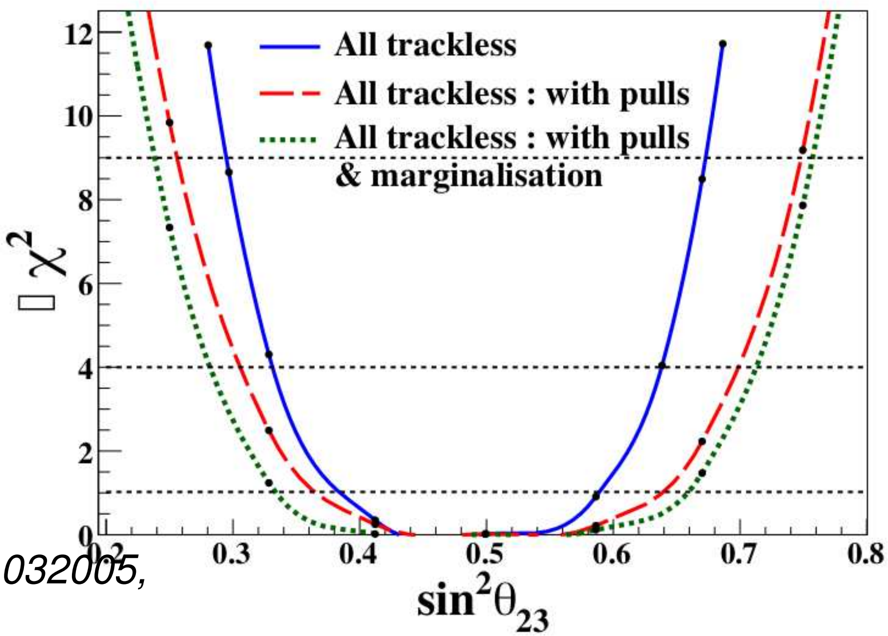


Sensitivity to electrons?

- NC, electron CC and muon CC (zero-track) all give “trackless" events.
- NC has no sensitivity to oscillation parameters; rest do
- Sensitivity to energy and direction of electrons







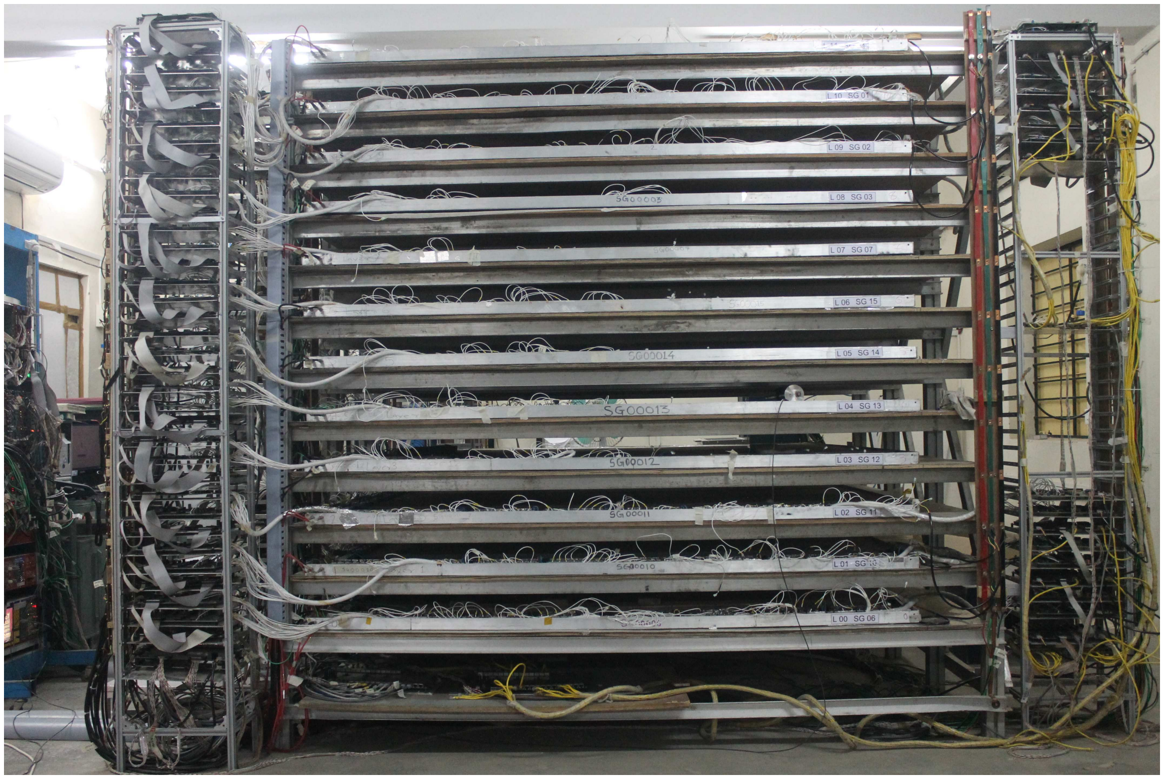
Main limitation due to the thick (5.6 cm) iron plates

Also, more systematic uncertainties due to presence of three different kinds of events.

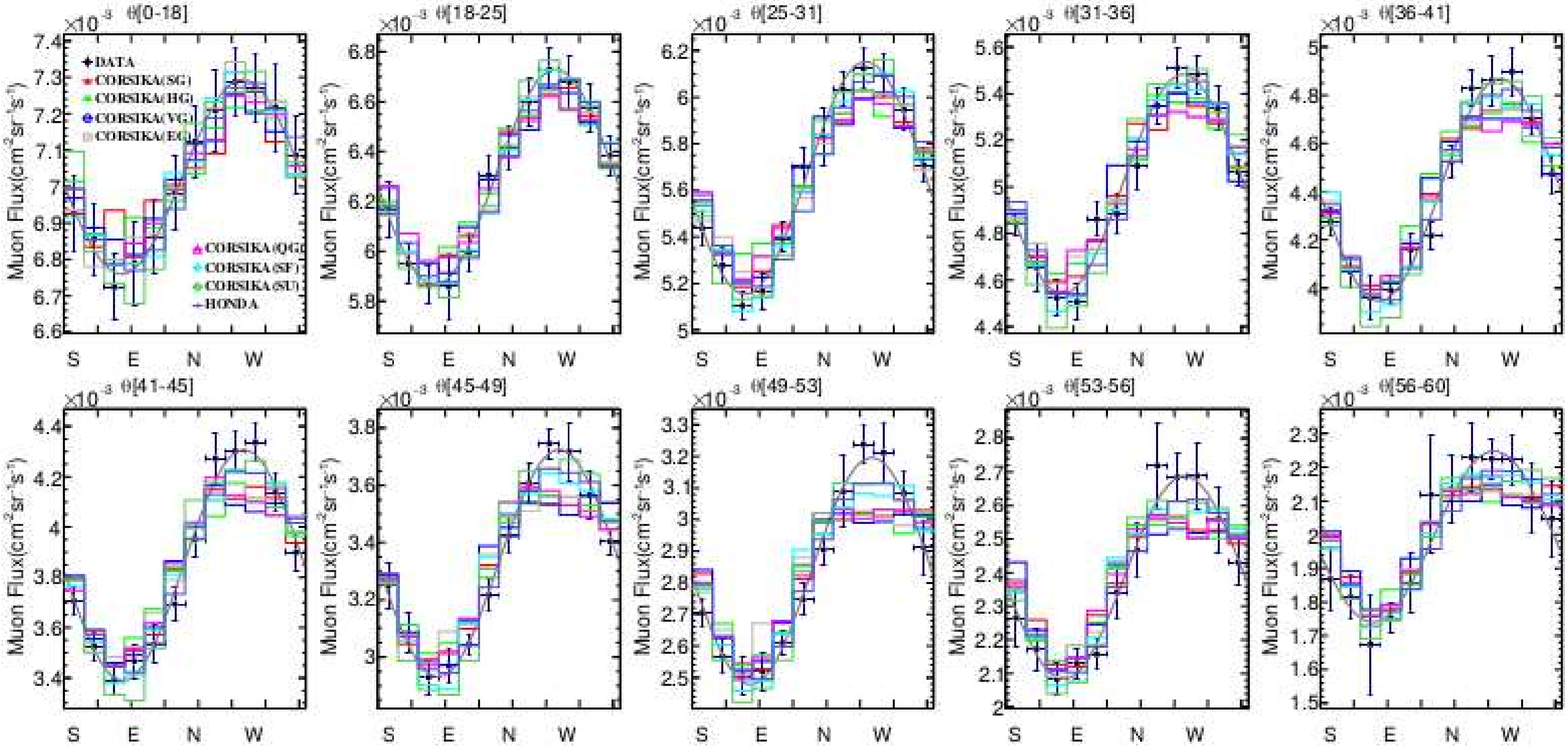
Aleena Chacko et al., Phys.Rev.D 102 (2020) 3, 032005, arXiv: 1912.07898 [physics.ins-det]

Cosmic muons and data from IICHEP

- Cosmic ray “stack" of RPCs only; no magnetic field.
- Vertical cosmic muon flux determined at Madurai, IICHEP
- Azimuthal dependence also found, with modified electronics



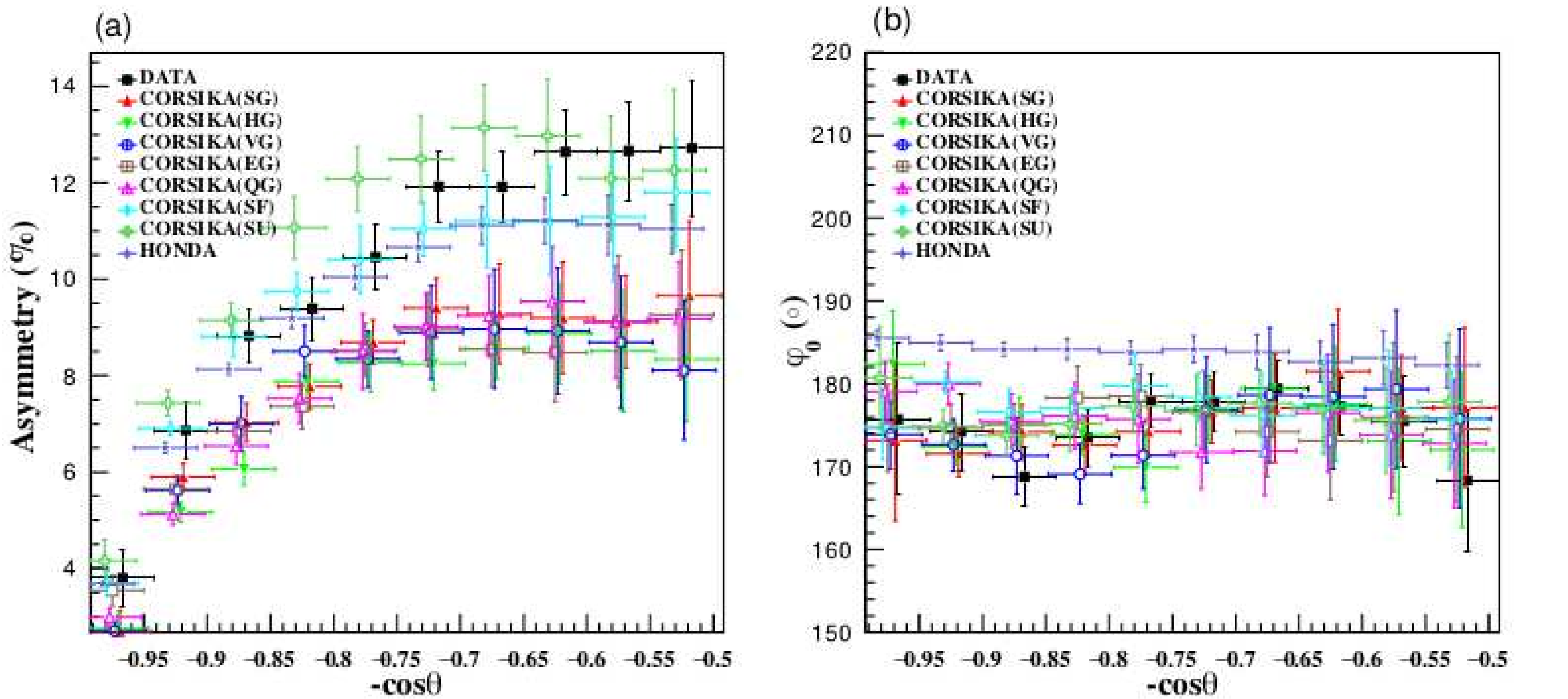
Azimuthal dependence of cosmic muons



Clear east-west asymmetry is seen, although the events are energy integrated

Comparison with models

$$f(\phi) = P_0\left[1 + A\sin(\phi_0 - \phi)\right].$$

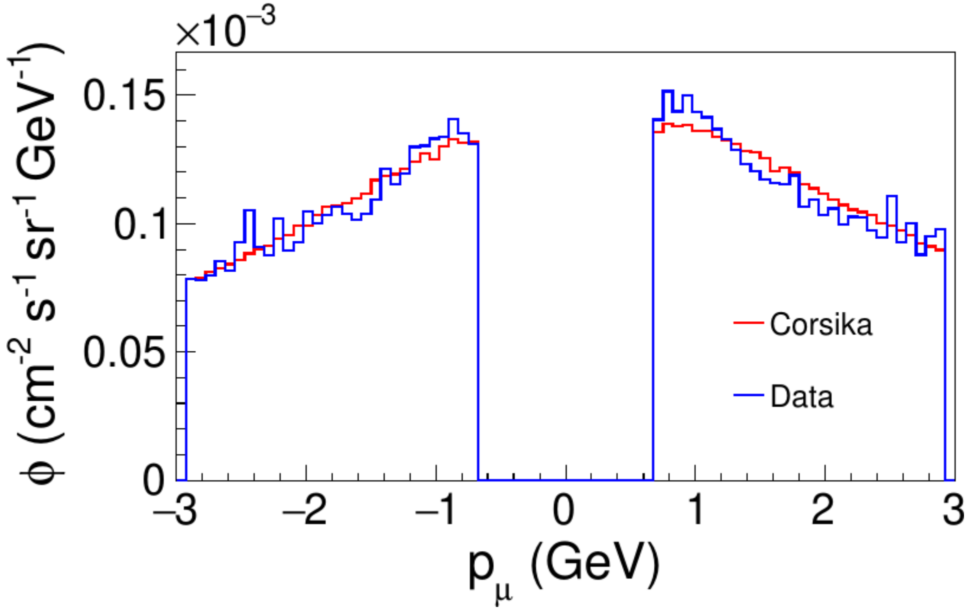


- Models based on GHEISHA are most deviated away from the data; HONDA best.
- Particle multiplicity does not agree with different hadronic models in CORSIKA

S. Pethuraj et al., JCAP 09 (2017) 021, arXiv: 1706.00901 [physics.ins-det]

S. Mondal et al., Exper.Astron. 51 (2021) 1, 17-32; arXiv: 1908.04589 [astro-ph.HE]

Mini-ICAL: Effect of magnetic field



- Magnetic field enables separation of μ^- and μ^+.
- The spectrum matches reasonably with CORSIKA from 0.6 GeV
- The Kalman filter codes that were used in the simulations studies of ICAL are now being validated
- Looking forward to the larger engineering module.

Apoorva Dipak Bhatt, PhD Thesis, HBNI, Mumbai, 2019

Additional Slides

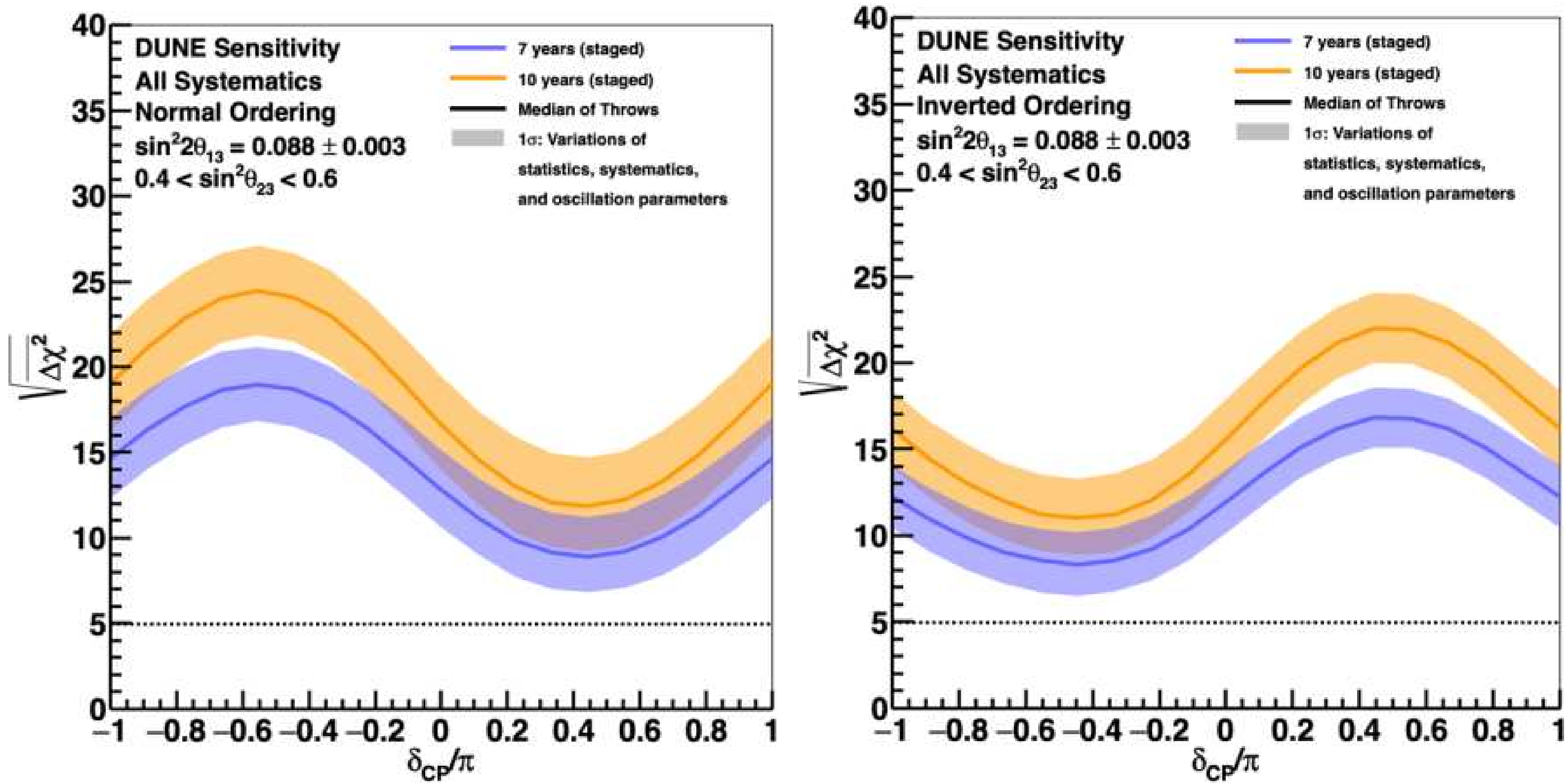
Current values of oscillation parameters

- Current values of neutrino oscillation parameters from global fits to the data.
- Data include: Solar: Cl, Ga, SK, SNO, Borexino, Atm: IceCube, SK, KamLAND, Double-Chooz, Daya Bay, Reno, Acclr: MINOS, T2K, NoνA.

Esteban et al., JHEP 09 (2020) 178, arXiv: 2007.14792 [hep-ph]

Parameter	True value	3σ range
θ_{12}	33.44°	[31.27–35.86]
θ_{23}	49.2°	[40.1–51.7]
$\sin^2\theta_{23}$	0.573	[0.415–0.616]
θ_{13}	8.57°	[8.2–8.93]
Δm^2_{21}	7.42×10^{-5} eV^2	[6.82–8.04]
Δm^2_{31} (NO)	2.517×10^{-3} eV^2	[2.435–2.598]
$-\Delta m^2_{31}$ (IO)	2.498×10^{-3} eV^2	[2.581–2.414]
δ_{CP}	0, $197°$, $\pm 180°$	[120–369]

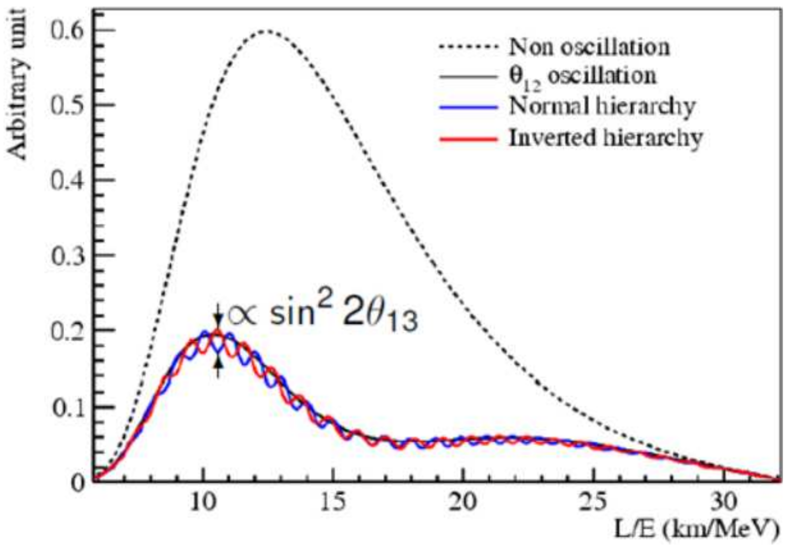
DUNE hierarchy reach

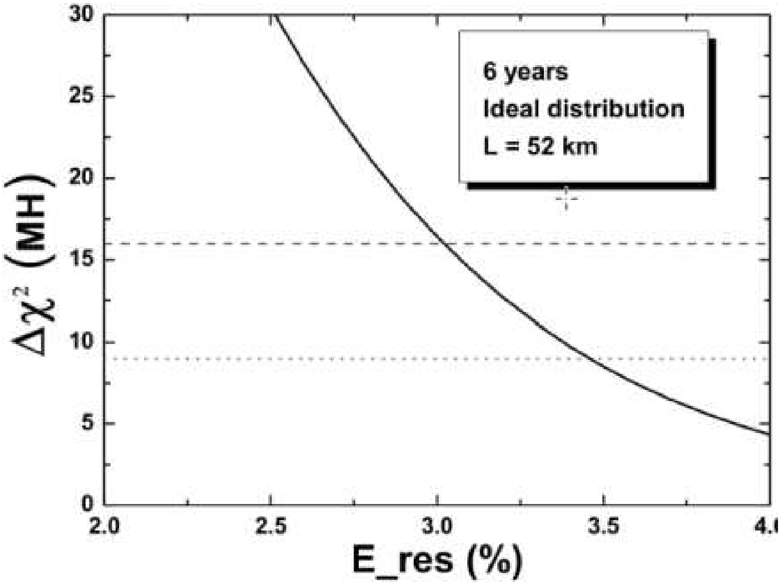


- DUNE 40 kton l-Ar TPC detector and a 1.1e21 POT beam;1.2–2.4 MW
- Note: $\nu_\mu \to \nu_e$ and shorter L so constant density approximation ok
- Seven years of data (3.5 plus 3.5 years in $\nu/\overline{\nu}$ mode) in purple
- MO is determined to $\sqrt(\Delta\chi^2) = 5$ (*) for nearly 100% of δ_{CP} values
- 3σ band $0.46 \le \sin^2\theta_{23} \le 0.57$ for 10 years (marginally improves in 15 years)

B. Abi et al., Eur.Phys.J.C 80 (2020) 10, 978; arXiv: 2006.16043 [hep-ex]. * The sqrt was missed in the original version

JUNO hierarchy reach





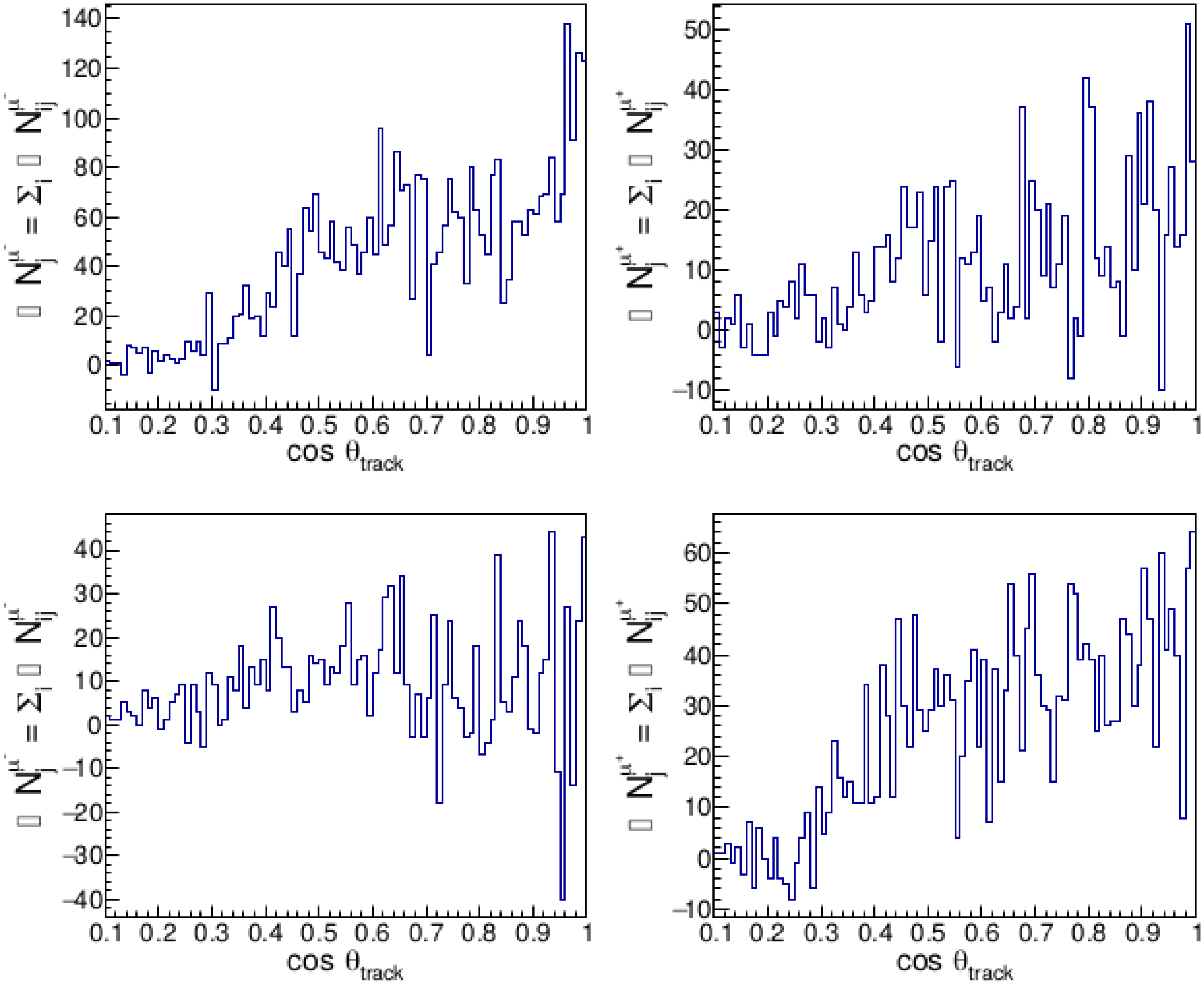
- JUNO 20 kton l-scintillator + PMT anti-neutrino detector (reactors, power of 36 GW (th)) (26 GW available in 2021); $L \sim 53$ km
- Used 3%$/\sqrt{E}$ muon energy resolution; scale uncertainty less than 1%, and 73% reco efficiency
- MO to 3–4 σ with 6 years; solar and atm (Δm^2_{32} only) oscillation parameters to 1% or better; latter at 0.5%

W. Wu, PoS Nufact2019, 030, F. Perrot, J.Phys.Conf.Ser. 1586 (2020) 1, 012047

Additional Material

This was not covered in the talk due to lack of time, oversight, etc.

Testing for matter sensitivity at ICAL

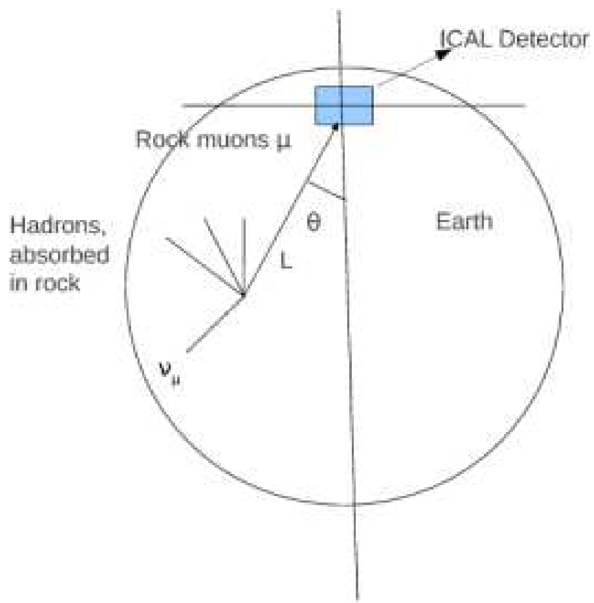


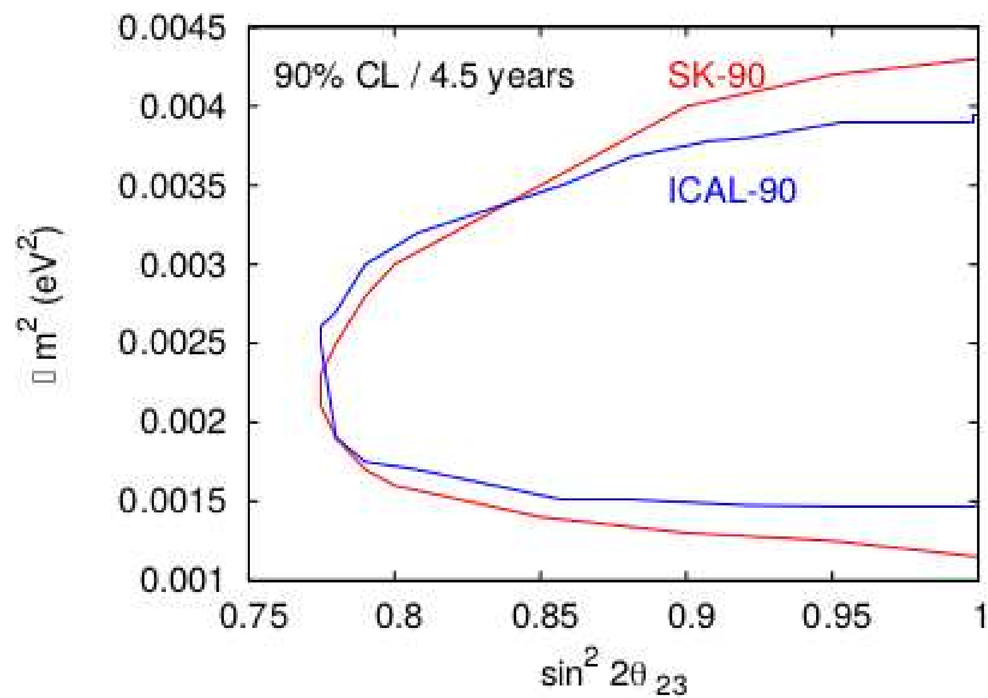
Difference between no. of muon events with matter vs. vacuum oscillations (ΔN_i^{μ}) for μ^- (left) and μ^+ (right). Top,bottom panels for $\Delta_{31} > 0, < 0$.

J. Datta, M. Nizam, Ali Ajmi, S. Uma Sankar, Nucl.Phys.B 961 (2020) 115251, arXiv: 1907.08966 [hep-ph]

Rock muons

- Atmospheric neutrinos can interact with rock surrounding detector. While the hadrons are absorbed, these "rock muons" can reach the detector.
- Significant energy loss of muons in rock; still carry oscillation signature
- Can probe muons from significantly higher energy source neutrinos; complementary to standard analysis, although lower sensitivity





• Plot shows comparison to 4.5 years SuperK rock muon data (*Y. Fukuda et al., Phys. Rev. Lett. 82 (1999) 2644, [arXiv:9812014v2]*).

Kanishka Rawat et al., PoS NUFACT2014 (2015) 127

Cosmic muon charge ratio at high energy

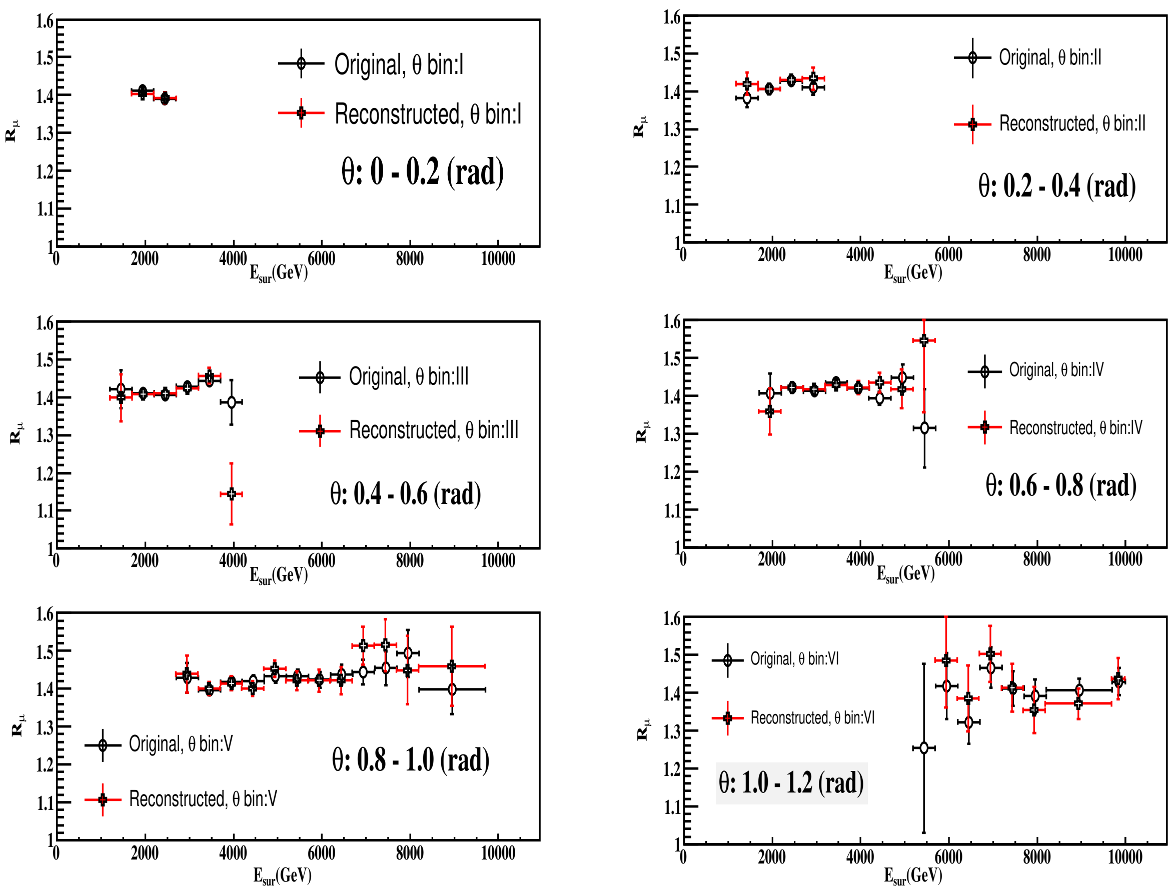
Table 1: DATA TABLE FOR CHARGE RATIO ANALYSIS FROM VERTICAL MUONS.

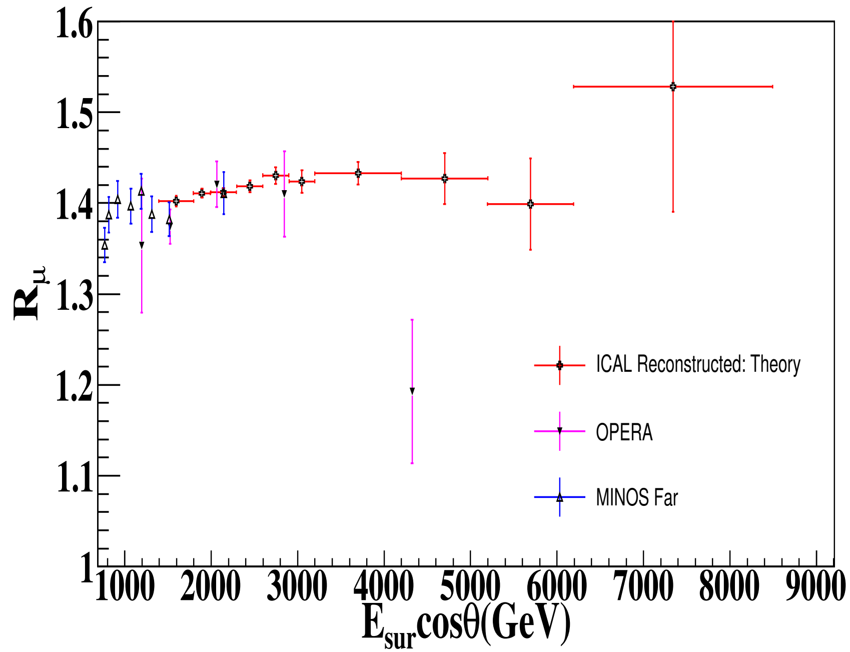
Energy (TeV)	$R_{\mu+/\mu-}$ at ICAL	$R^{\mathrm{Surface}}_{\mu+/\mu-}$ CORSIKA	$R^{\mathrm{Surface}}_{\mu+/\mu-}$ PIKA
1.60-1.65	1.32±0.013	1.31	1.41
1.65-1.70	1.31 ±0.022	1.34	1.41
1.70-1.75	1.32±0.014	1.34	1.41
1.75-1.80	1.32±0.034	1.37	1.41
1.80-1.85	1.41±0.008	1.40	1.41
1.85-1.90	1.36±0.008	1.37	1.41
1.90-1.95	1.41±0.026	1.37	1.41
1.95-2.00	1.32±0.030	1.36	1.41
$\langle R_{\mu+/\mu-} \rangle$	1.35±0.019	1.36	1.41

J. Singh et al., Adv.High Energy Phys. 2019 (2019) 9585234, arXiv: 1709.01064 [physics.ins-det]

High energy cosmic muons, cont'd

- The cosmic muons that reach ICAL from the surface are reconstructed in momentum/direction and the *surface muon distribution* is determined from the inverse process: check for accuracy (compare original surface muon charge ratio R_μ to reconstructed one)
- Check for sensitivity to the charge ratio, compare with current data





Meghha K.K., PhD Thesis, HBNI, 2014