Standard and Non-Standard Oscillation Physics at ICAL-INO

Sanjib Kumar Agarwalla

sanjib@iopb.res.in

Institute of Physics, Bhubaneswar, India

Press Release on INO

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

National Centre of the Government of India for Nuclear Science & Mathematics

HOMI BHABHA ROAD, COLABA, MUMBAI- 400 005

Telephone : 2278-2227
Fax : 2280-4610

05.01.2015

Press Release

The Union Cabinet of the Govt. of India chaired by the Prime Minister, Shri Narendra Modi, has given its approval for the establishment of India-based Neutrino Observatory (INO) at an estimated cost of Rs. 1500 crores.

The INO project is jointly supported by the Department of Atomic Energy and the Department of Science and Technology. Infrastructural support is provided by the Government of Tamil Nadu where the project is located. Tata Institute of Fundamental Research (TIFR), Mumbai is the host institute for INO.

Finally the wait of 15 years is over! But, we have miles to go…

INO/ICAL/PHY/NOTE/2015-01

Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO)

The ICAL Collaboration

arXiv:1505.07380v1 [physics.ins-det] 27 May 2015

Plan of this talk:

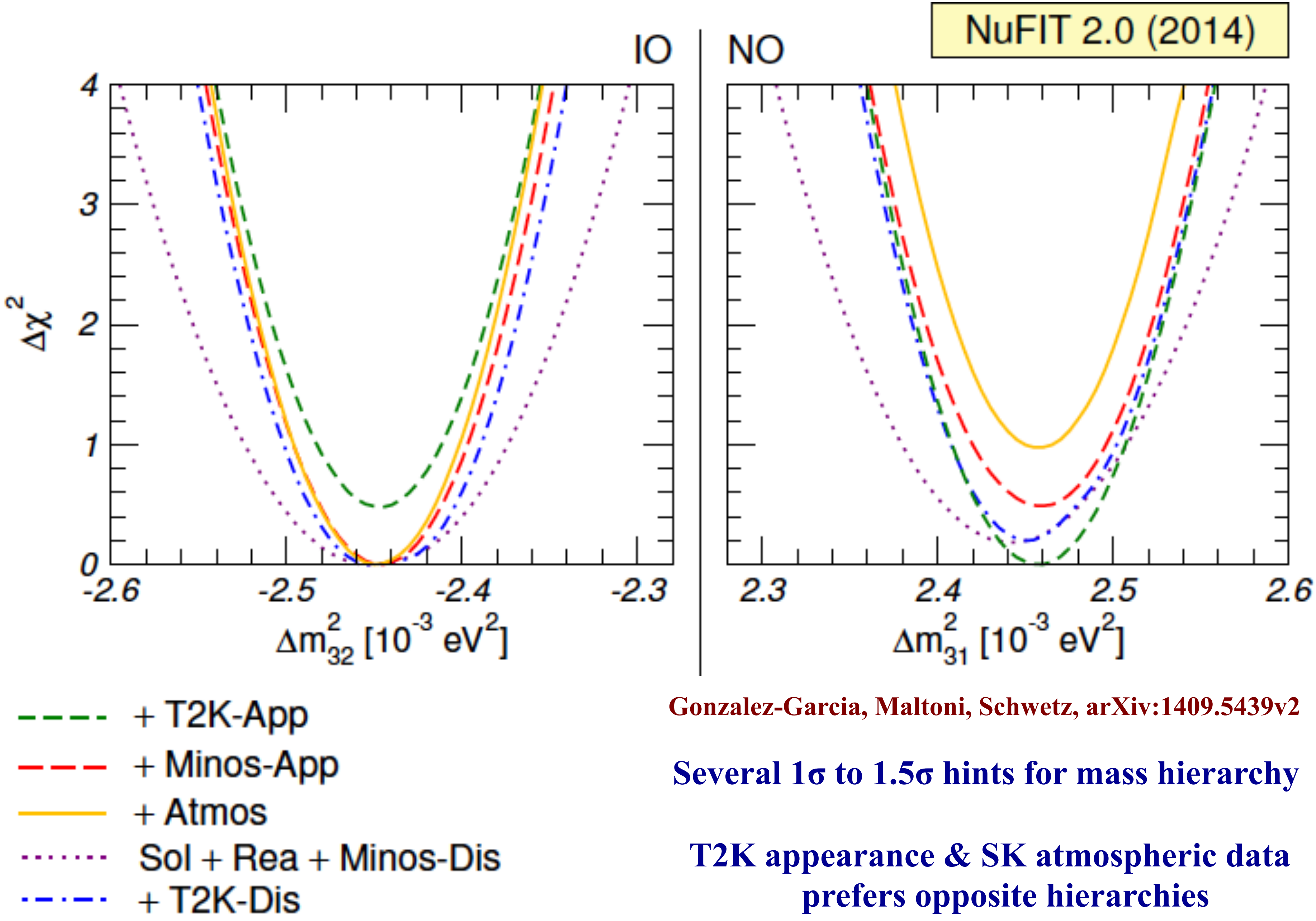
Standard Oscillation Physics:

1) Issue of neutrino mass ordering
2) Precision measurements of oscillation parameters
3) Sensitivity to the octant of 2-3 mixing angle

Non-Standard Oscillation Physics:

1) Active – Sterile Oscillation
2) Non-Standard Neutrino Interactions (NSI's) in propagation

Neutrino Mass Hierarchy from the Global Fit

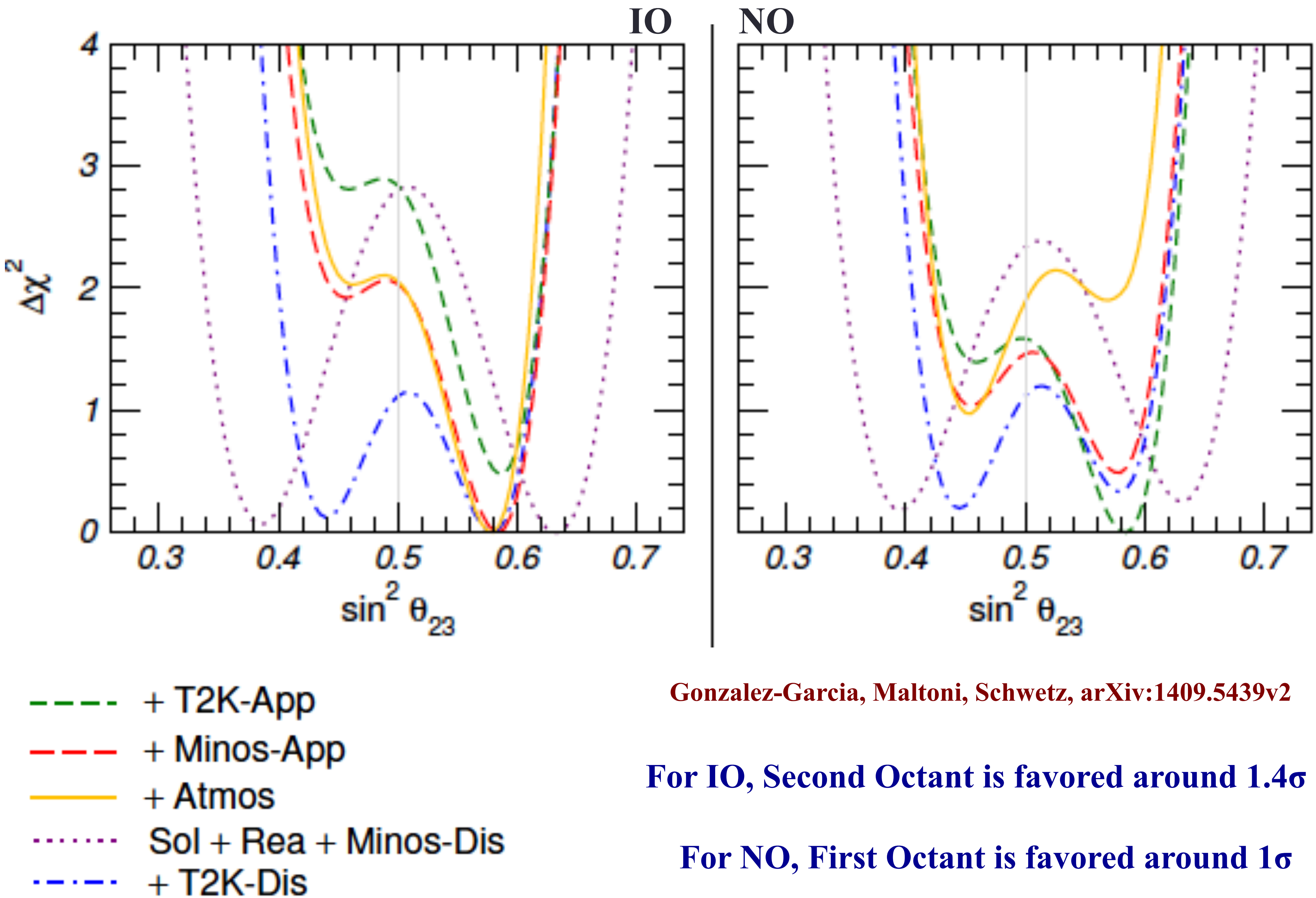


Gonzalez-Garcia, Maltoni, Schwetz, arXiv:1409.5439v2

Several 1σ to 1.5σ hints for mass hierarchy

T2K appearance & SK atmospheric data prefers opposite hierarchies

2-3 Mixing Angle from the Global Fit



Gonzalez-Garcia, Maltoni, Schwetz, arXiv:1409.5439v2

For IO, Second Octant is favored around 1.4σ

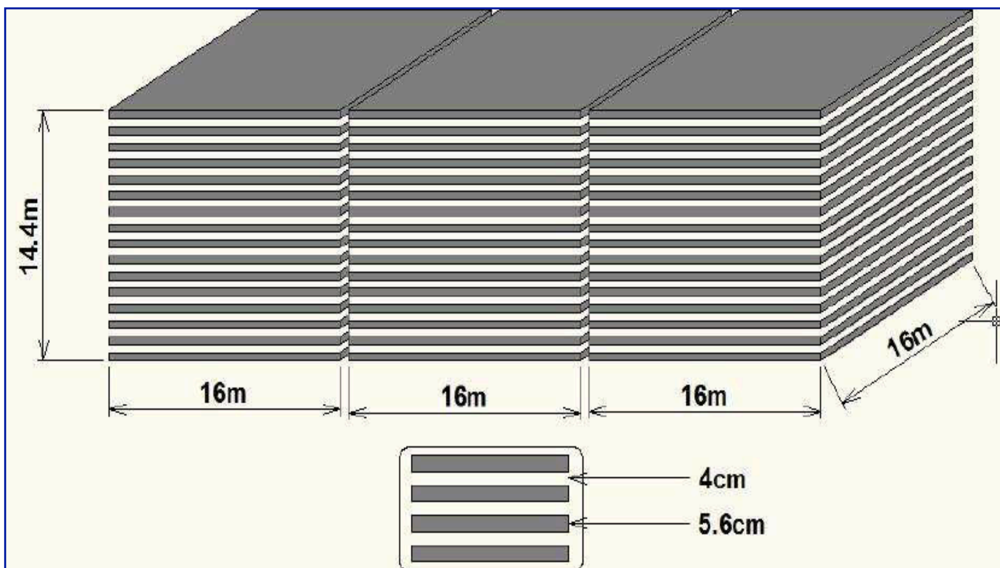
For NO, First Octant is favored around 1σ

Detector Characteristics

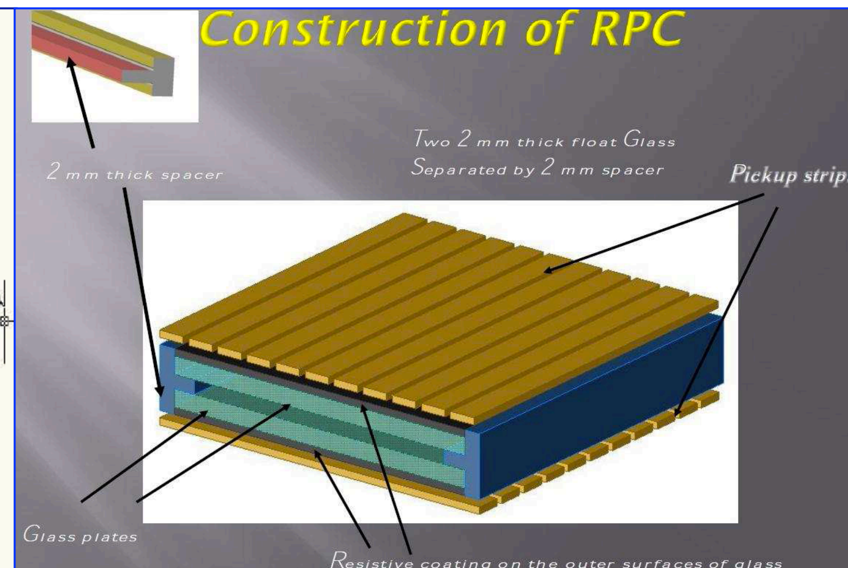
- *Should have large target mass (50 – 100 kt)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*
- *Complementary to the other existing and proposed detectors*

Our choice

Magnetized iron (target mass): ICAL



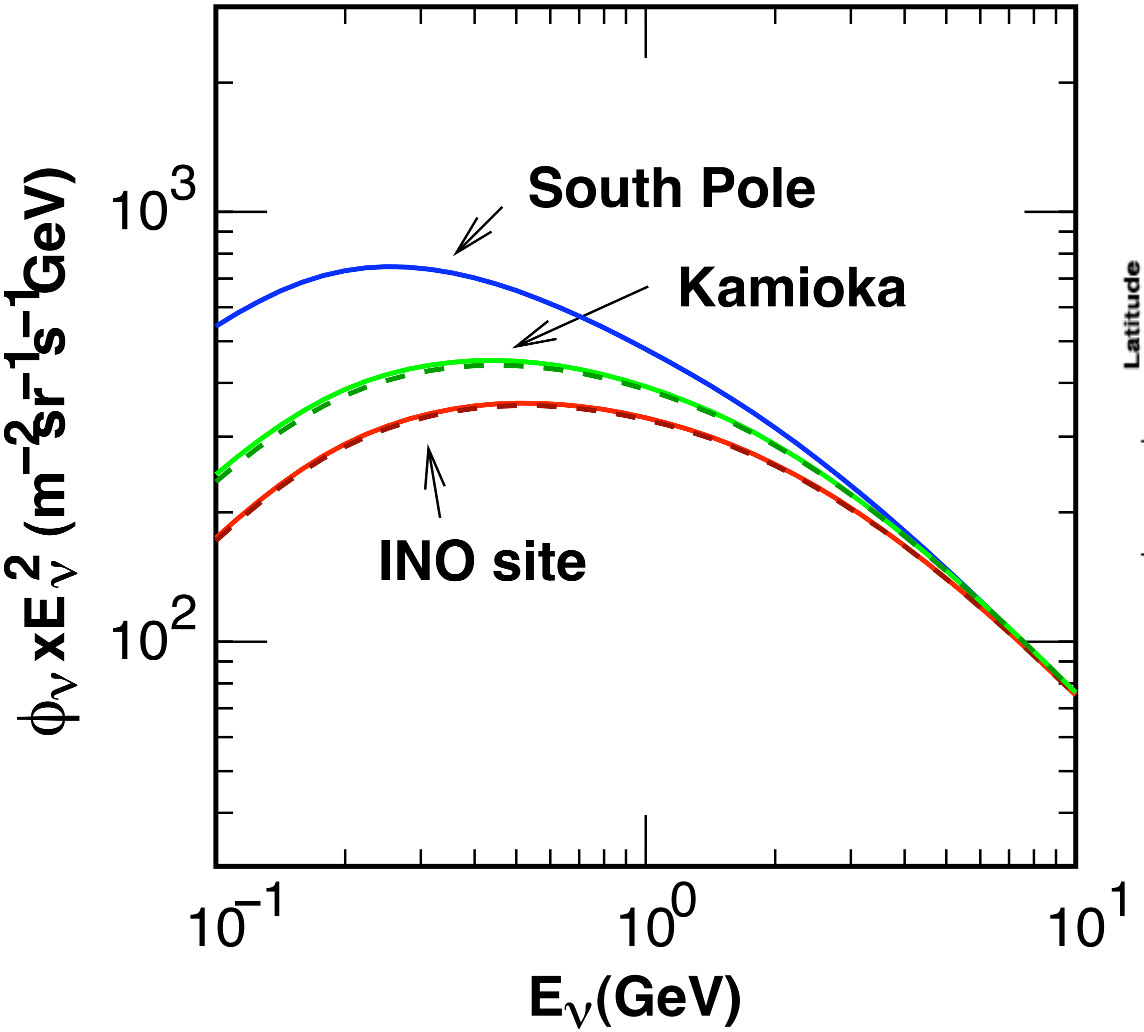
RPC (active detector element)

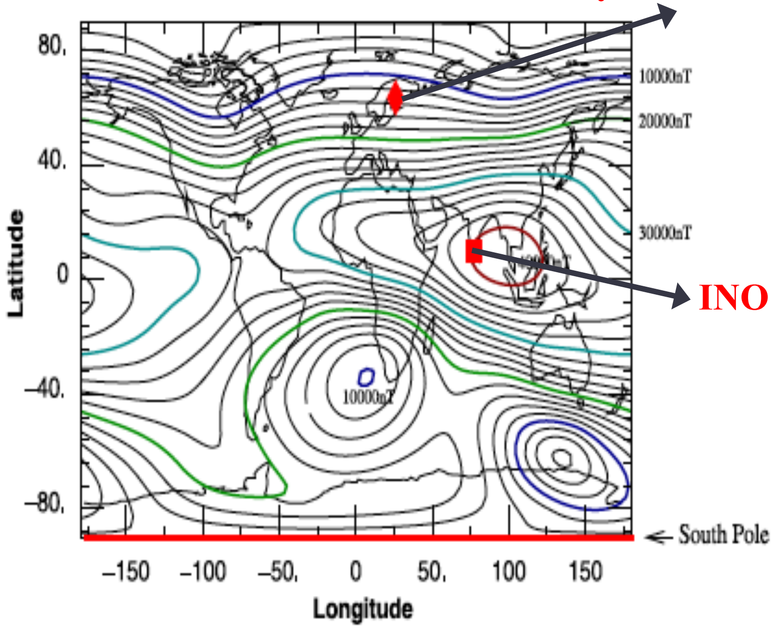


Specifications of the ICAL Detector

No of modules	3
Module dimension	16 m X 16 m X 14.4m
Detector dimension	48.4 m X 16 m X 14.4m
No of layers	150
Iron plate thickness	5.6cm
Gap for RPC trays	4 cm
Magnetic field	1.4 Tesla
RPC unit dimension	195 cm x 184 cm x 2.4 cm
Readout strip width	3 cm
No. of RPCs/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no of RPC units	28800
No of Electronic channels	3.7×10^6

Atmospheric Neutrino Flux





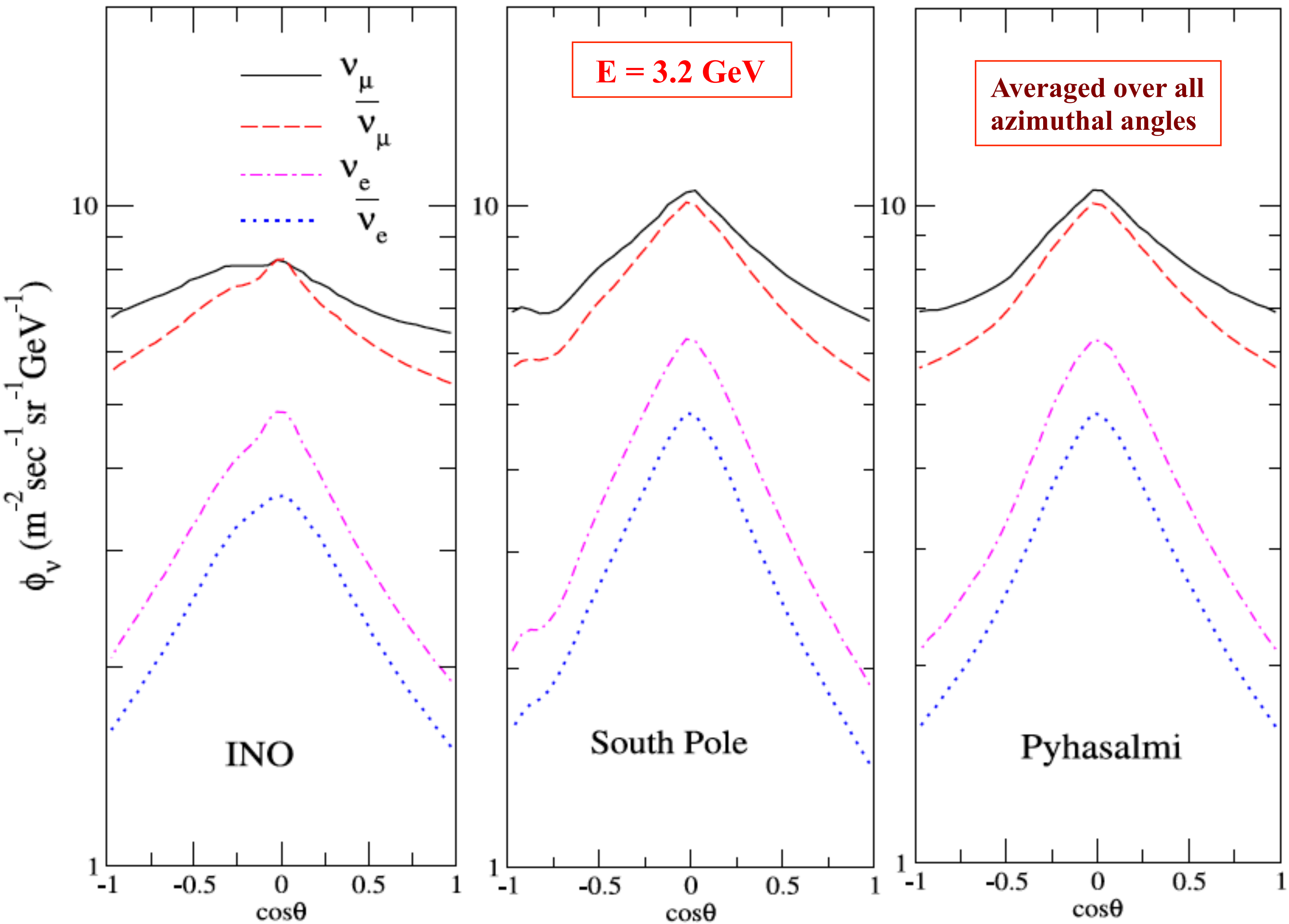
Horizontal component of the geomagnetic field

Magnitude at the Earth's surface ranges from 25 to 65 microtesla

Averaged over all directions
Summed over all flavors of neutrino and anti-neutrino

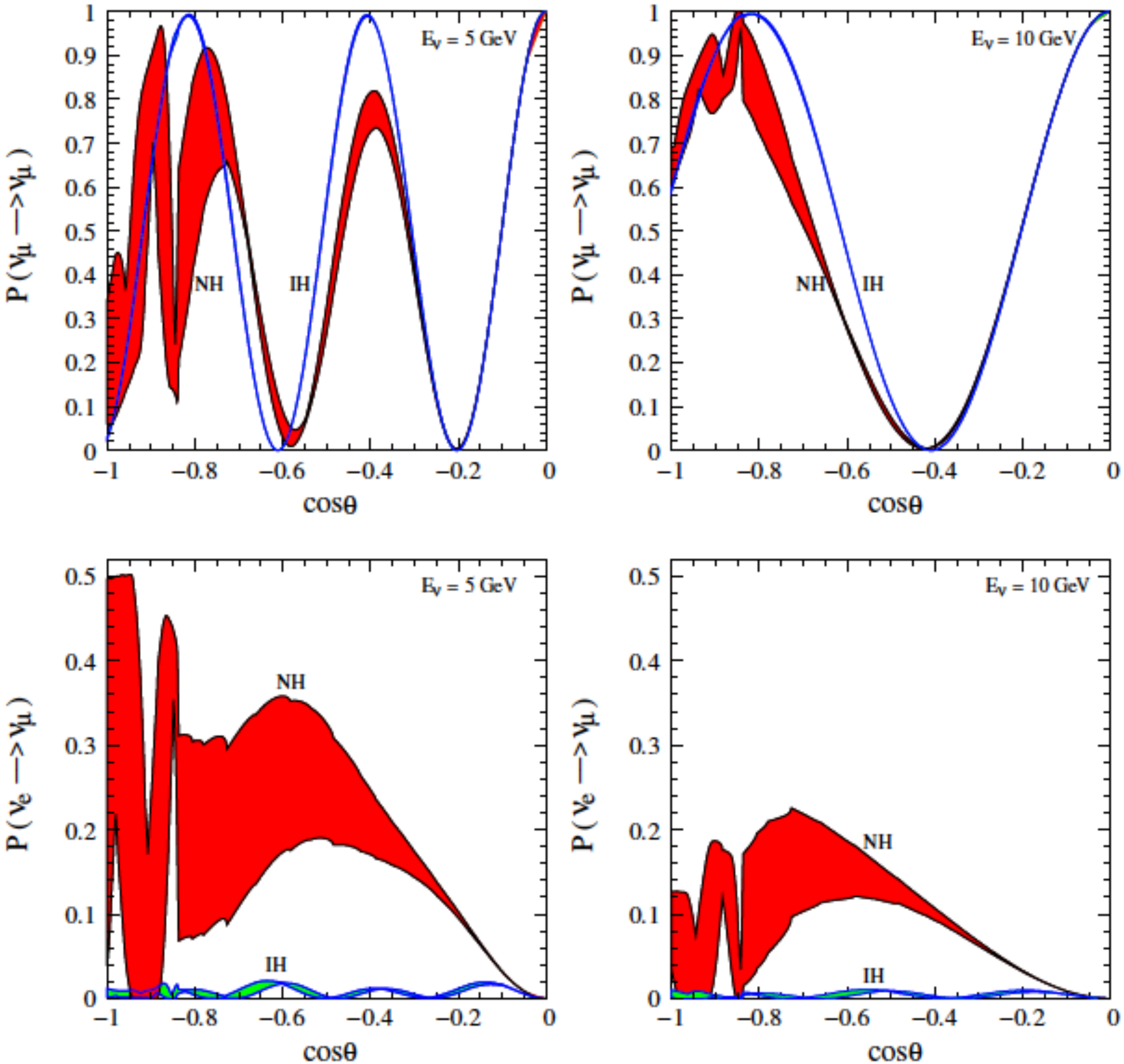
Athar, Honda, Kajita, Kasahara, Midorikawa, arXiv:1210.5154 [hep-ph]

Atmospheric Neutrino Flux



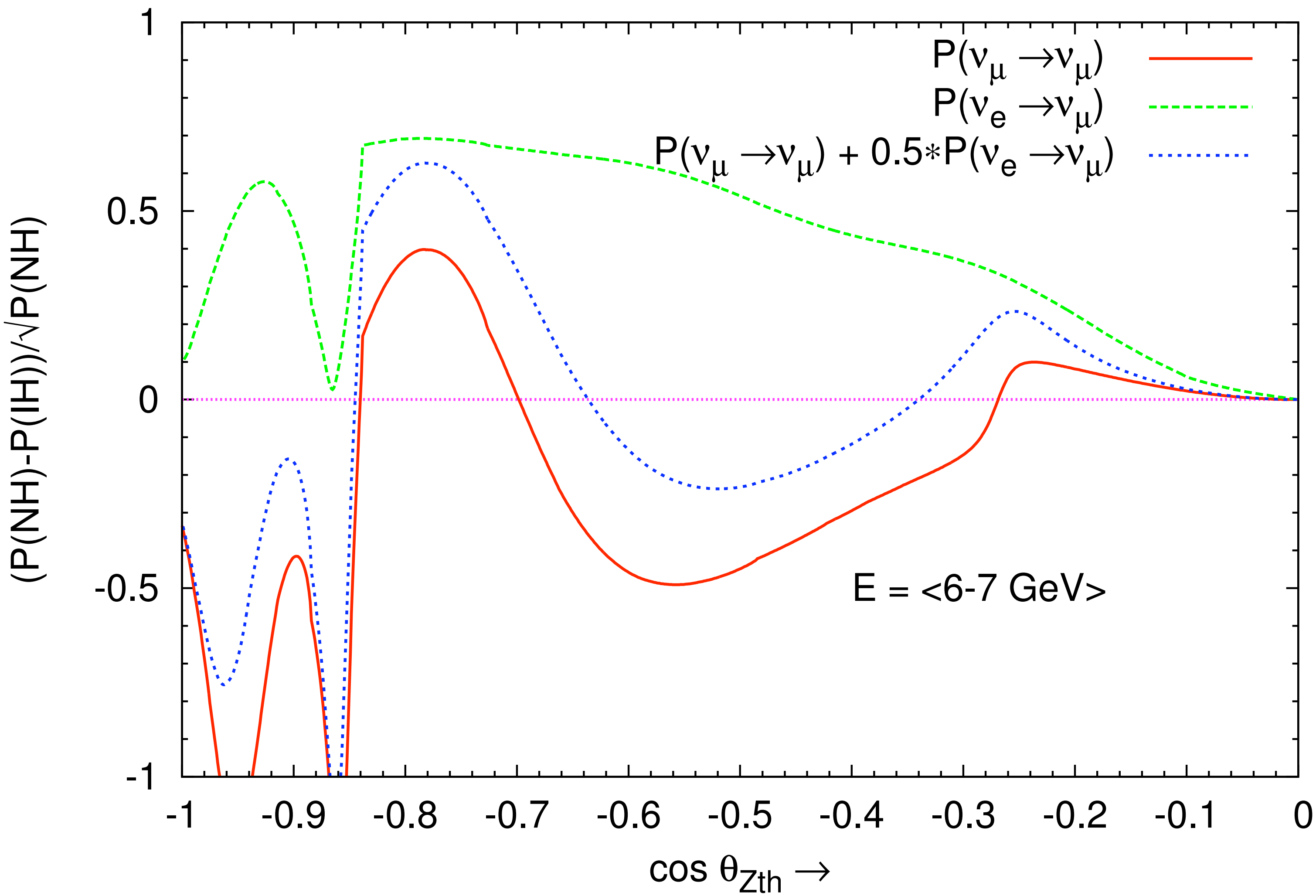
Athar, Honda, Kajita, Kasahara, Midorikawa, arXiv:1210.5154 [hep-ph]

Matter effect in Atmospheric Experiments



Bands:
vary the matter
density by ±10%

Agarwalla, Li,
Mena, Palomares-Ruiz,
arXiv:1212.2238v1 [hep-ph]



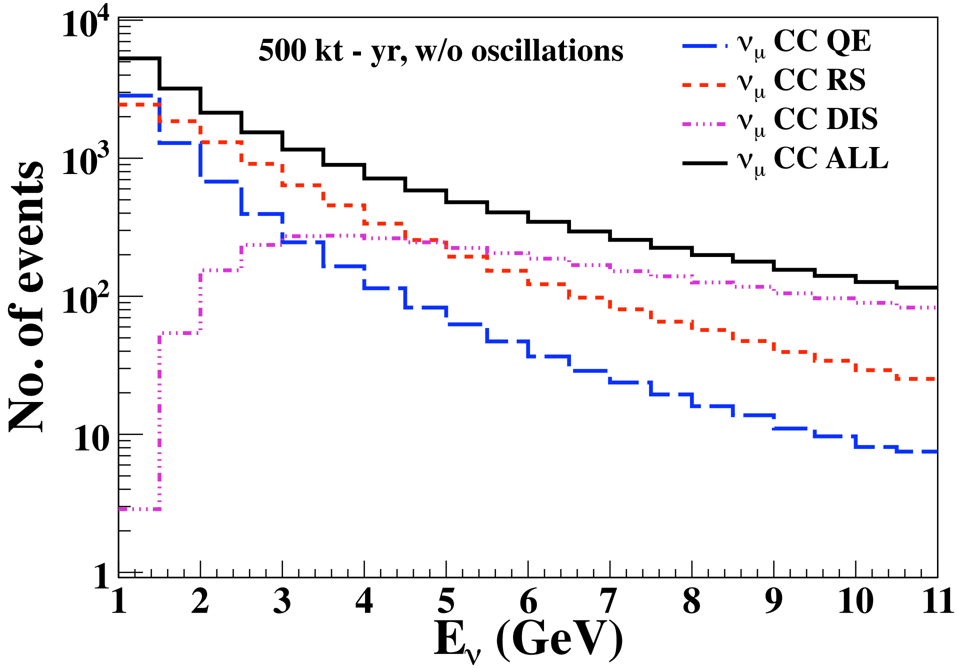
Presence of different flavors dilutes the MH effect in oscillation

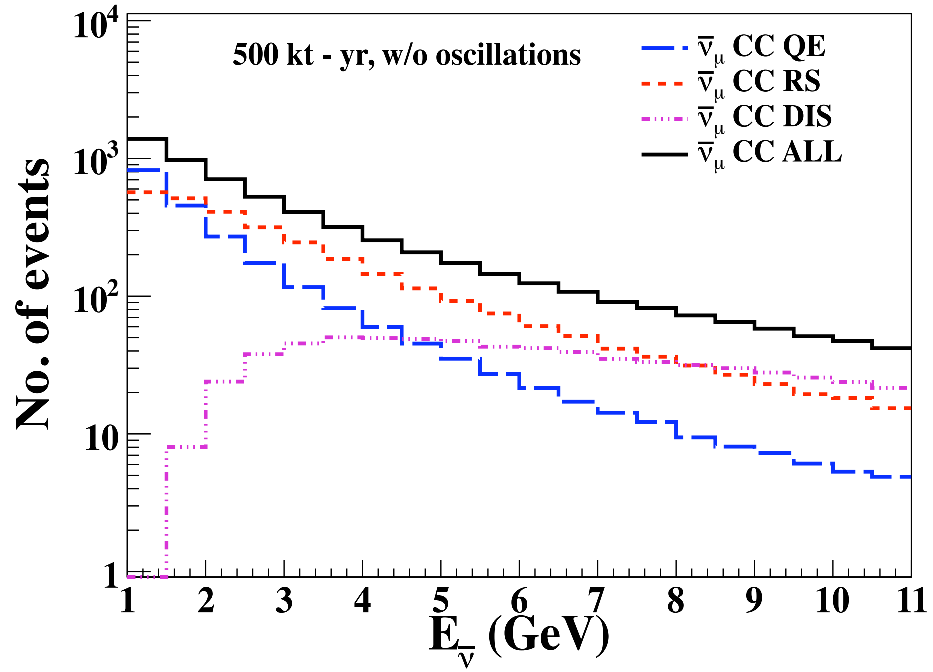
Overview of Simulation Framework

NUANCE work in progress to adopt GENIE	**Neutrino Event Generation** $\nu_\ell + N \to \ell + X$. Generates particles that result from a random interaction of a neutrino with matter using theoretical models for both neutrino fluxes and cross-sections. ⇓	**Output:** (i) Reaction Channel (ii) Vertex and time information (iii) Energy and momentum of all final state particles
GEANT	**Event Simulation** $\ell + X$ through simulated ICAL Simulates propagation of particles through the ICAL detector with RPCs and magnetic field. ⇓	**Output:** (i) x, y, z, t of the particles as they propagate through detector (ii) Energy deposited (iii) Momentum information
DIGITISATION	**Event Digitisation** (X, Y, Z, T) of final states on including noise and detector efficieny Add detector efficiency and noise to the hits. ⇓	**Output:** (i) Digitised output of the previous stage
ANALYSIS	**Event Reconstruction** $(E, \vec{p})$ of ℓ, X (total hadrons) Fit the muon tracks using Kalman filter techniques to reconstruct muon energy and momentum; use hits in hadron shower to reconstruct hadron information.	**Output:** (i) Energy and momentum of muons and hadrons, for use in physics analyses.

Simulation work is under progress in full swing!

Events in Various Channels



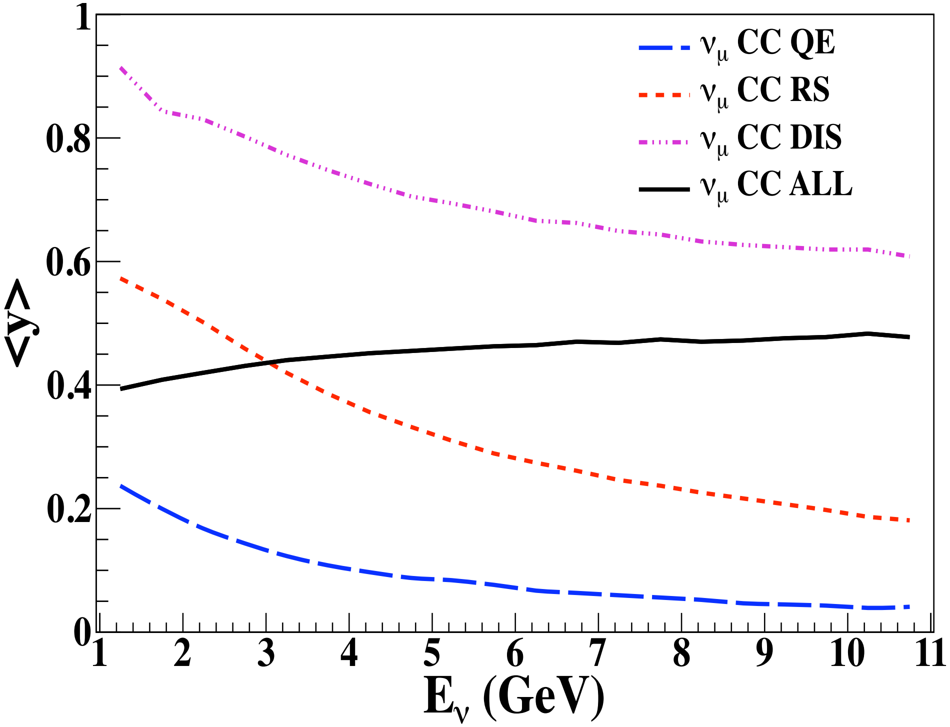


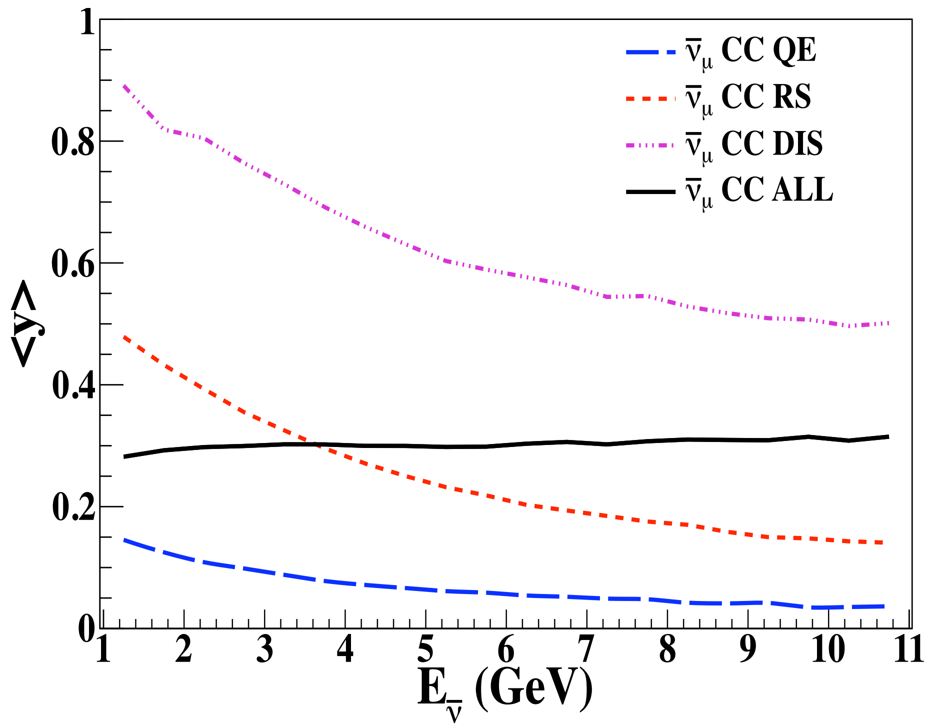
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

Relative contributions of three cross-section processes to the total events in the absence of oscillation and without detector efficiency and resolutions

Average Inelasticities in Various Channels

$$y \equiv (E_\nu - E_\mu)/E_\nu = E'_{\rm had}/E_\nu$$



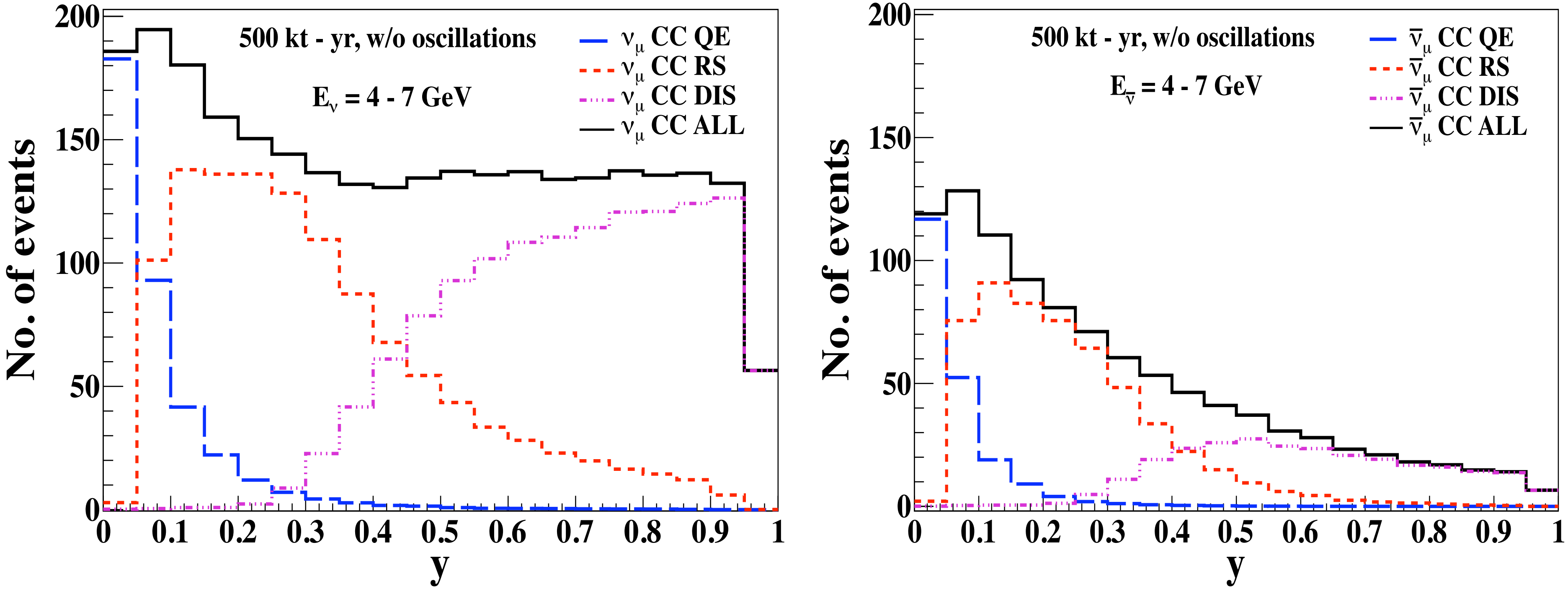


Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

Average Inelasticity in the deep-inelastic events is significant

Crucial for mass hierarchy identification

Distribution of Inelasticities in Events

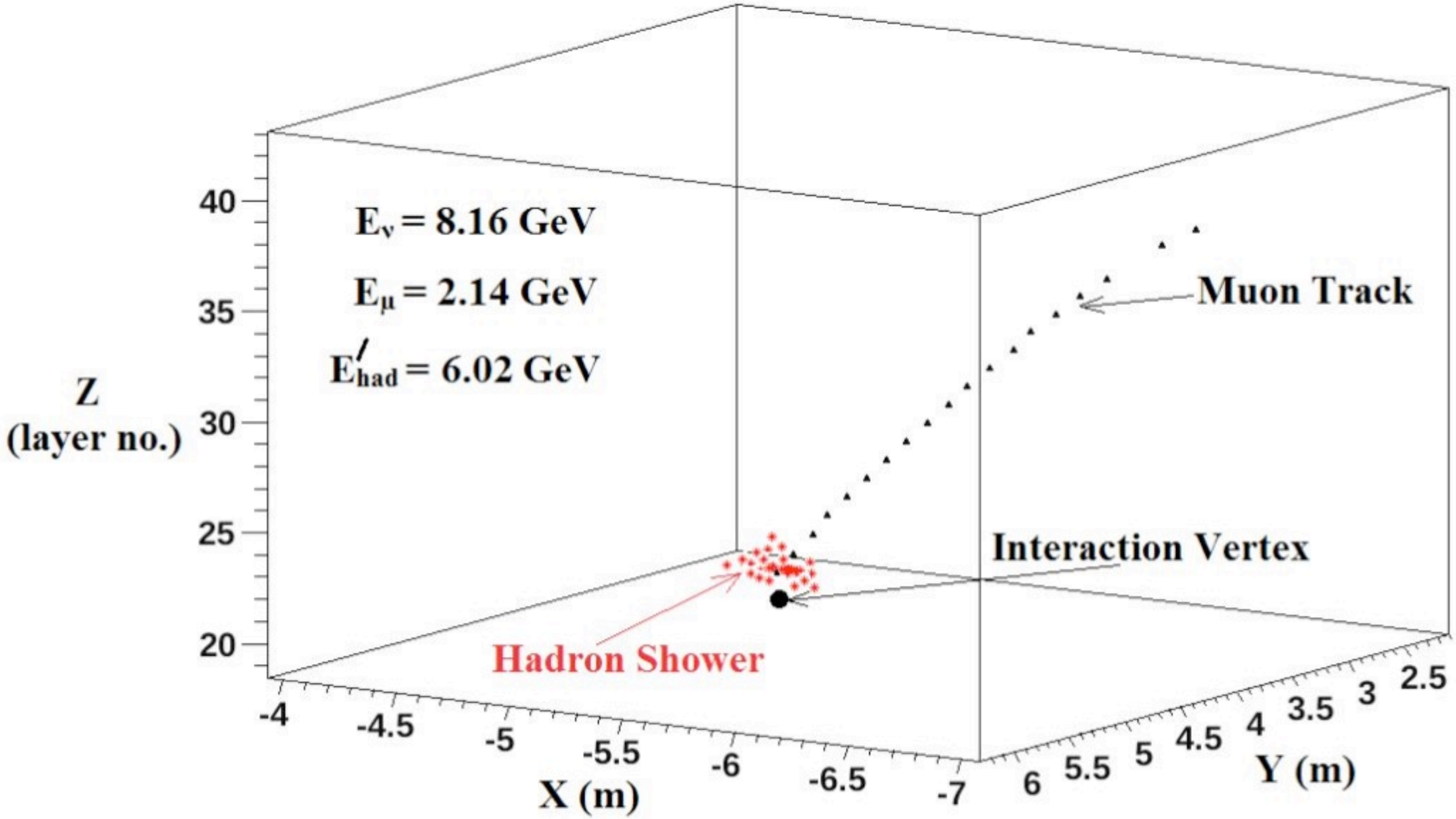


Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Inelasticities in individual events have a wide distribution

Important to measure inelasticity in individual events

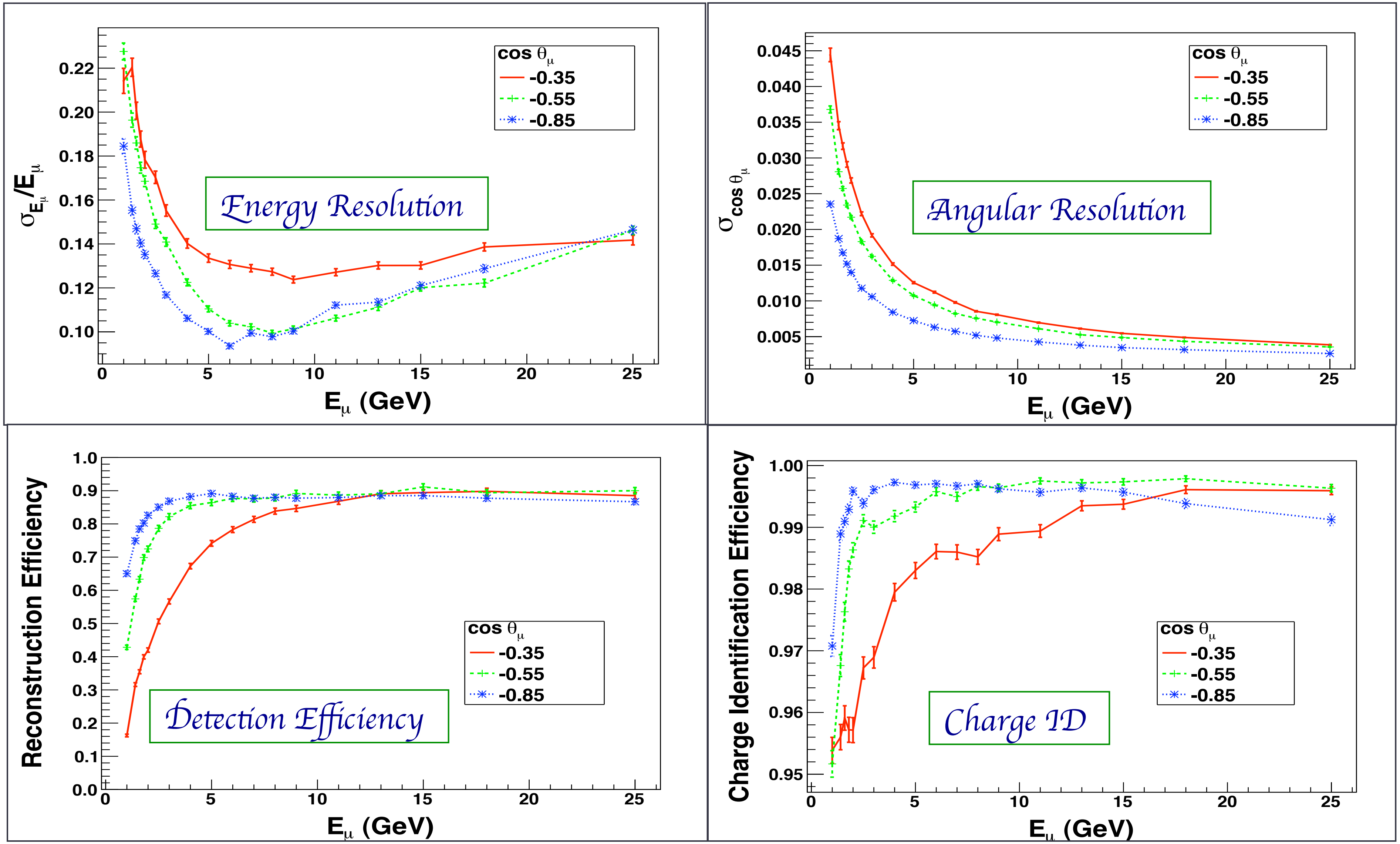
Event Display Inside the ICAL Detector



Using GEANT4 simulation

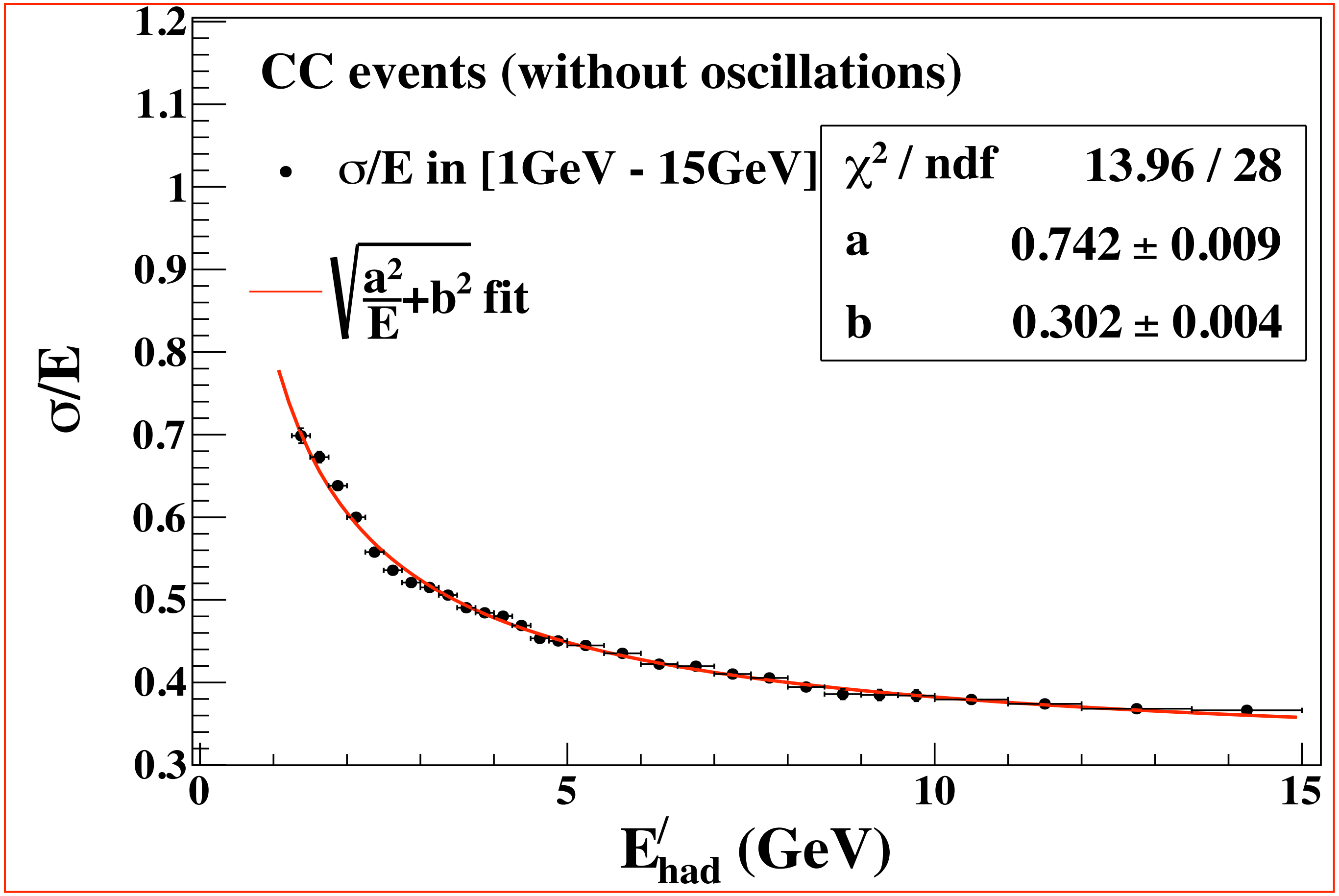
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

Muon Efficiencies and Resolutions



Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore etal., arXiv:1405.7243 [physics.ins-det]

Hadron Energy Response of ICAL



$E^{/}_{h} = E_{\nu} - E_{\mu}$ **(from hadron hit calibration)**

Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV

Moon Moon Devi, Anushree Ghosh, Daljeet Kaur, Lakshmi S. Mohan etal., JINST 8 (2013) P11003

The χ^2 Analysis

We define the Poissonian χ^2_- for μ^- events as :

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'_{\rm had}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos\theta_\mu}} \left[2(N_{ijk}^{\rm theory} - N_{ijk}^{\rm data}) - 2N_{ijk}^{\rm data} \ln\left(\frac{N_{ijk}^{\rm theory}}{N_{ijk}^{\rm data}}\right)\right] + \sum_{l=1}^{5} \xi_l^2 \,,$$

where

$$N_{ijk}^{\rm theory} = N_{ijk}^0 \left(1 + \sum_{l=1}^{5} \pi_{ijk}^l \xi_l\right) .$$

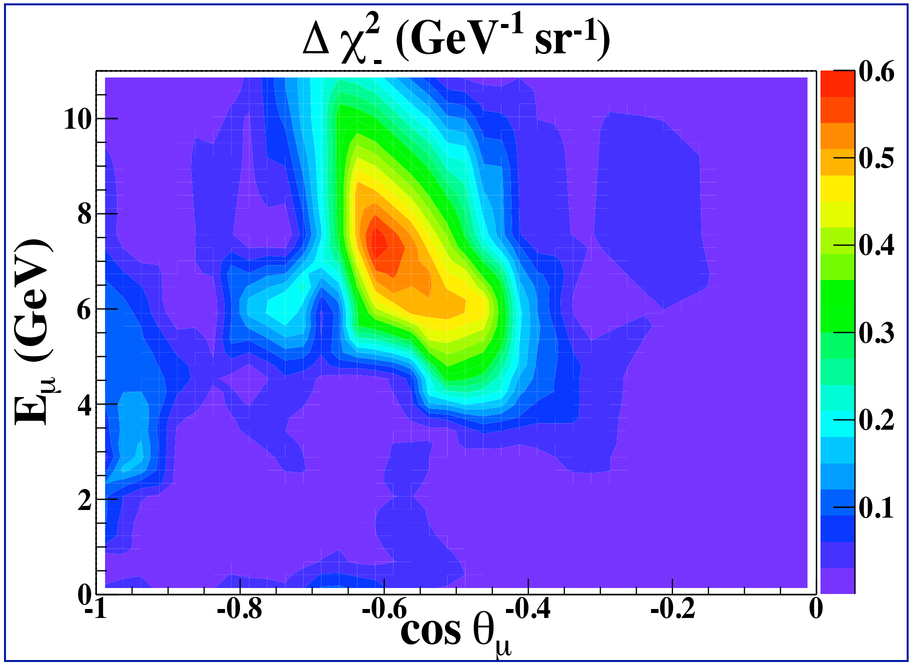
Observable	Range	Bin width	Total bins	
E_μ (GeV)	$[1, 4)$	0.5	6	10
	$[4, 7)$	1	3	
	$[7, 11)$	4	1	
$\cos\theta_\mu$	$[-1.0, -0.4)$	0.05	12	21
	$[-0.4, 0.0)$	0.1	4	
	$[0.0, 1.0]$	0.2	5	
$E'_{\rm had}$ (GeV)	$[0, 2)$	1	2	4
	$[2, 4)$	2	1	
	$[4, 15)$	11	1	

1) Overall 5% systematic uncertainty
2) Overall flux normalization: 20%
3) Overall cross-section normalization: 10%

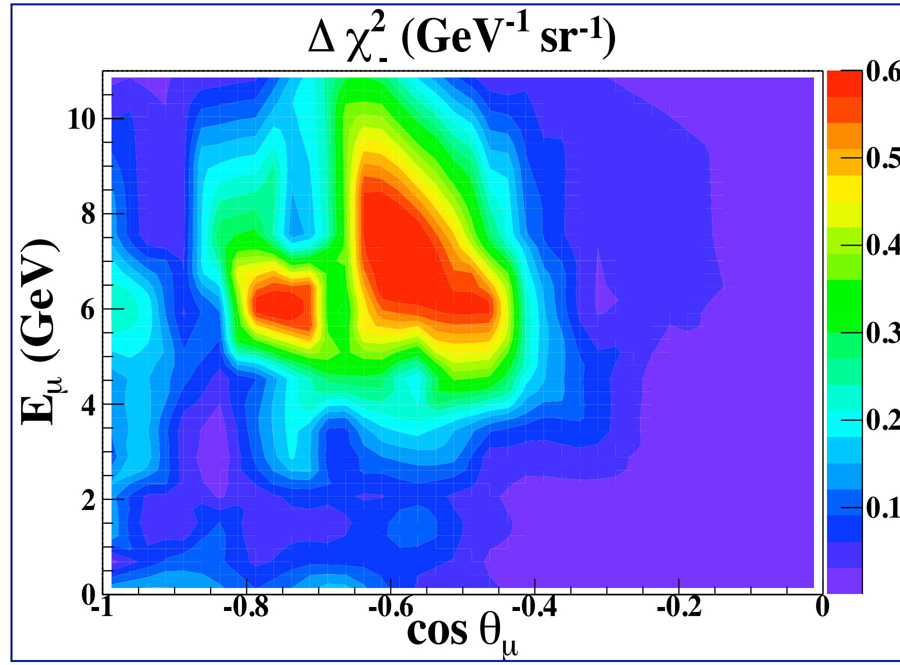
4) 5% uncertainty on the zenith angle dependence of the fluxes
5) Energy dependent tilt factor:
$\Phi_\delta(E) = \Phi_0(E)\, [E/E_0]^\delta \approx \Phi_0(E)\, [1+\delta \ln E/E_0]$
where $E_0 = 2$ GeV and
δ is the 1σ systematic error of 5%

Neutrino Mass Hierarchy Discrimination

Distribution of $\Delta\chi^2$ [χ^2 (IH) - χ^2 (NH)] for mass hierarchy discrimination considering μ^- events



Hadron energy information not used



Hadron energy information used

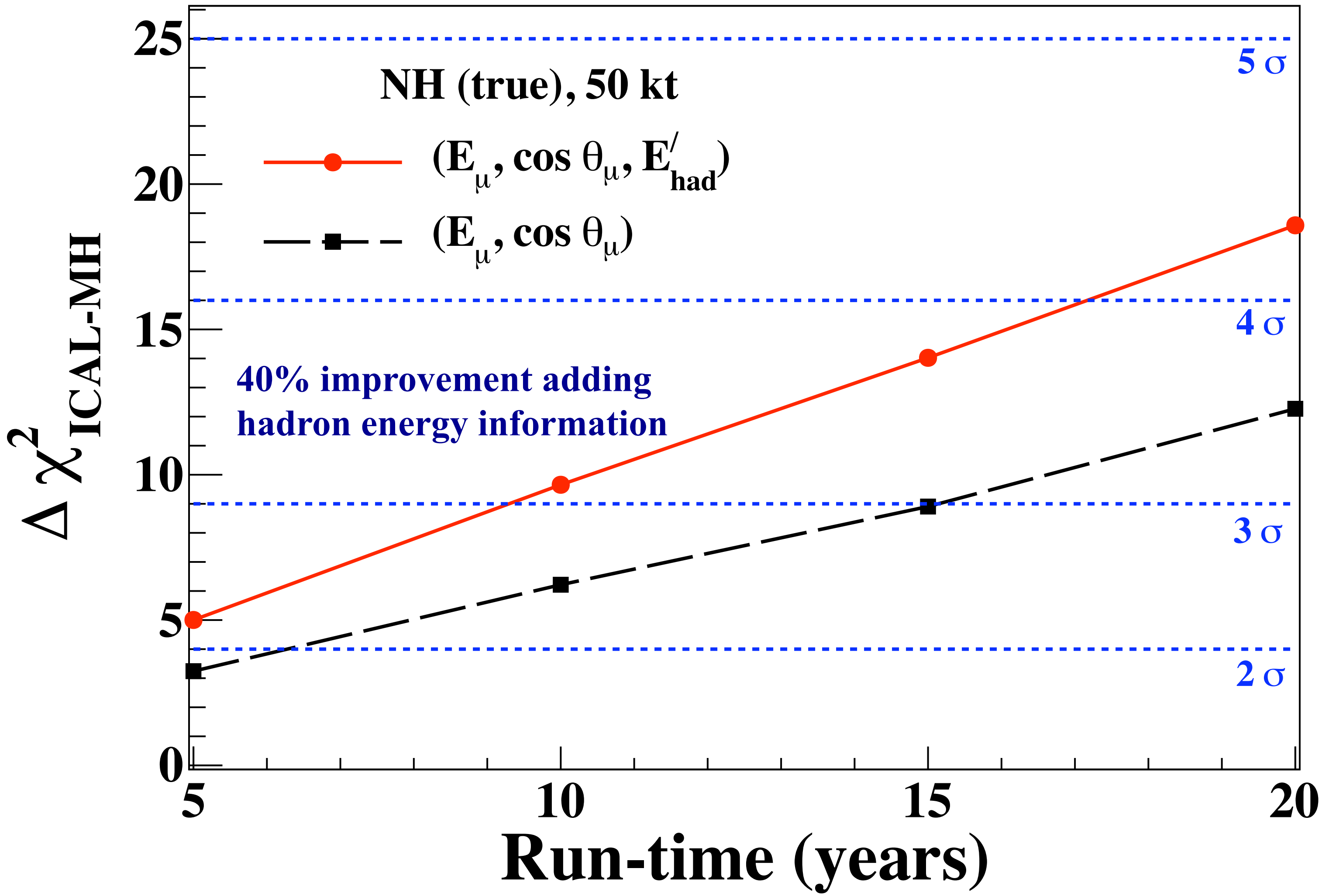
- Further subdivide the events into four hadron energy bins
- Hadron energy carries crucial information
- Correlation between hadron energy and muon momentum is very important

Contribution of Various Hadron Bins

E'_{had} (GeV)	events	$\Delta\chi^2$	$\Delta\chi^2$/events
0–1	3995	5.8	0.0014
1–2	1152	1.9	0.0017
2–4	742	1.7	0.0023
4-15	677	1.2	0.0018
0–15 (with E'_{had} information)	6566	10.7	0.0016
without E'_{had} information	6775	6.3	0.0009

- Enhancement in the sensitivity is not simply due to the events with low hadron energy
- The normalized $\Delta\chi^2$ per event is slightly higher for larger hadron energy bins

Identifying Neutrino Mass Hierarchy with ICAL

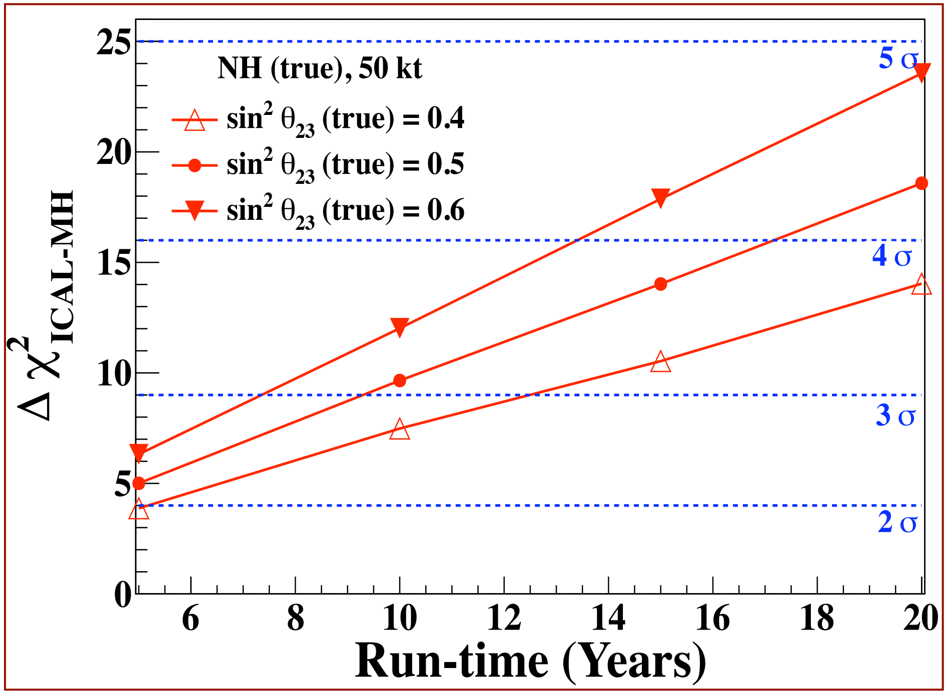


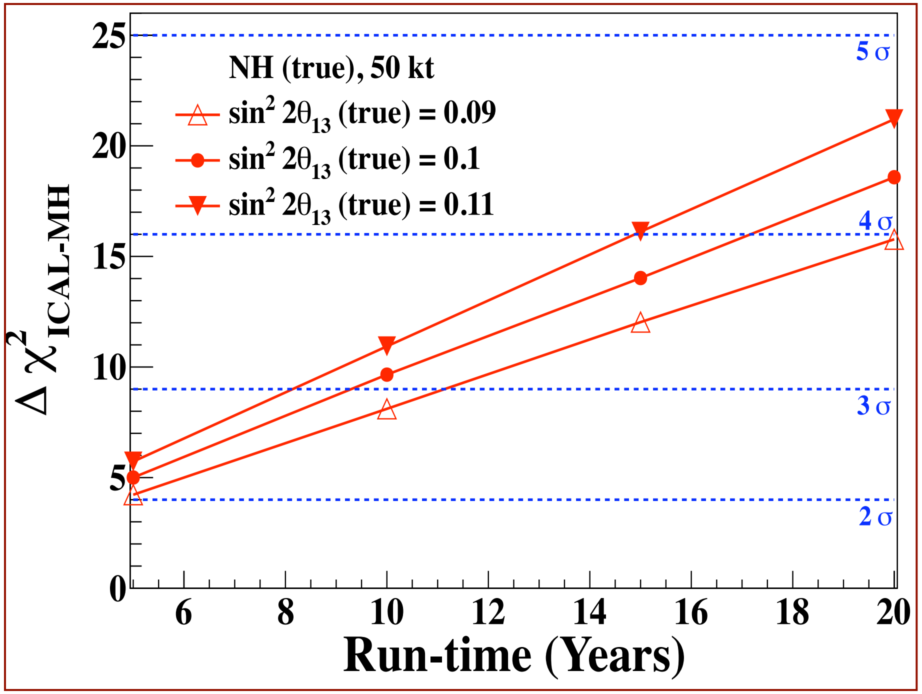
Median Sensitivity

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

50 kt ICAL can rule out the wrong hierarchy with $\Delta\chi^2 \approx 9.5$ in 10 years

Impact of θ_{23} and θ_{13} on Mass Hierarchy

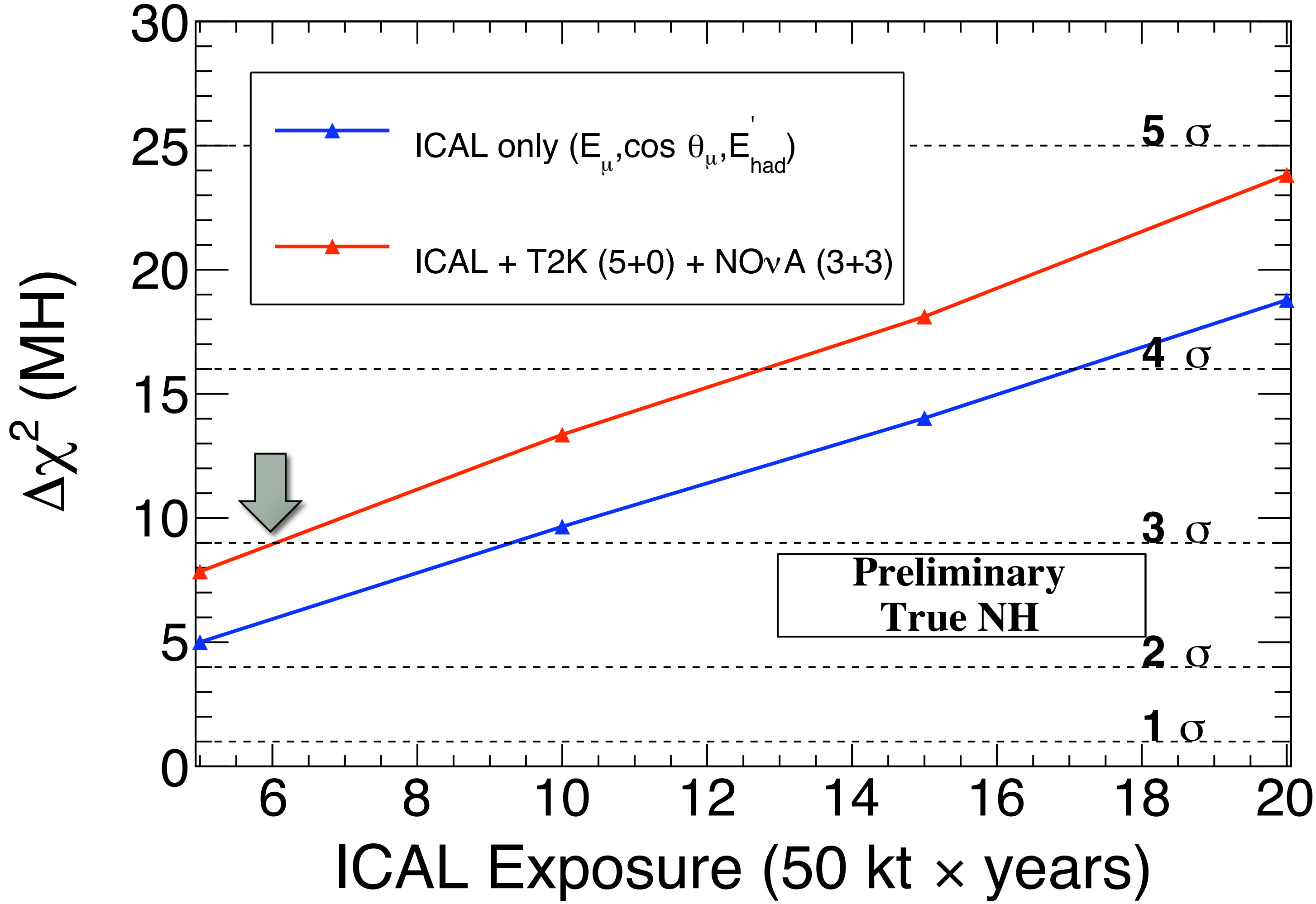




Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

50 kt ICAL can rule out the wrong hierarchy with median $\Delta\chi^2 \approx 7$ to 12 depending on the true values of θ_{23} and θ_{13} in 10 years

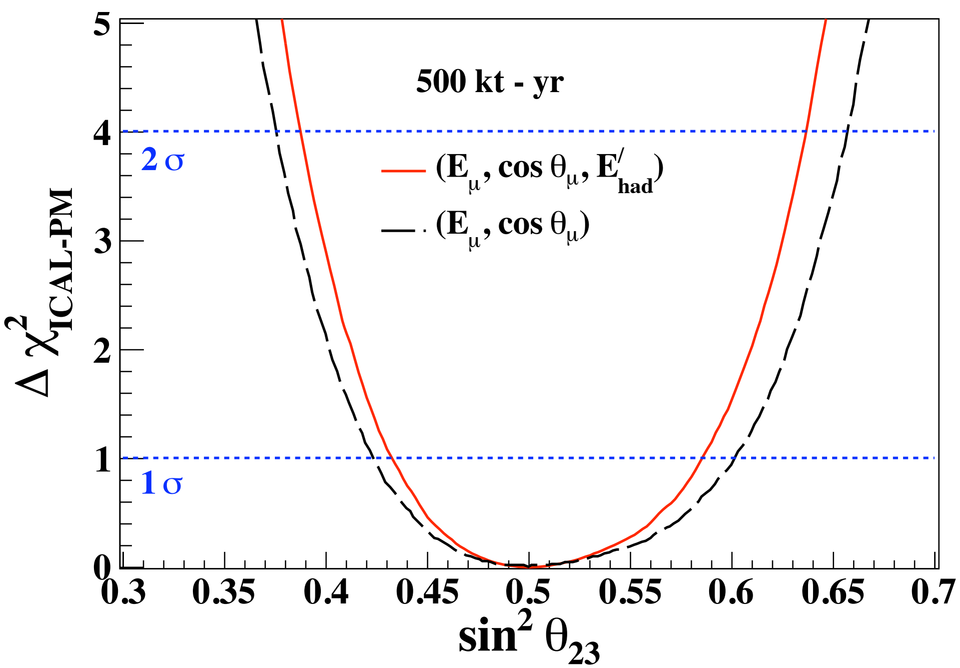
MH Discovery with ICAL+T2K+NOvA



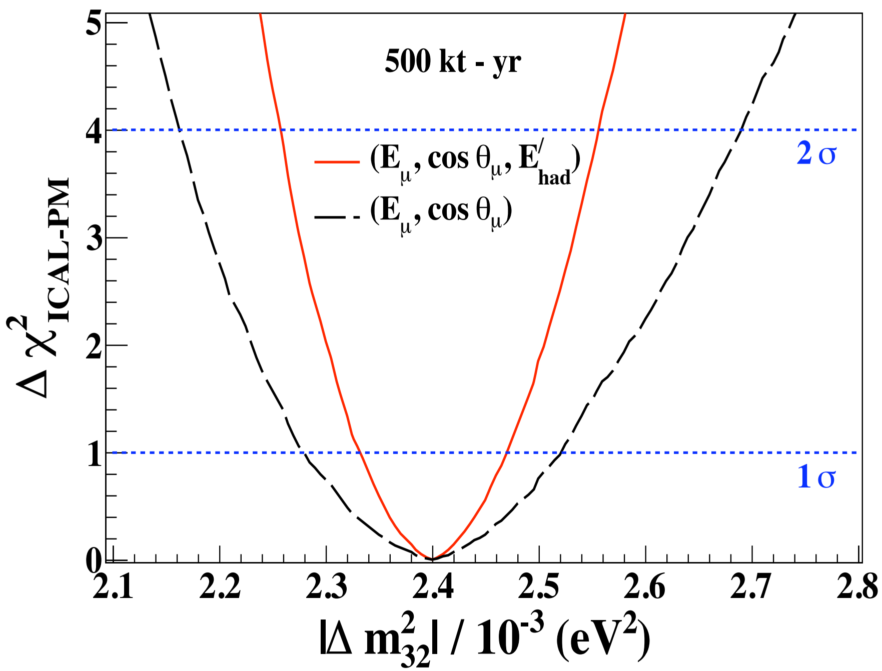
Thakore, Agarwalla, work in progress

3σ median sensitivity can be achieved in 6 years

Precision of Atmospheric Oscillation Parameters



Relative 1σ precision: 12%

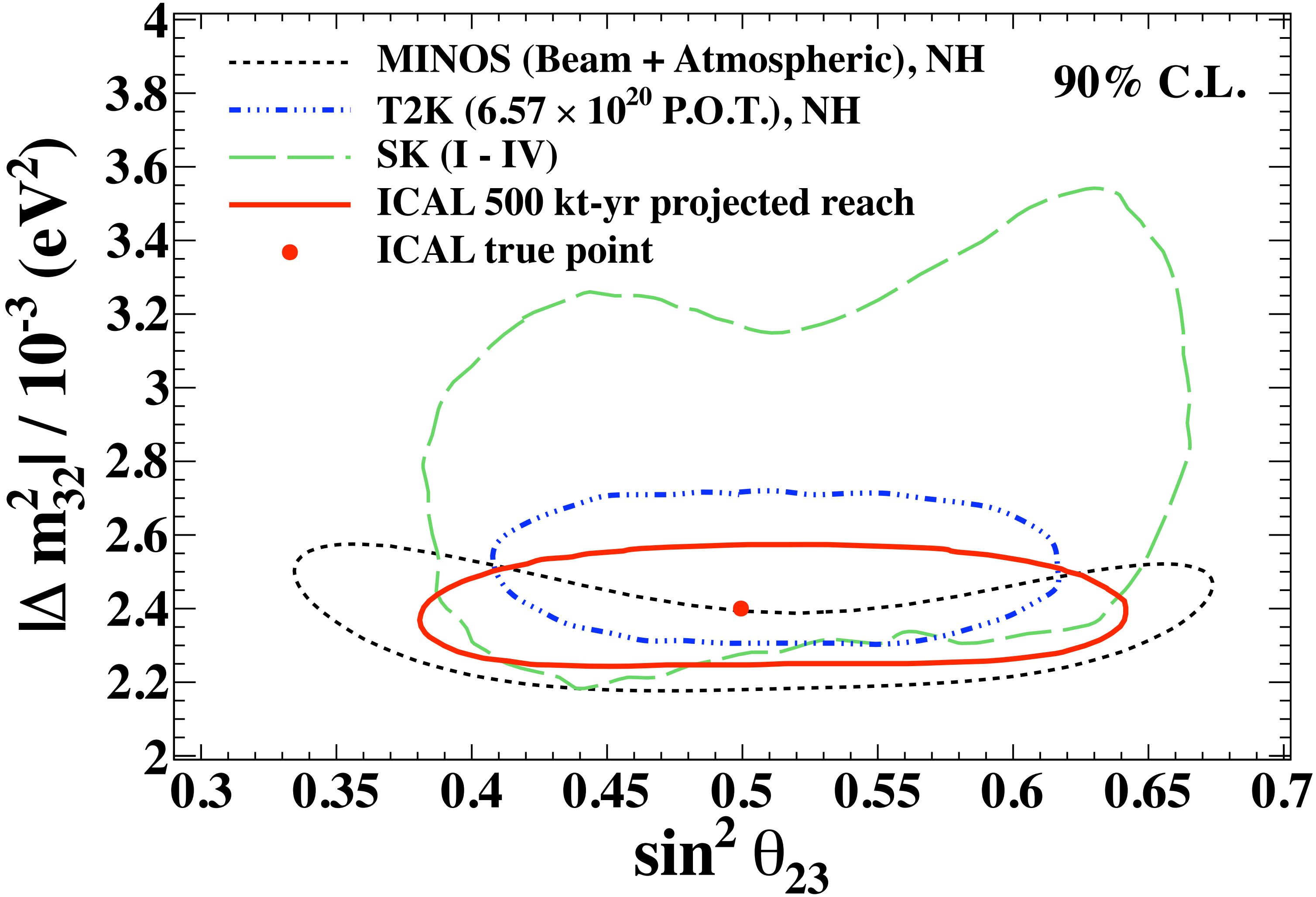


Relative 1σ precision: 2.9%

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

Significant improvement in the precision measurement of atmospheric mass splitting by adding hadron energy information with muon momentum

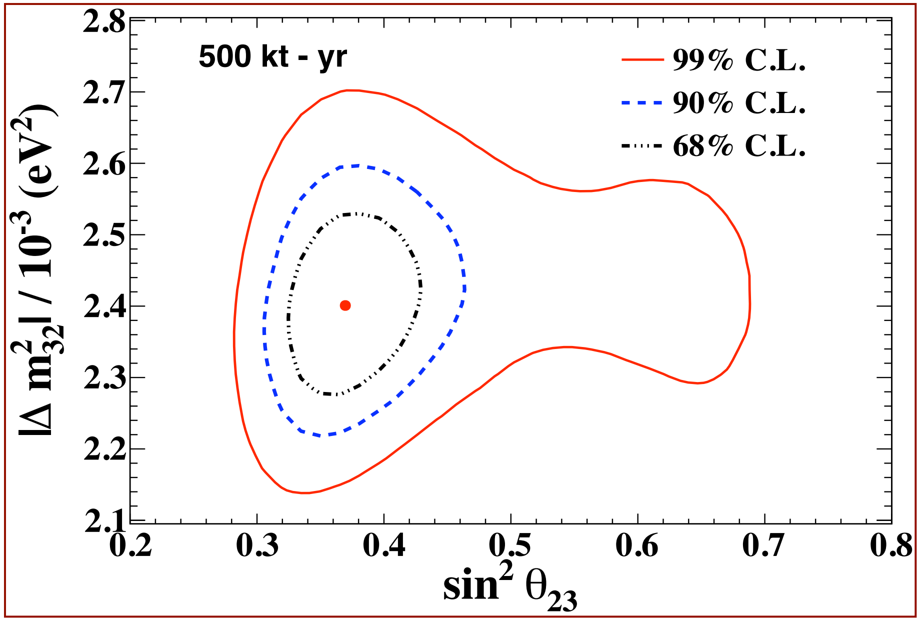
Precision Measurement of Atmospheric Parameters

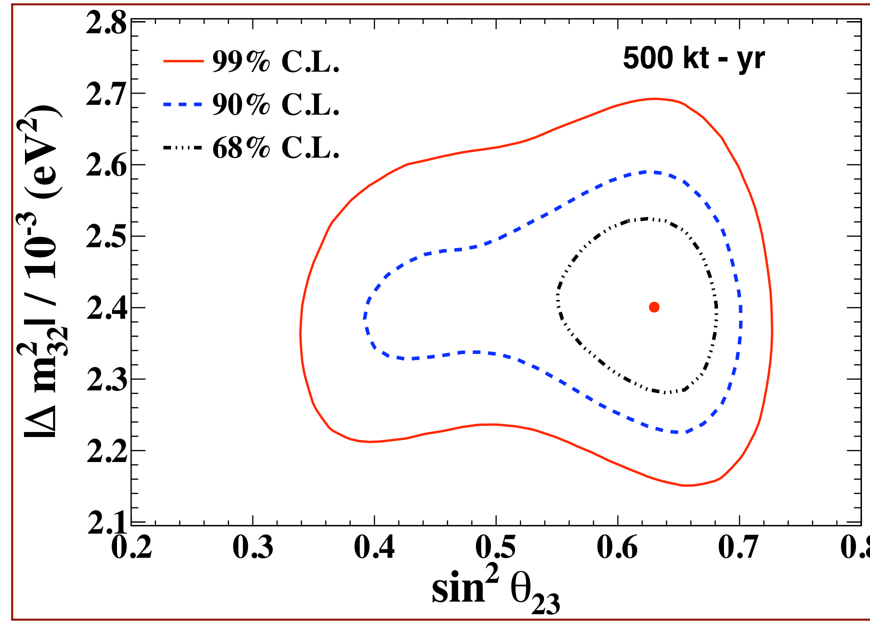


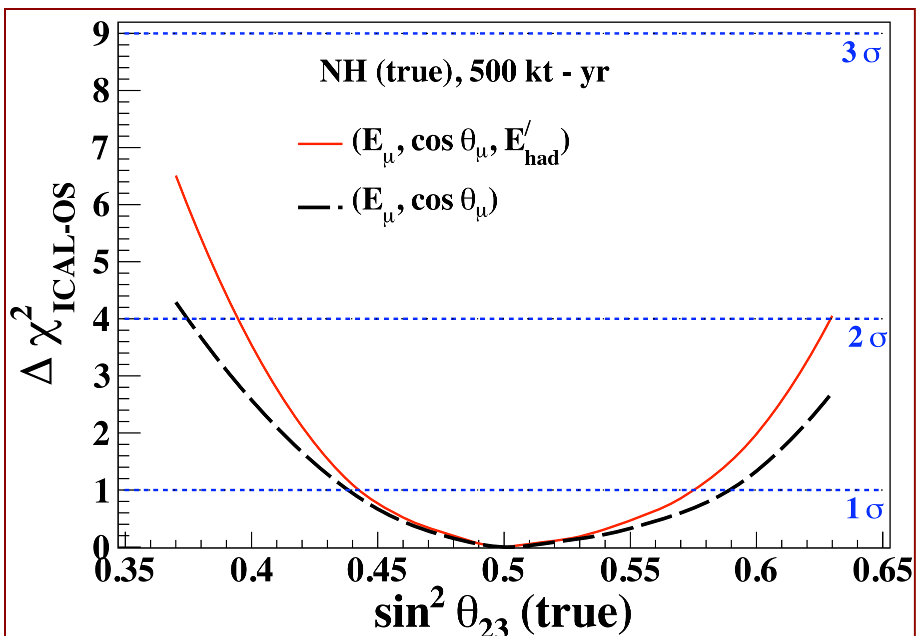
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

ICAL's expected precision on atmospheric mass splitting is better than SK

Octant of θ_{23} with ICAL-INO





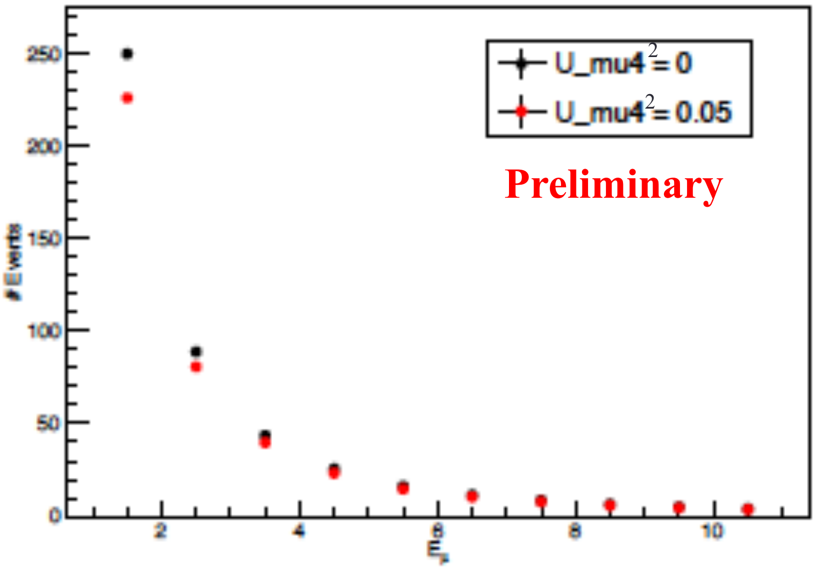


Median 2σ discovery of θ_{23} octant is possible if θ_{23} is sufficiently away from maximal value

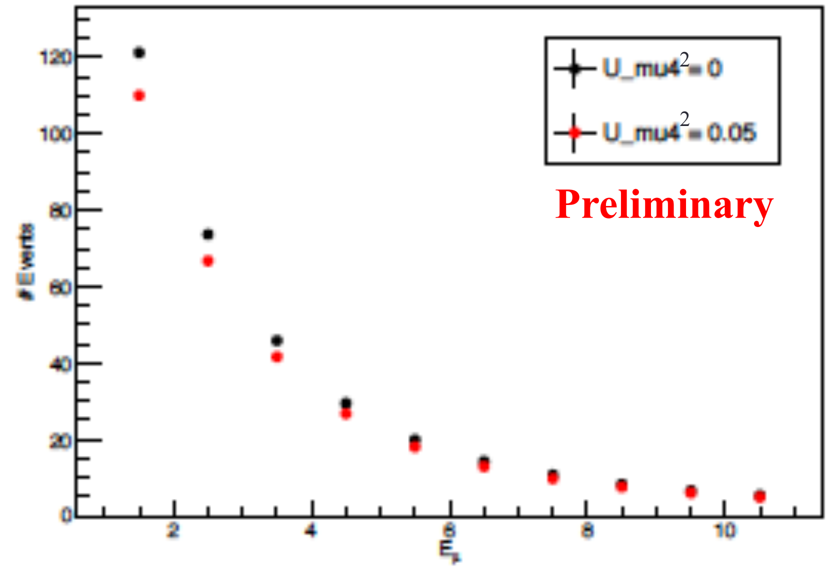
Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689

Non-Standard Oscillation Physics

μ^- Event Distributions $\Delta m^2_{41} = 10\ \text{eV}^2$ $\theta_{14} = \theta_{34} = 0$



$\cos\theta_\mu = 0.95$

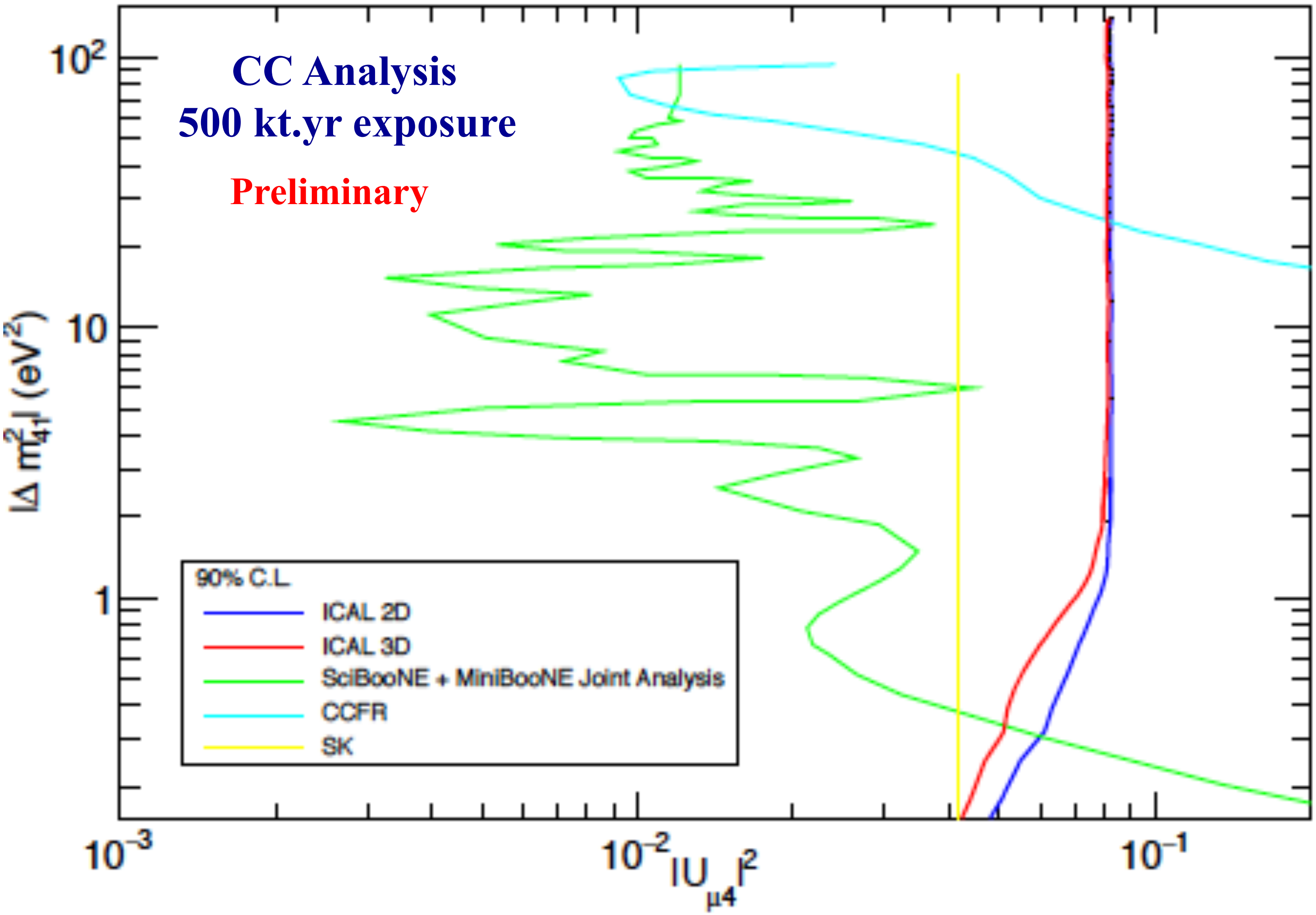


$\cos\theta_\mu = 0.45$

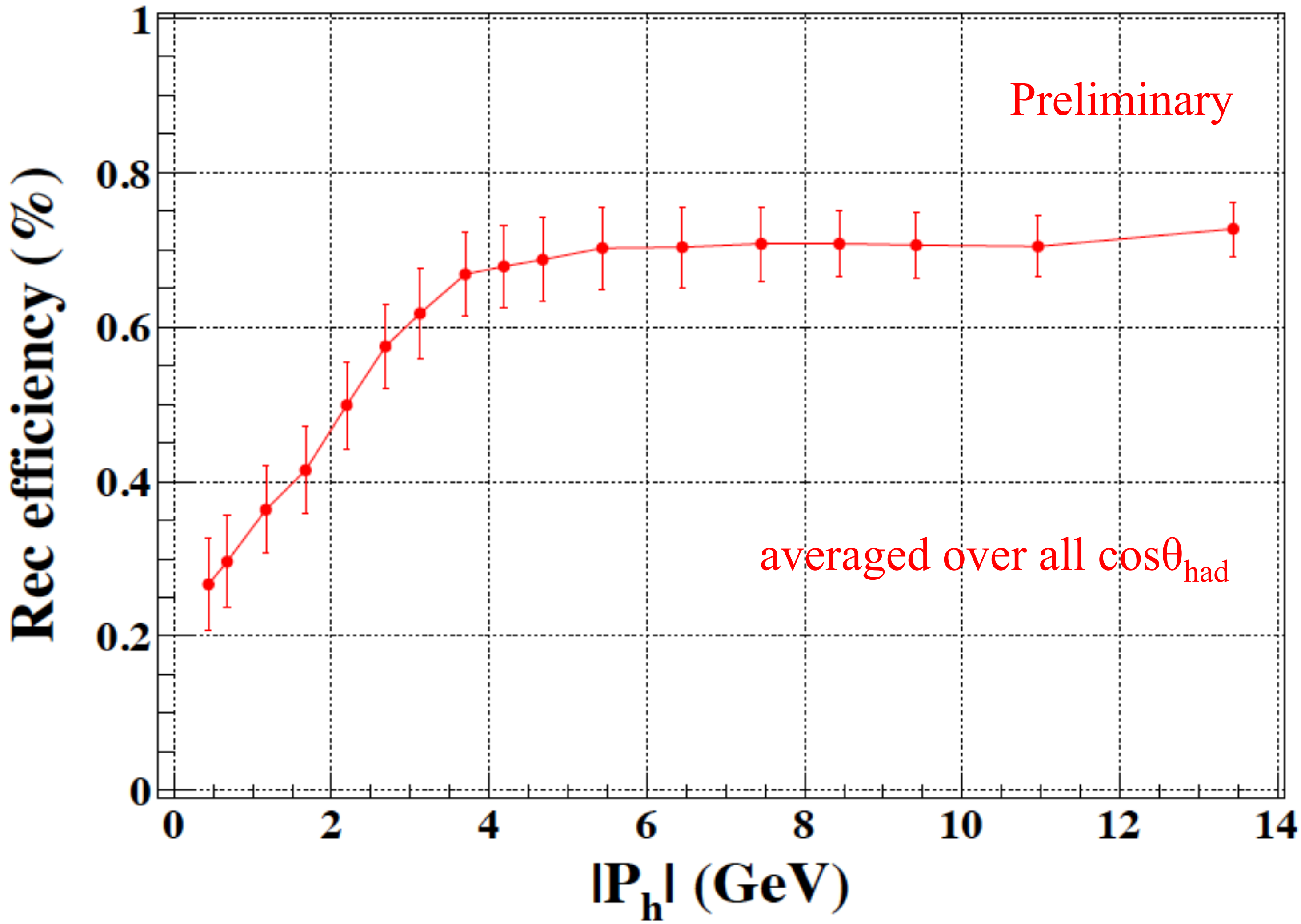
Case	$\#\ \mu^-$	$\#\ \mu^+$
4f Matter Oscillations	4295.59	1877.41
3f Matter Oscillations	4736.1	2070.05

Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)

Possible Constraints from ICAL-INO



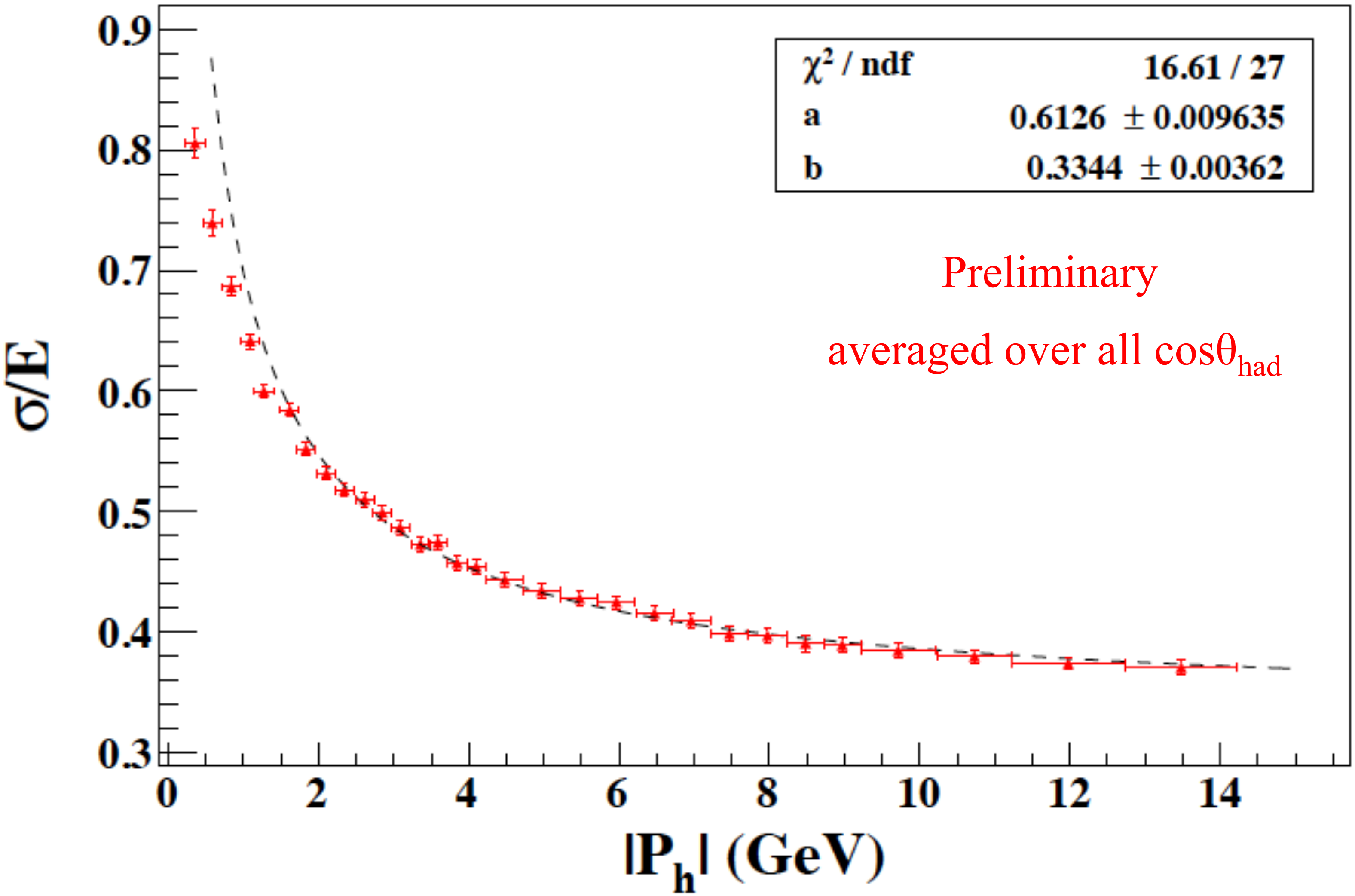
Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)



$|P_h| = \sum_i |p_i|$, where i is the total hadrons in the final state

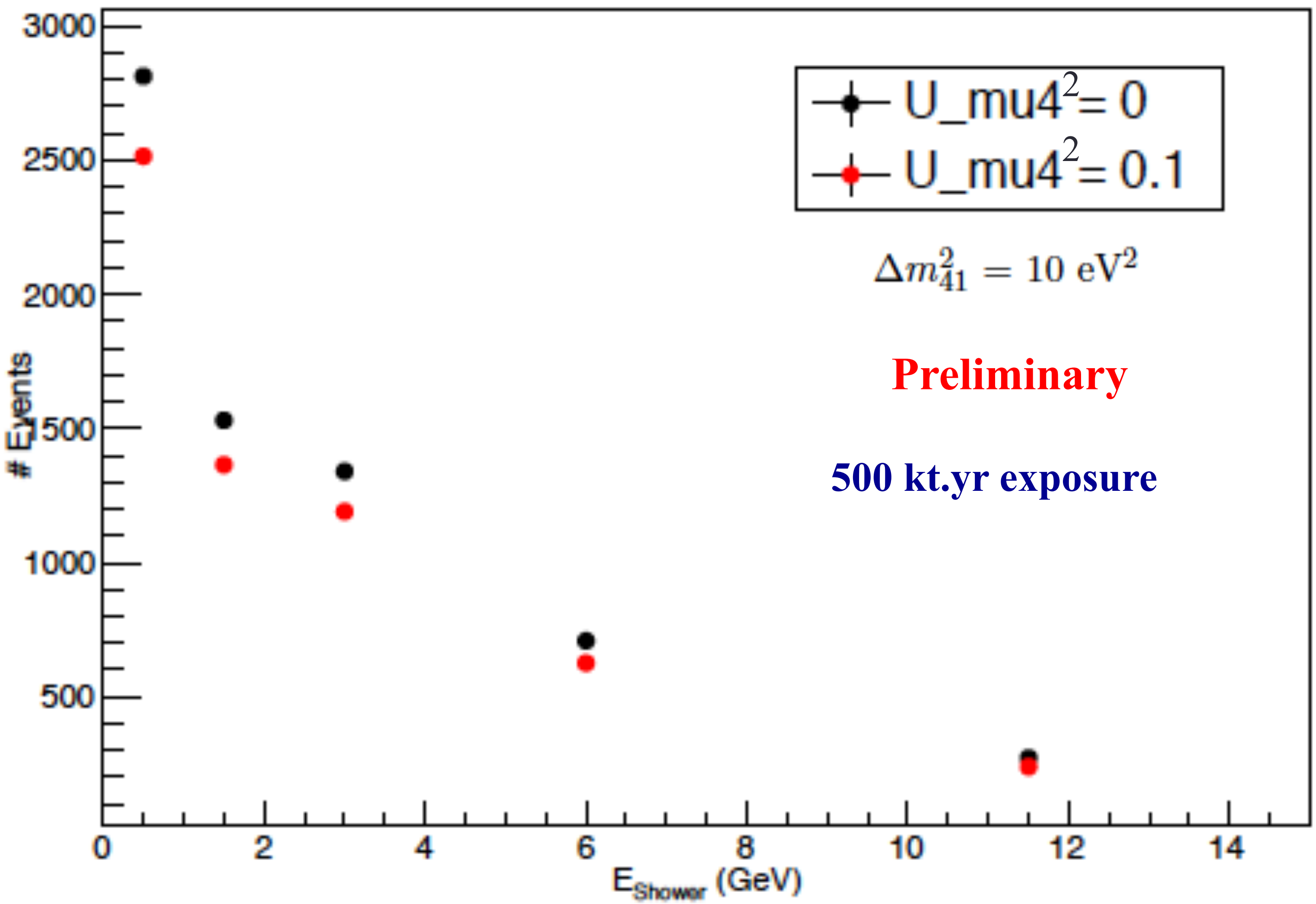
Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)

NC Analysis to Probe Active-Sterile Oscillation



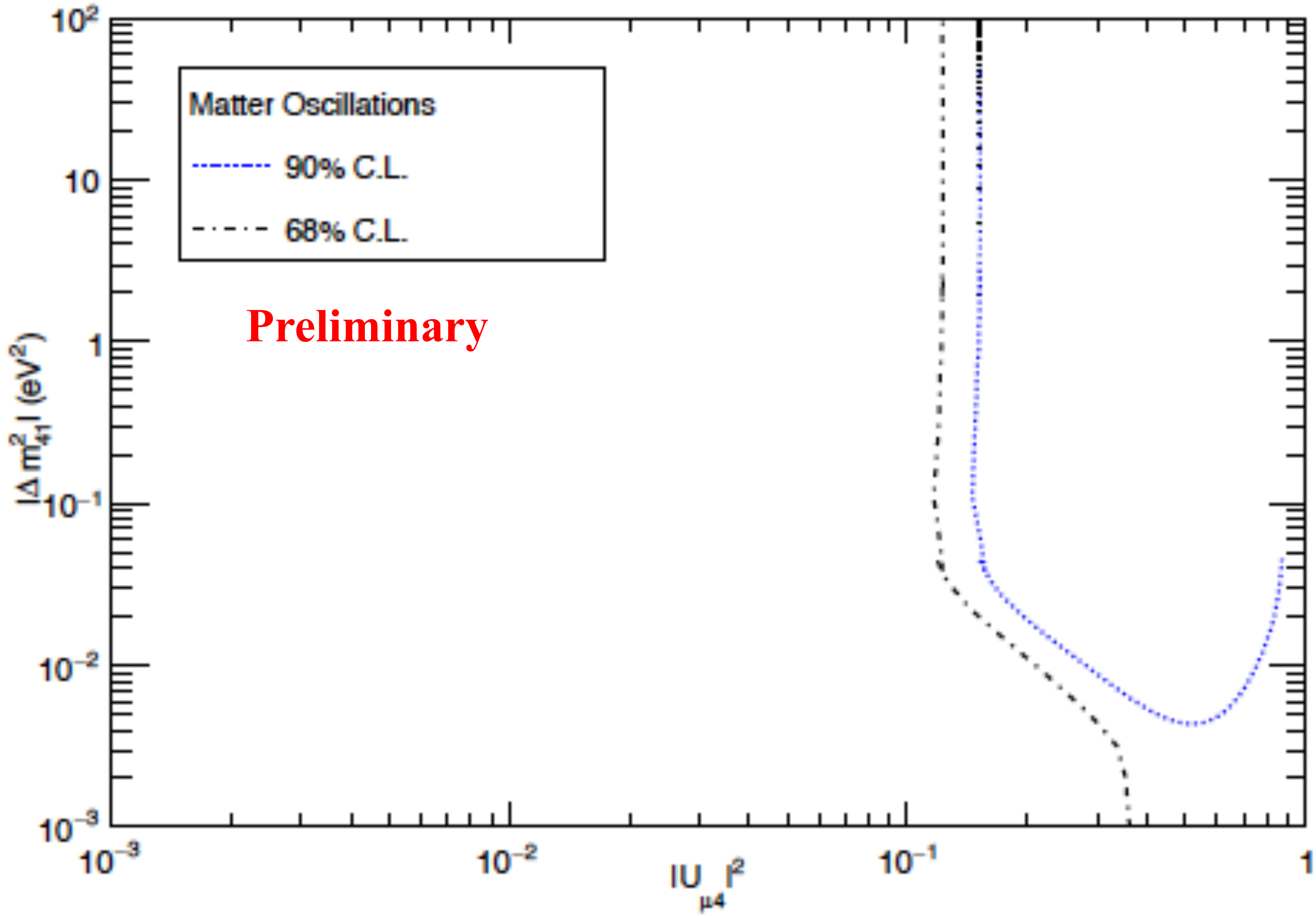
$|P_h|$ resolution

Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)



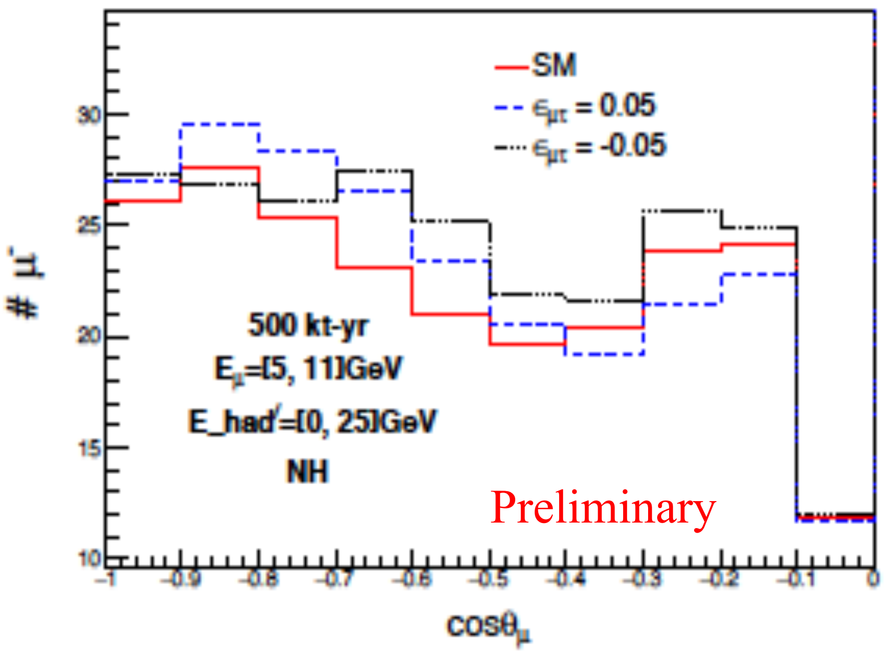
Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)

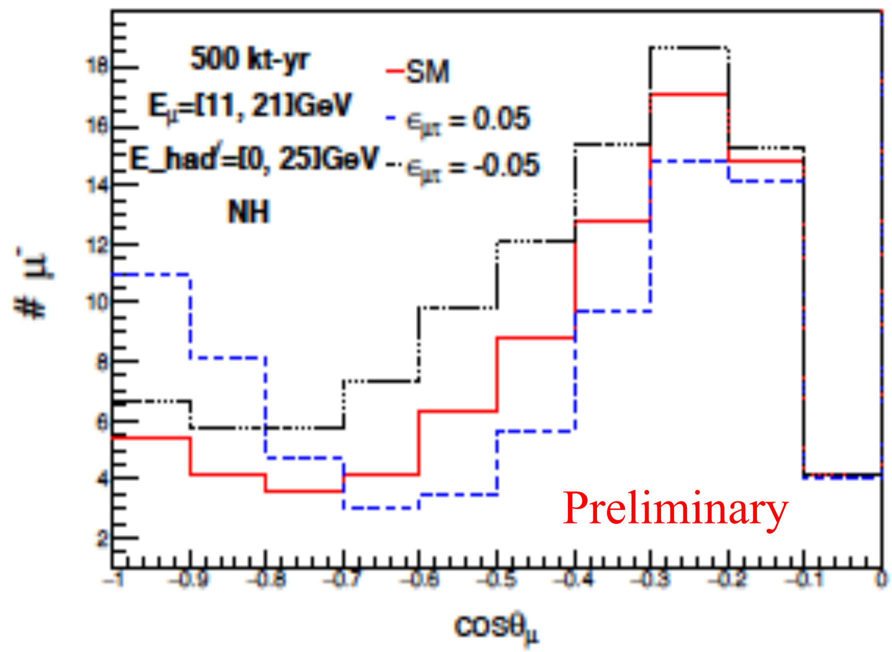
Exclusion Plot from NC Analysis



Thakore, Devi, Agarwalla, Dighe, in preparation (INO Collaboration)

NSI's in Propagation

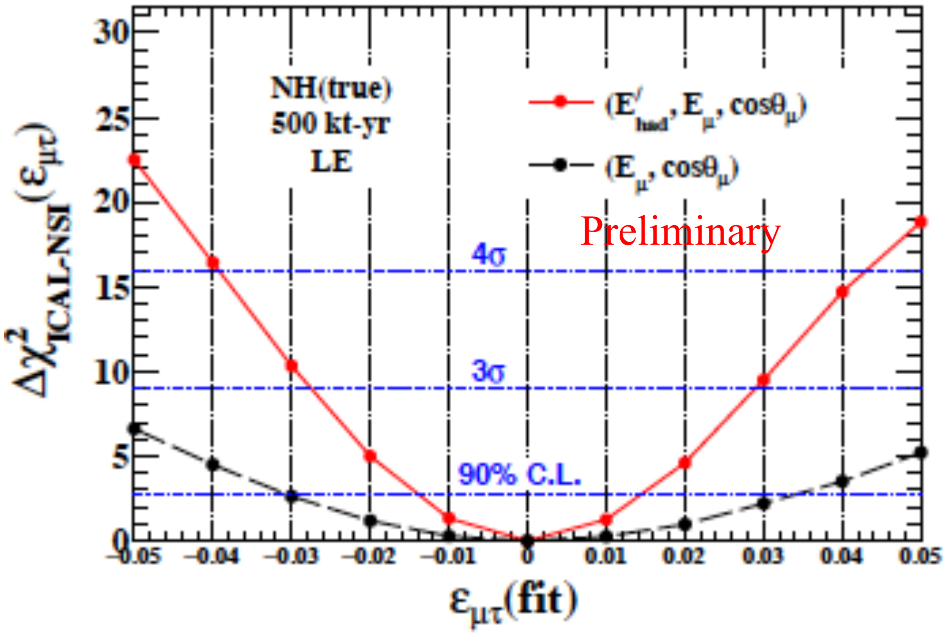


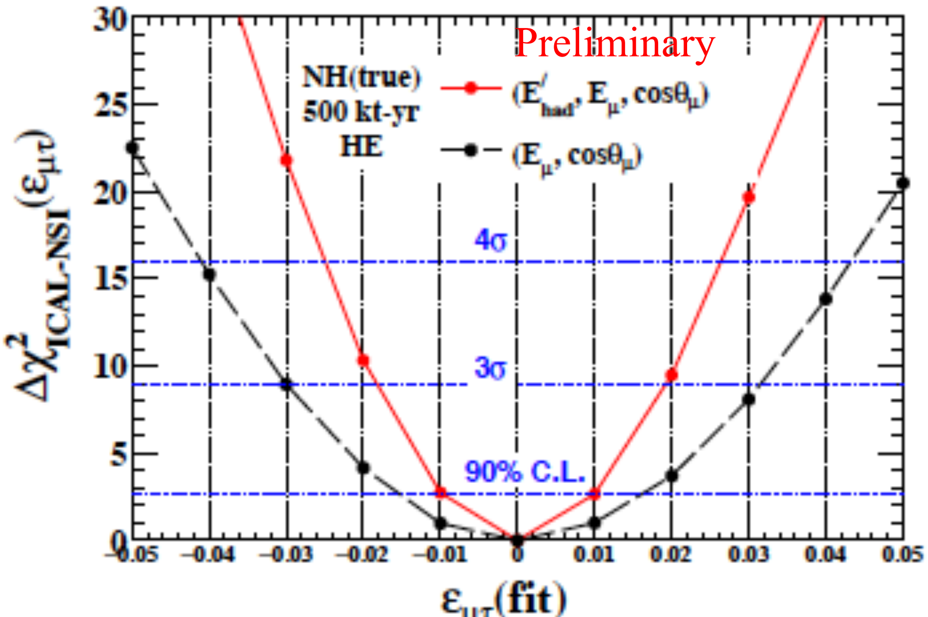


Spectral Study is must for NSI'S. Nothing can be done with only rates

Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)

Constraints on NSI's



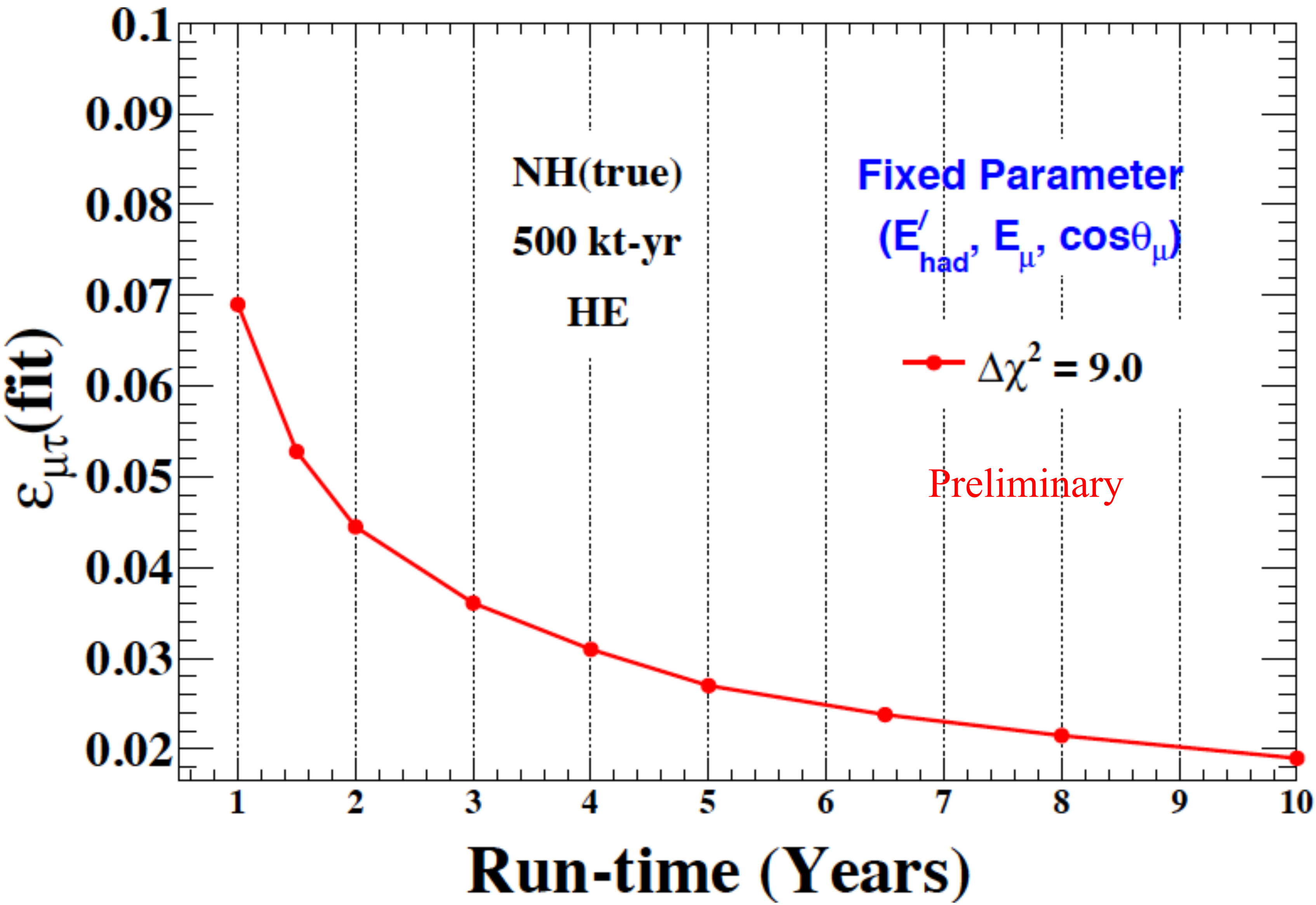


Observable	Binning Scheme	Range	Bin width
E_μ (GeV)	LE & HE	$[1, 11]$	1
	HE	$[11, 21]$	5
$\cos\theta_\mu$	LE & HE	$[-1.0, 0.0]$	0.1
		$[0.0, 1.0]$	0.2
E'_{had} (GeV)	LE & HE	$[0, 2]$	1
	LE & HE	$[2, 4]$	2
	LE	$[4, 15]$	11
	HE	$[4, 25]$	21

Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)

See also, Choubey, Ghosh, Ohlsson, Tiwari, arXiv: 1507.02211 [hep-ph]

How quickly can we constrain these NSI's ?



Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)

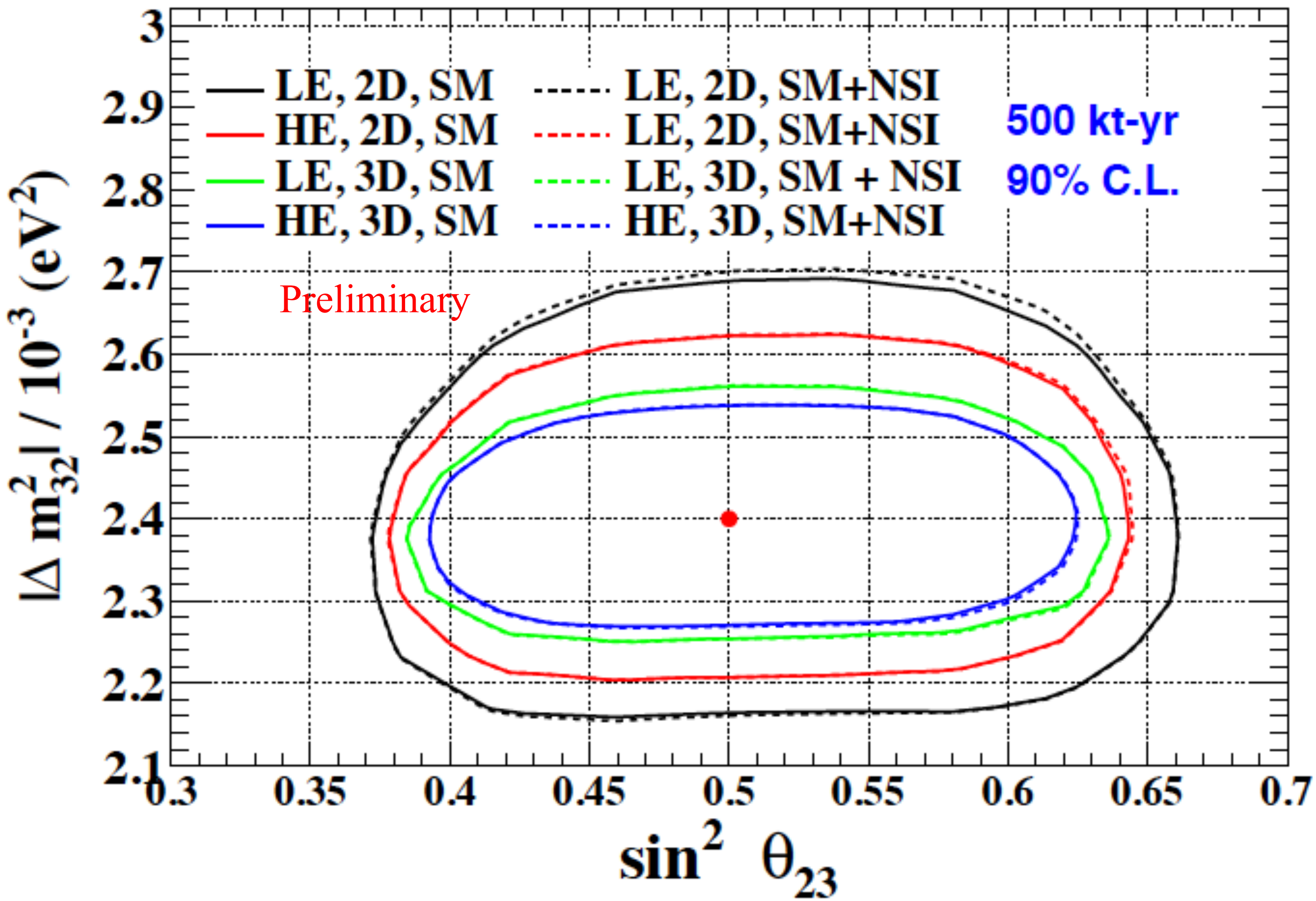
How Robust is MH Study with NSI's ?

True MO	Analysis Mode	SM	With NSI	Reduce
LE			Preliminary	
NH	$(E_\mu, \cos\theta_\mu)$	5.62	4.81	14.4%
	$(E'_{had}, E_\mu, \cos\theta_\mu)$	8.66	7.49	13.5%
IH	$(E_\mu, \cos\theta_\mu)$	5.31	4.14	22.0%
	$(E'_{had}, E_\mu, \cos\theta_\mu)$	8.48	6.88	18.8%
HE				
NH	$(E_\mu, \cos\theta_\mu)$	5.96	5.37	9.9%
	$(E'_{had}, E_\mu, \cos\theta_\mu)$	9.13	8.16	10.6%
IH	$(E_\mu, \cos\theta_\mu)$	5.66	4.95	12.5%
	$(E'_{had}, E_\mu, \cos\theta_\mu)$	8.99	7.66	14.8%

One extra parameter in the fit: $\varepsilon_{\mu\tau}$ in the range $\pm$ 10%

Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)

How Robust are Precision Measurements with NSI's ?



One extra parameter in the fit: $\varepsilon_{\mu\tau}$ in the range ± 10%

Khatun, Chatterjee, Thakore, Agarwalla, in preparation (INO Collaboration)

Current Status of INO

Pre-project activities started with an initial grant of ~ 15 M$

- **Site infrastructure development**
- **Development of INO centre at Madurai city (110 km from underground lab)**
  - Inter-Institutional Centre for High Energy Physics (IICHEP)
- **Construction of an 1/8th size engineering prototype module**

- **Detector R&D is now over**
- **Detailed Project Report for Detector and DAQ system is ready**
- **Soon go for industrial production of RPCs & associated front-end electronics**
- **Full project approved by PM's cabinet committee to start construction**

Glimpse of Activities at the IICHEP Site

Glimpse of Activities at the INO Site

Human Resource Development and Training

- **INO Graduate Training Program started in August 2008, students are affiliated to HBNI**
- **At present students being trained for 1 year at TIFR in both experimental techniques & theory**
- **After completion of coursework, attached to Ph.D. guides at various collaborating institutions**
- **Many short/long term visits to RPC labs (Mumbai & Kolkata) of students & faculties from Universities in last several years**
- **Several students from 1st batch (2008) and 2nd batch (2009) are already working as post-docs at different places**
- **7th batch of 6 students have started their course work at TIFR in 2014**

Stay Tuned!

More Analyses and Results are going to come soon

Comments and Suggestions are most welcome

Just drop an email to our Physics Coordinators

(amol@theory.tifr.res.in or sruba@prl.res.in)

A Request: INO Students are extremely hard working and motivated!

Hire them as Post-docs

Thank you!

The Vavilov Distribution Function

The Vavilov probability density function in the standard form is defined by:

$$P(x;\kappa,\beta^2) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} \phi(s) e^{xs} ds \,, \tag{C.1}$$

where

$$\phi(s) = e^{C} e^{\psi(s)}, \quad C = \kappa(1+\beta^2\gamma)\,, \tag{C.2}$$

and

$$\psi(s) = s\ln\kappa + (s+\beta^2\kappa)\cdot\left[\int_0^1 \frac{1-e^{-st/\kappa}}{t}\,dt \;-\; \gamma\right] - \kappa\, e^{-s/\kappa}\,, \tag{C.3}$$

where $\gamma = 0.577\ldots$ is the Euler's constant.

The parameters mean and variance (σ^2) of the distribution in Eq. (C.1) are given by

$$\text{mean} = \gamma - 1 - \ln\kappa - \beta^2; \quad \sigma^2 = \frac{2-\beta^2}{2\kappa}. \tag{C.4}$$

For $\kappa \leq 0.05$, the Vavilov distribution may be approximated by the Landau distribution, while for $\kappa \geq 10$, it may be approximated by the Gaussian approximation, with the corresponding mean and variance.

We have used the Vavilov distribution function $P(x;\kappa,\beta^2)$ defined above, which is also built into ROOT, as the basic distribution for the fit. However the hadron hit distribution itself is fitted to the modified distribution $(\mathrm{P}_4/\mathrm{P}_3)\ P((\mathrm{x}-\mathrm{P}_2)/\mathrm{P}_3;\ \mathrm{P}_0,\ \mathrm{P}_1)$, to account for the x-scaling (P_3), normalization P_4 and the shift of the peak to a non-zero value, P_2. Clearly $\mathrm{P}_0 = \kappa$ and $\mathrm{P}_1 = \beta^2$. The modified mean and variance are then

$$\text{Mean}_{\text{Vavilov}} = (\gamma \;-\; 1 \;-\; \ln \mathrm{P}_0 - \mathrm{P}_1)\ \mathrm{P}_3 + \mathrm{P}_2\,, \quad \sigma^2_{\text{Vavilov}} = \frac{(2-\mathrm{P}_1)}{2\mathrm{P}_0}\mathrm{P}_3^2\,. \tag{C.5}$$

These are the quantities used while presenting the energy response of hadrons in the ICAL detector.

Three Flavor Effects in $\nu_\mu \rightarrow \nu_e$ oscillation probability

The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ (0.03) and $\sin 2\theta_{13}$ (0.3),

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

$\sin^2 2\theta_{13}$: 0.09 → θ_{13} Driven

$\sin^2\theta_{23}$ → Resolves octant

$$- \alpha \sin 2\theta_{13} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

$\alpha \sin 2\theta_{13}$: 0.009 → CP odd

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP even

$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

α^2: 0.0009 → Solar Term

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

- changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!
- changes sign with polarity causes fake CP asymmetry!

Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracy! How can we break them?

Present Understanding of the 2-3 Mixing Angle

Information on θ_{23} comes from: a) atmospheric neutrinos and b) accelerator neutrinos

In two-flavor scenario: $$P_{\mu\mu} = 1 - \sin^2 2\theta_{\rm eff} \sin^2\left(\frac{\Delta m^2_{\rm eff} L}{4E}\right)$$

For accelerator neutrinos: relate effective 2-flavor parameters with 3-flavor parameters:

$$\Delta m^2_{\rm eff} = \Delta m^2_{31} - \Delta m^2_{21}(\cos^2\theta_{12} - \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})$$

$$\sin^2 2\theta_{\rm eff} = 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)$$ where $$\frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2\theta_{23}$$

Nunokawa etal, hep-ph/0503283; A. de Gouvea etal, hep-ph/0503079

Combining beam and atmospheric data in MINOS, we have:

MINOS Collaboration: arXiv:1304.6335v2 [hep-ex]

$$\sin^2 2\theta_{\rm eff} = 0.95^{+0.035}_{-0.036}\ (10.71 \times 10^{21}\ \text{p.o.t})$$

$$\sin^2 2\bar{\theta}_{\rm eff} = 0.97^{+0.03}_{-0.08}\ (3.36 \times 10^{21}\ \text{p.o.t})$$

Atmospheric data, dominated by Super-Kamiokande, still prefers maximal value of $\sin^2 2\theta_{\rm eff} = 1$ (≥ 0.94 (90% C.L.))

Talk by Y. Itow in Neutrino 2012 conference, Kyoto, Japan

Bounds on θ_{23} from the global fits

In ν_μ survival probability, the dominant term mainly sensitive to $\sin^2 2\theta_{23}$

If $\sin^2 2\theta_{23}$ differs from 1 (as indicated by recent data), we get two solutions for θ_{23}:

one in lower octant (LO: $\theta_{23} < 45$ degree), other in higher octant (HO: $\theta_{23} > 45$ degree)

In other words, if ($0.5 - \sin^2\theta_{23}$) is +ve (-ve) then θ_{23} belongs to LO (HO)

This is known as the octant ambiguity of θ_{23}

Fogli and Lisi, hep-ph/9604415

Conferences	After Neutrino 2012	After NeuTel 2013	After TAUP 2013
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.437^{+0.061}_{-0.031}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$
3σ range	$0.34 \to 0.67$	$0.357 \to 0.654$	$0.366 \to 0.663$
1σ precision (relative)	13.4%	11.3%	11.1%

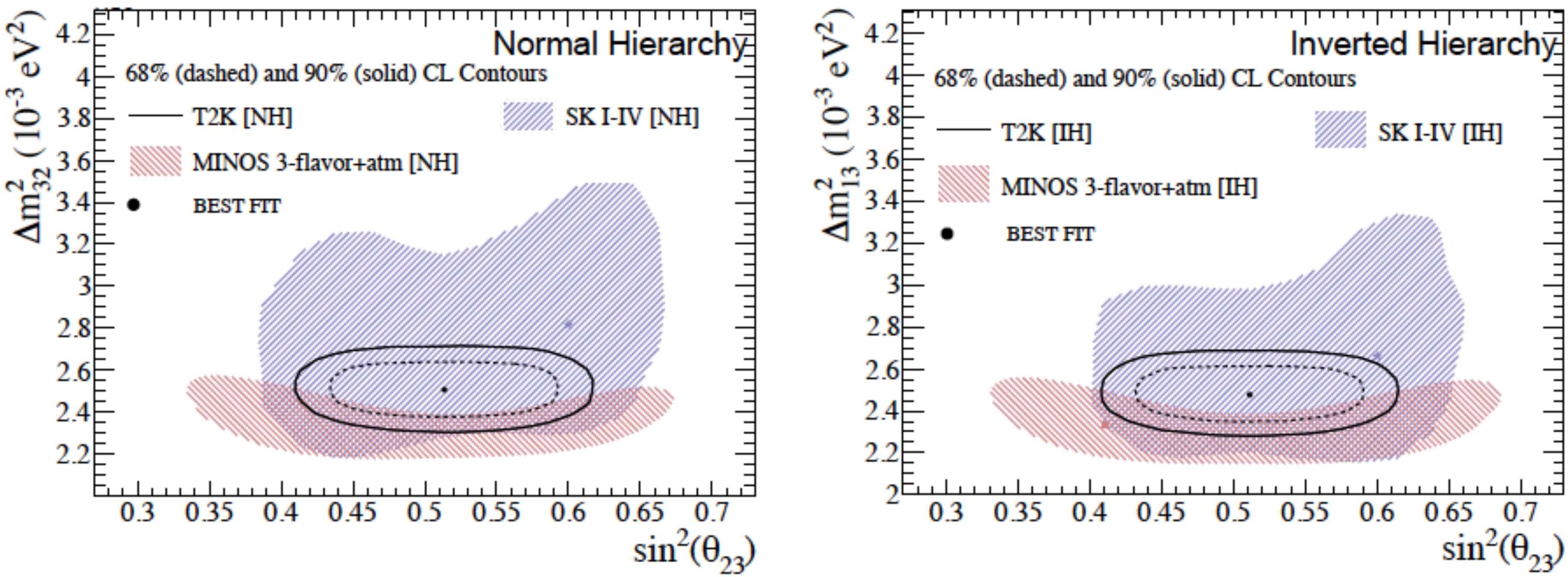
Based on Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

Global fit disfavors maximal 2-3 mixing at 1.4σ confidence level (mostly driven by MINOS)

ν_μ to ν_e oscillation data can break this degeneracy

The preferred value would depend on the choice of the neutrino mass hierarchy

New Measurements of Atmospheric Parameters



		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

Already mixing angle is better constrained by T2K in comparison to SK and MINOS

Talk by C. Walter in Neutrino 2014

Present Status of Neutrino Oscillation Parameters

	bfp $\pm 1\sigma$	3σ range	Relative 1σ Precision
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	4%
$\theta_{12}/^\circ$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	
$\sin^2\theta_{23}$	$[0.451^{+0.001}_{-0.001}] \oplus 0.577^{+0.027}_{-0.035}$	$0.385 \to 0.644$	9.6%
$\theta_{23}/^\circ$	$[42.2^{+0.1}_{-0.1}] \oplus 49.4^{+1.6}_{-2.0}$	$38.4 \to 53.3$	
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0011}$	$0.0188 \to 0.0251$	4.8%
$\theta_{13}/^\circ$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$	
$\delta_{CP}/^\circ$	251^{+67}_{-59}	$0 \to 360$	(Not Known)
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	2.4%
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$[+2.458^{+0.002}_{-0.002}]$	$+2.325 \to +2.599$	1.9%
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$	

Non-maximal $> 1.4\sigma$

Non-zero $> 10\sigma$

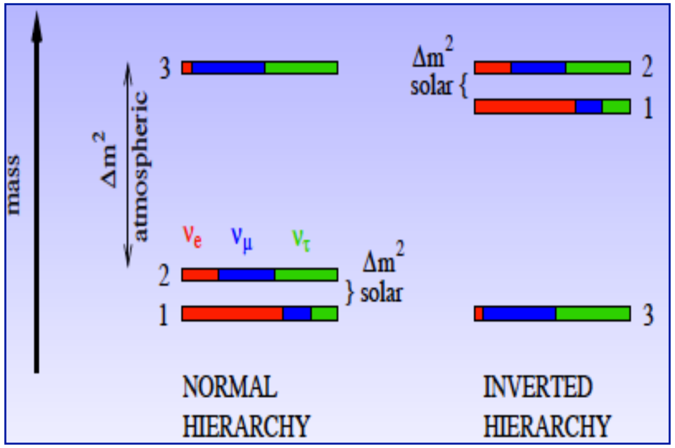
$\sin\delta_{CP} < 0$ at 90% C.L.

Based on the data available after Neutrino 2014 conference

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

Fundamental Unknowns in Neutrino Oscillation

1. What is the hierarchy of the neutrino mass spectrum, normal or inverted?



- *The sign of* $\Delta m^2_{31} = m^2_3 - m^2_1$ *is not known!*
- *Currently do not know which neutrino is the heaviest?*
- *Only have a lower bound on the mass of the heaviest ν!*

$$\sqrt{2.5 \cdot 10^{-3} \mathrm{eV}^2} \sim 0.05 \text{ eV}$$

2. What is the octant of the 2-3 mixing angle, lower ($\theta_{23} < 45°$) or higher ($\theta_{23} > 45°$)?

Measure θ_{23} precisely, Establish deviation from maximality at higher C.L. Then look for Octant

2. Is there CP violation in the leptonic sector, as in the quark sector?

Mixing can cause CP violation in the leptonic sector (if δ_{CP} differs from 0° and 180°)
Need to measure the CP-odd asymmetries: $\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L) \;\; (\alpha \neq \beta)$

With current knowledge of θ_{13}, resolving these unknowns fall within our reach
Sub-leading 3 flavor effects are extremely crucial in current & future oscillation expts

Introducing INO Collaboration

Ahmadabad: Physical Research Laboratory
Aligarh: Aligarh Muslim University
Allahabad: HRI
Bhubaneswar: IoP, Utkal University
Calicut: University of Calicut
Chandigarh: Panjab University
Chennai: IIT-Madras, IMSc
Delhi: University of Delhi
Kalpakkam: IGCAR
Kolkata: SINP, VECC, University of Calcutta
Lucknow: Lucknow University
Madurai: American College
Mumbai: BARC, IIT-Bombay, TIFR, CMEMS
Mysore: University of Mysore
Srinagar: University of Kashmir
Varanasi: Banaras Hindu University

Nearly 100 scientists from 23 research institutes & universities all over India

One of the largest basic science projects in India in terms of man power & cost as well

We are growing day by day
International Collaborators are most welcome

India-Based Neutrino Observatory

- *A multi-institutional attempt to build a world-class underground facility to study fundamental issues in science with special emphasis on neutrinos*

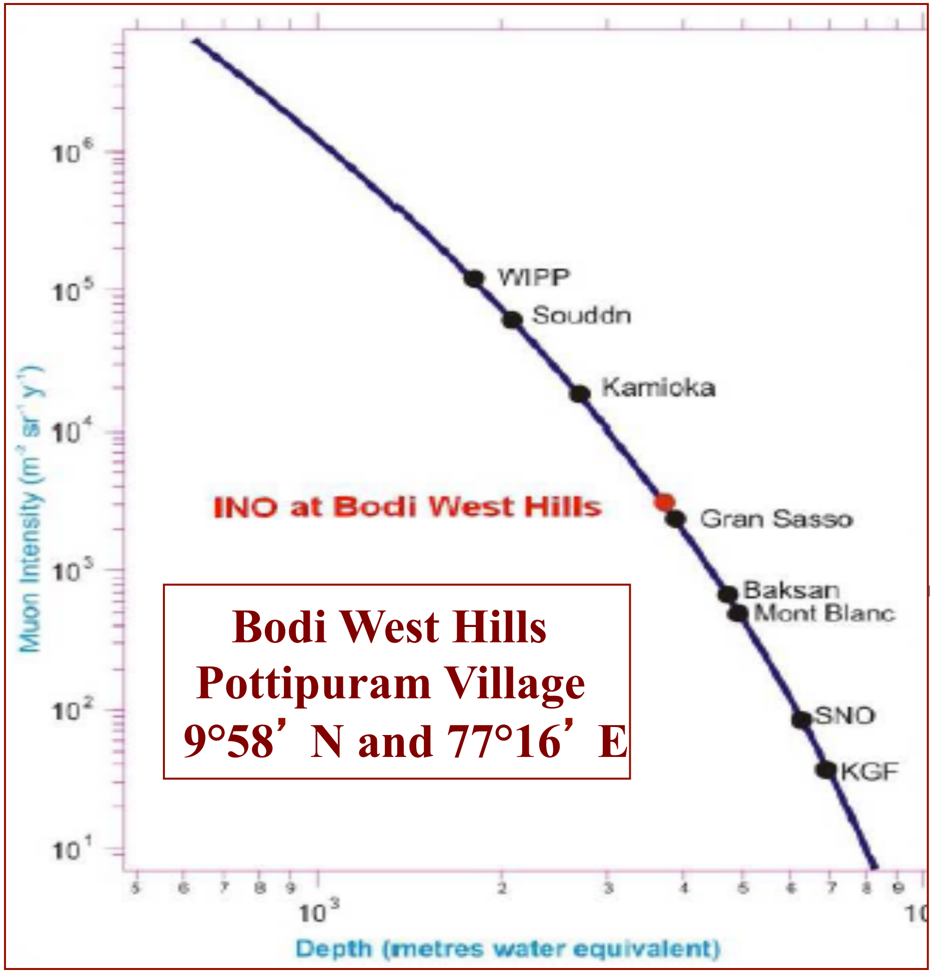
- *With ~1 km all-round rock cover accessed through a 2 km long tunnel. A large and several smaller caverns to pursue many experimental programs*

- *Complementary to ongoing efforts worldwide to explore neutrino properties*

- *A mega-science project (~250 M$) in India, jointly funded (50:50) by the Department of Atomic Energy and the Department of Science and Technology*

- *International Community is welcome to participate in ICAL@INO activity. INO facility is also available to the entire community for setting up experiments like Neutrino-less Double Beta Decay, Direct Dark Matter searches*

Coordinates of INO

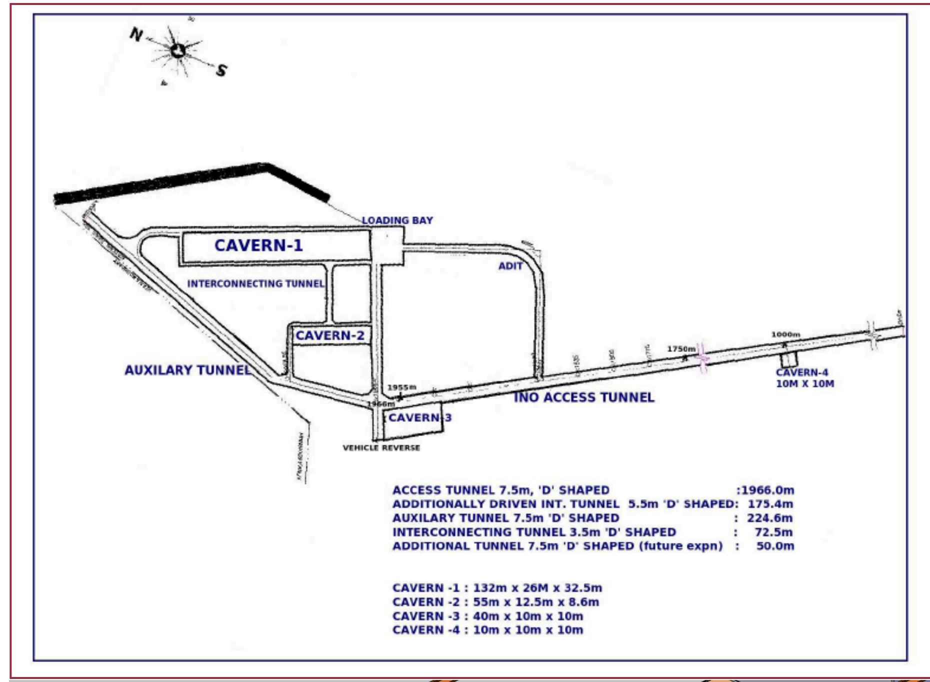


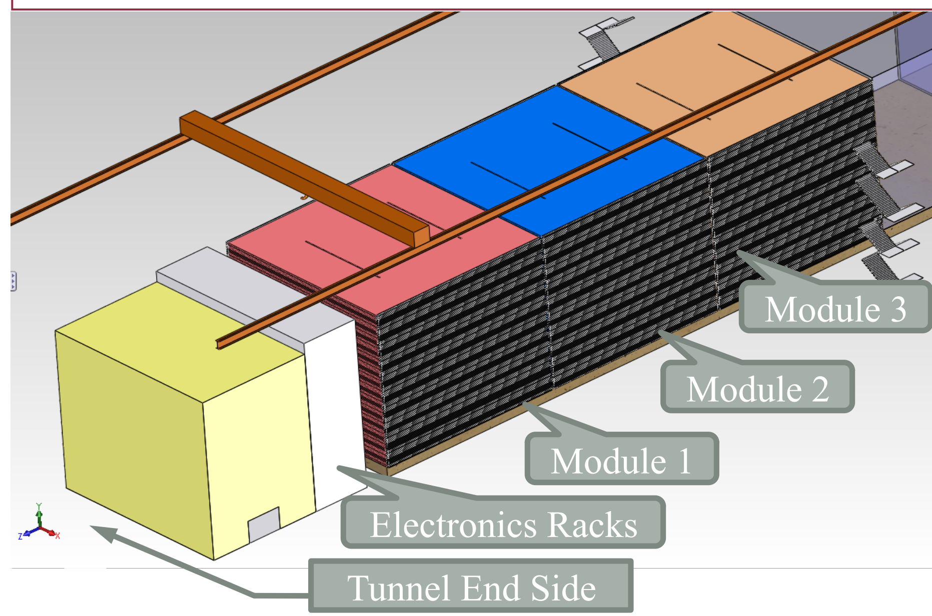
Located 115 km west of the Madurai city in the Theni district of Tamil Nadu

Madurai has an International Airport

Approved projects under INO

- *Come up with an underground lab & surface facilities near Pottipuram village in Theni district of Tamil Nadu*
- *Build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of neutrinos*
- *Construction of INO centre at Madurai: Inter-Institutional Centre for High Energy Physics (IICHEP)*
- *Human Resource Development (INO Graduate Training Program)*
- *Completely in-house Detector R&D with substantial INO-Industry interface*
- *Time Frame for 1st module: 2019*





Physics Issues with ICAL-INO

Study Atmospheric neutrinos w/ a wide range of Baselines & Energies

Recent discovery of large θ_{13} : A good news for ICAL-INO

What do we want to achieve?

- ***Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately***
- ***Improved precision of atmospheric oscillation parameters***
- ***Determine neutrino mass hierarchy using matter effects via charge discrimination***
- ***Measure the deviation of 2-3 mixing angle from its maximal value and its octant***
- ***Test bed for various new physics like NSI, CPT violation, long range forces***
- ***Detect Ultra High Energy Neutrinos, Cosmic Muons, Indirect searches of DM***