Enhancing Sensitivity to Neutrino Parameters with Inelasticity measurement in Atmospheric Neutrinos at ICAL-INO

Sanjib Kumar Agarwalla

sanjib@iopb.res.in

Institute of Physics, Bhubaneswar, India

S. K. Agarwalla, Instituto De Fisica Corpuscular, Valencia, Spain, 10th July, 2014

Neutrino Physics: An Exercise in Patience

Three most fundamental questions were being asked in the past century…

1. How tiny is the neutrino mass? (Pauli, Fermi, ’30s)

Planck + BAO + WMAP polarization data: upper limit of 0.23 eV for the sum of ν masses!

Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]

2. Can a neutrino turn into its own antiparticle? (Majorana, ’30s)

Hunt for ν-less Double-β decay (Z,A → Z+2, A) is still on, demands lepton number violation!

Nice Review by Avignone, Elliott, Engel, Rev.Mod.Phys. 80 (2008) 481-516

3. Do different ν flavors ‘oscillate’ into one another? (Pontecorvo, Maki-Nakagawa-Sakata, ’60s)

B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)]

Last question positively answered only in recent years. Now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**!

Recent measurement of $\boldsymbol{\theta}_{13}$, a clear first order picture of the 3-flavor lepton mixing matrix has emerged, signifies a major breakthrough in ν physics!

This year marks the 60th anniversary since ν detector of Reines & Cowan was turned on

Neutrino Oscillations in 3 Flavors

It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by
Atoms. ν and ν beam

θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by
Reactor and solar ν

Three mixing angles: θ_{23} , θ_{13} , θ_{12} and one CP violating (Dirac) phase δ_{CP}

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \qquad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \qquad U_{e3} \equiv \sin\theta_{13}e^{-i\delta}$$

3 mixing angles simply related to flavor components of 3 mass eigenstates

Over a distance L, changes in the relative phases of the mass states may induce flavor change!

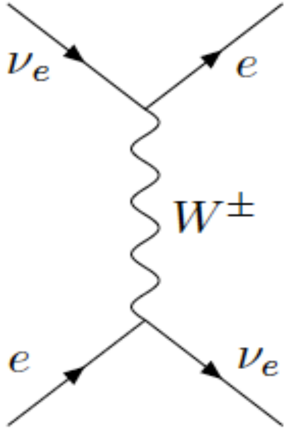
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij},$$

$$\Delta_{ij} = \Delta m^2_{ij}L/4E_\nu$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

2 independent mass splittings Δm^2_{21} and Δm^2_{32} , for anti-neutrinos replace δ_{CP} by $-\delta_{CP}$

Neutrino Oscillations in Matter



Neutrino propagation through matter modify the oscillations significantly

Coherent forward elastic scattering of neutrinos with matter particles

Charged current interaction of ν_e with electrons creates an extra potential for ν_e

Wolfenstein matter term: $\boxed{A = \pm 2\sqrt{2} G_F N_e E}$ or $\boxed{A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho\ (\mathrm{g/cc}) E(\mathrm{GeV})}$

N_e = electron number density , + (-) for neutrinos (anti-neutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino mode to anti-neutrino mode

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → ***even if $\delta_{CP} = 0$, causes fake CP asymmetry***

Matter term modifies oscillation probability differently depending on the sign of Δm^2

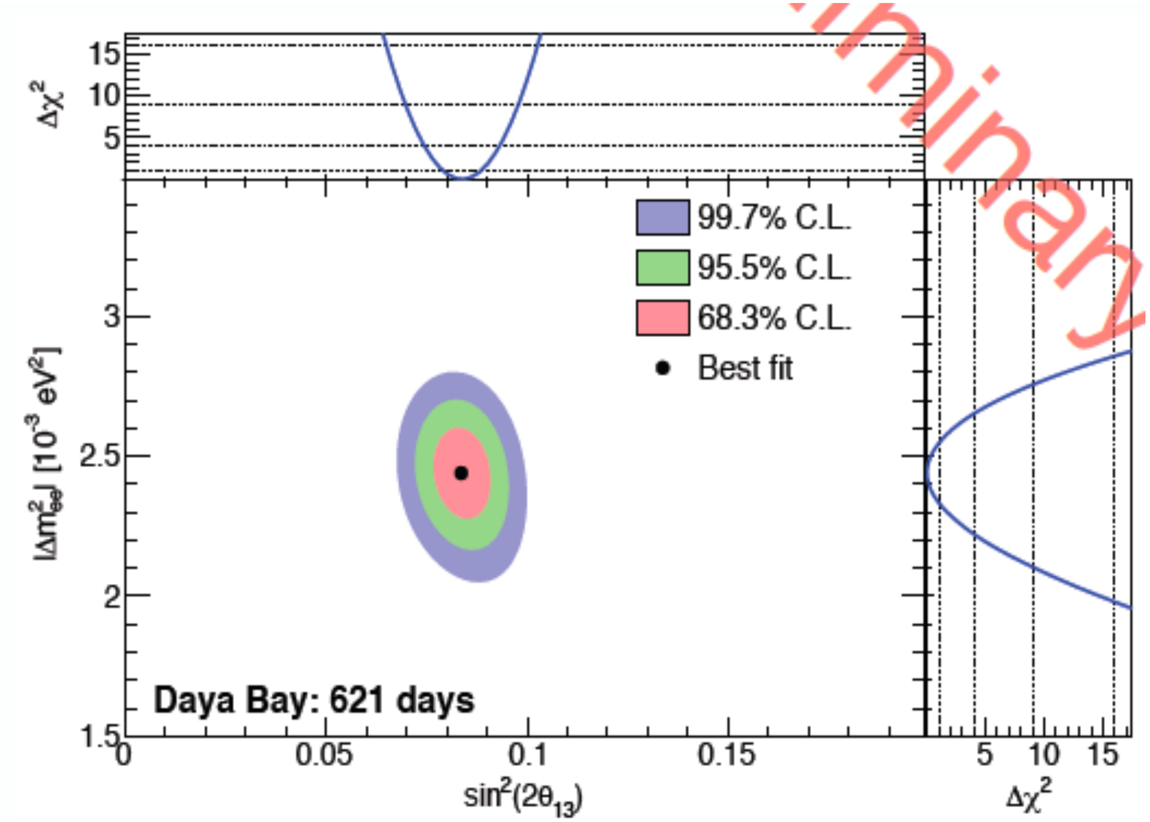
$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E^{\mathrm{Earth}}_{\mathrm{res}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – Matter effect***

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ ***Resonance occurs for neutrinos (anti-neutrinos) if Δm^2 is positive (negative)***

Latest Oscillation Results from Daya Bay

Rate + Shape Oscillation Results [Announced in Neutrino 2014]



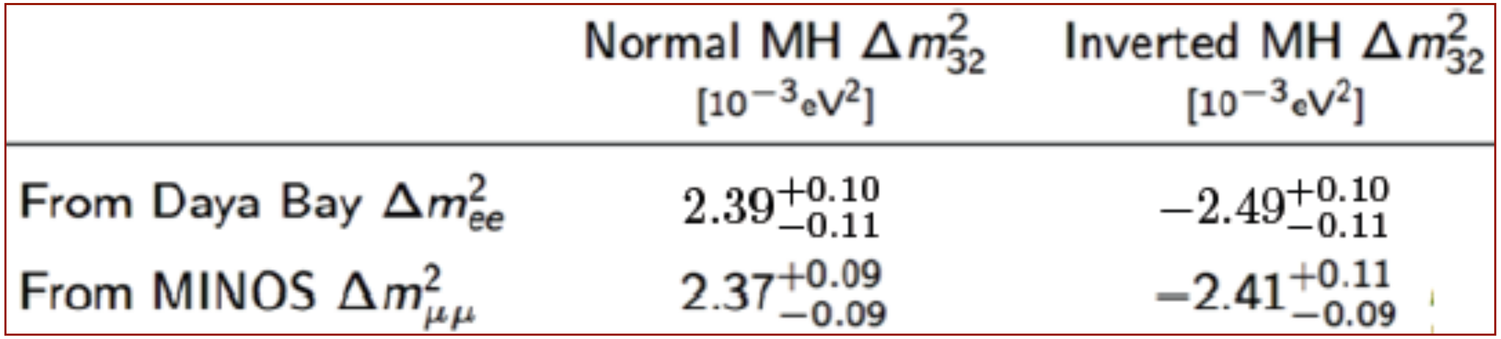
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\text{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

6% precision in $\sin^2 2\theta_{13}$ achieved

Strong confirmation of oscillation-interpretation of observed $\bar{\nu_e}$ deficit



	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.39^{+0.10}_{-0.11}$	$-2.49^{+0.10}_{-0.11}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

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: $\mathrm{P}_{\mu\mu} = 1 - \sin^2 2\theta_{\text{eff}} \sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$

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

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

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

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]

$$\boxed{\sin^2 2\theta_{\text{eff}} = 0.95^{+0.035}_{-0.036}\ (10.71 \times 10^{21}\ \text{p.o.t})}$$ $$\boxed{\sin^2 2\bar{\theta}_{\text{eff}} = 0.97^{+0.03}_{-0.08}\ (3.36 \times 10^{21}\ \text{p.o.t})}$$

Atmospheric data, dominated by Super-Kamiokande, still prefers maximal value of $\sin^2 2\theta_{\text{eff}} = 1$ (≥ 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 $\sin^2 2\theta_{23}$

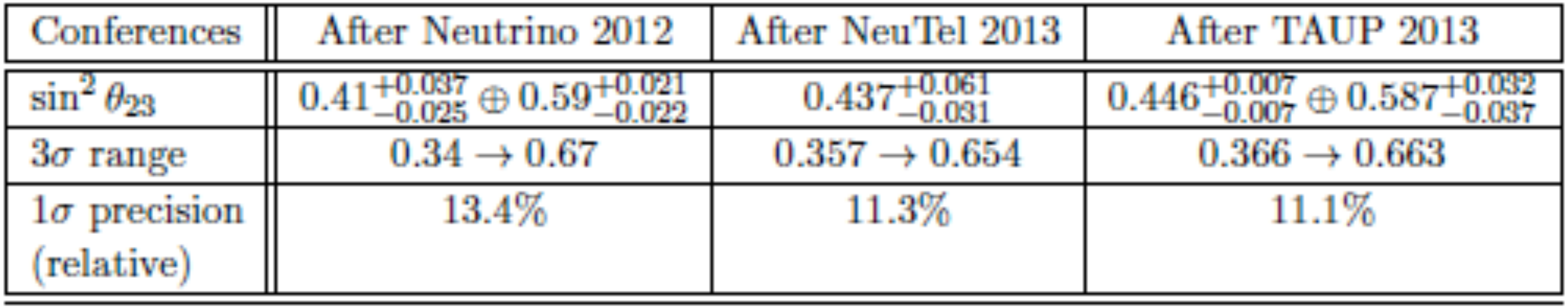
If $\sin^2 2\theta_{23}$ differs from 1 (as indicated by recent data), we get two solutions for θ_{23}:

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	$0.34 \rightarrow 0.67$	$0.357 \rightarrow 0.654$	$0.366 \rightarrow 0.663$
1σ precision (relative)	13.4%	11.3%	11.1%

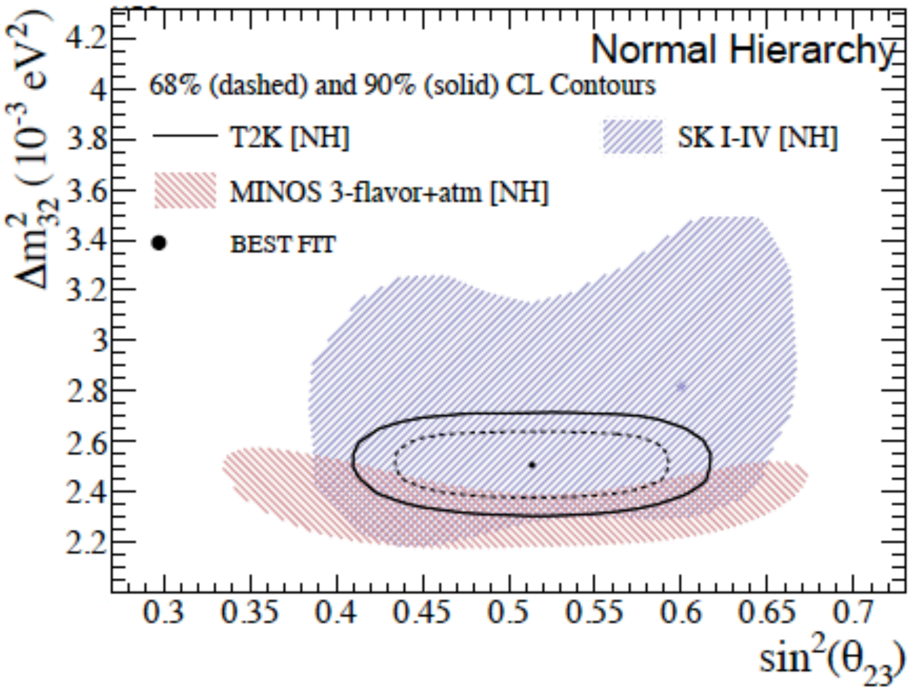
Based on Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

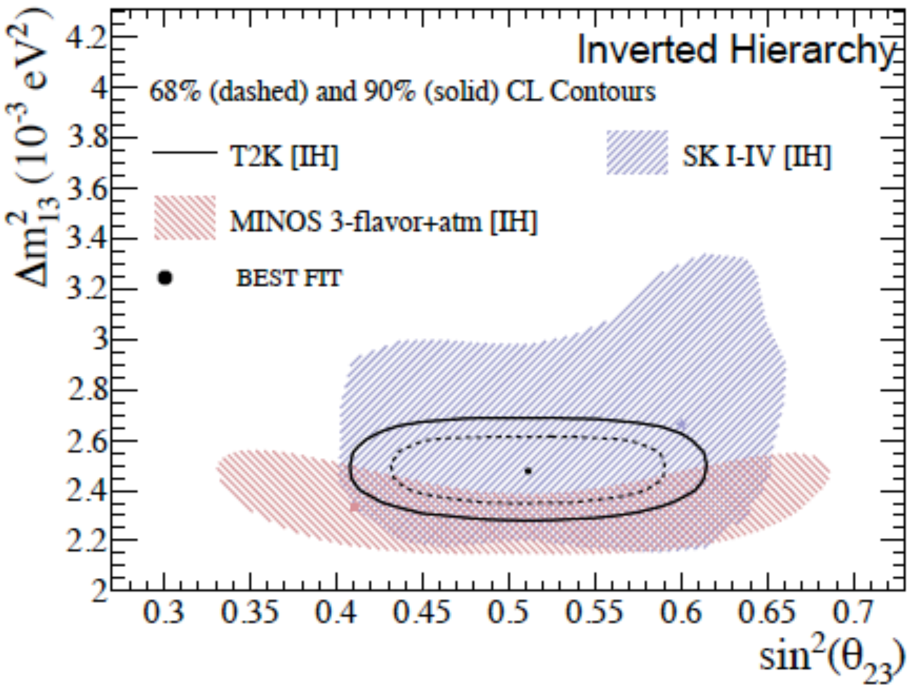
Global fit disfavors maximal 2-3 mixing at 1.4σ confidence level (mostly driven by MINOS)

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



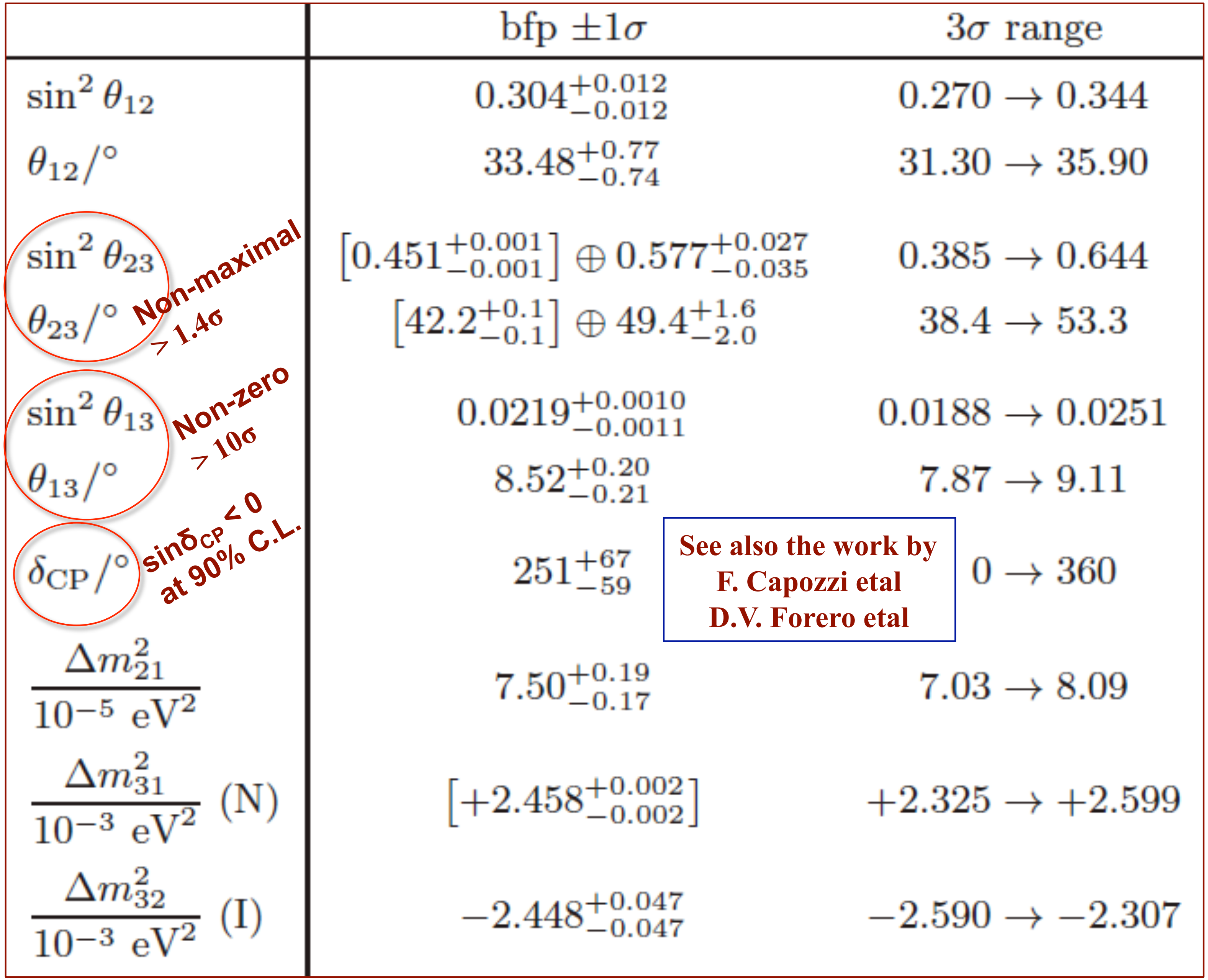


		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

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

Talk by C. Walter in Neutrino 2014

Oscillation Parameters After Neutrino 2014



	bfp ±1σ	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%
$\theta_{13}/^\circ$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$	
$\delta_{\rm CP}/^\circ$	251^{+67}_{-59}	$0 \to 360$	(Not Known)
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	2.4%
$\frac{\Delta m^2_{31}}{10^{-3}\ \rm eV^2}$ (N)	$[+2.458^{+0.002}_{-0.002}]$	$+2.325 \to +2.599$	1.9%
$\frac{\Delta m^2_{32}}{10^{-3}\ \rm eV^2}$ (I)	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$	

Non-maximal $> 1.4\sigma$

Non-zero $> 10\sigma$

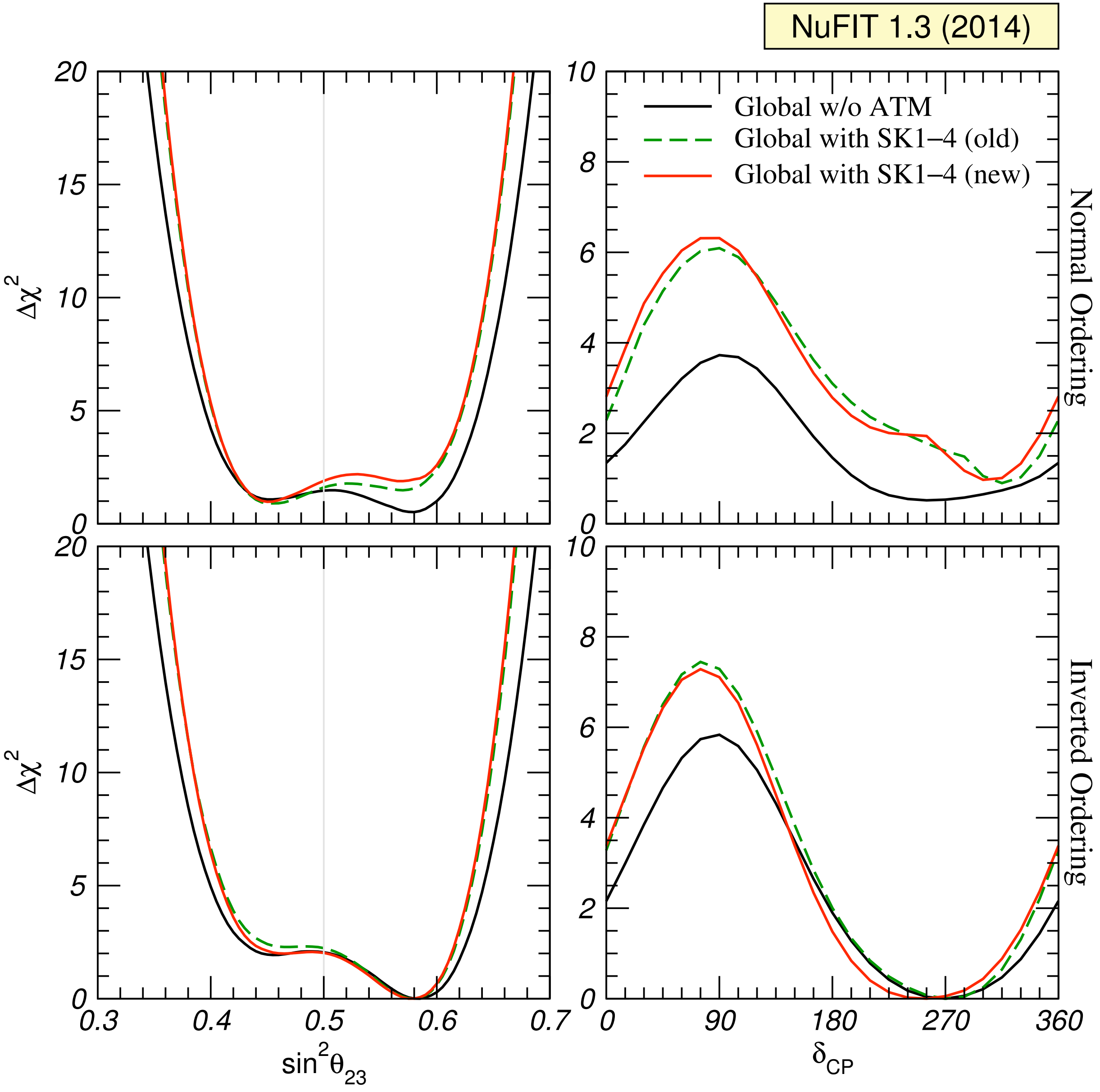
$\sin\delta_{CP} < 0$ at 90% C.L.

See also the work by
F. Capozzi etal
D.V. Forero etal

Based on the data available after Neutrino 2014 conference

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

Role of Atmospheric Neutrinos in Global Fit

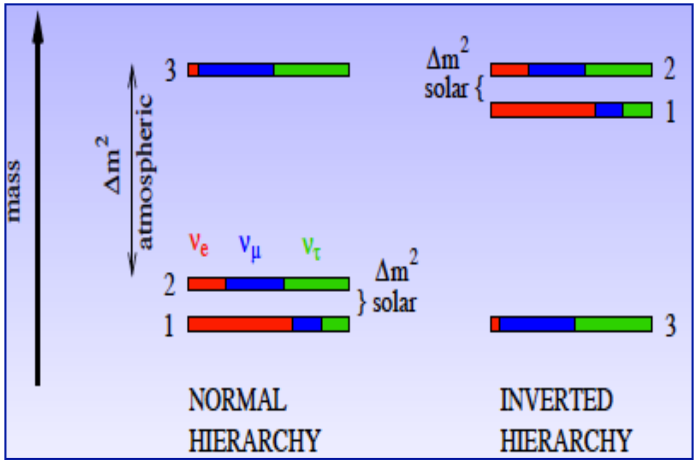


Based on the data available after Neutrino 2014 conference

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!*

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

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

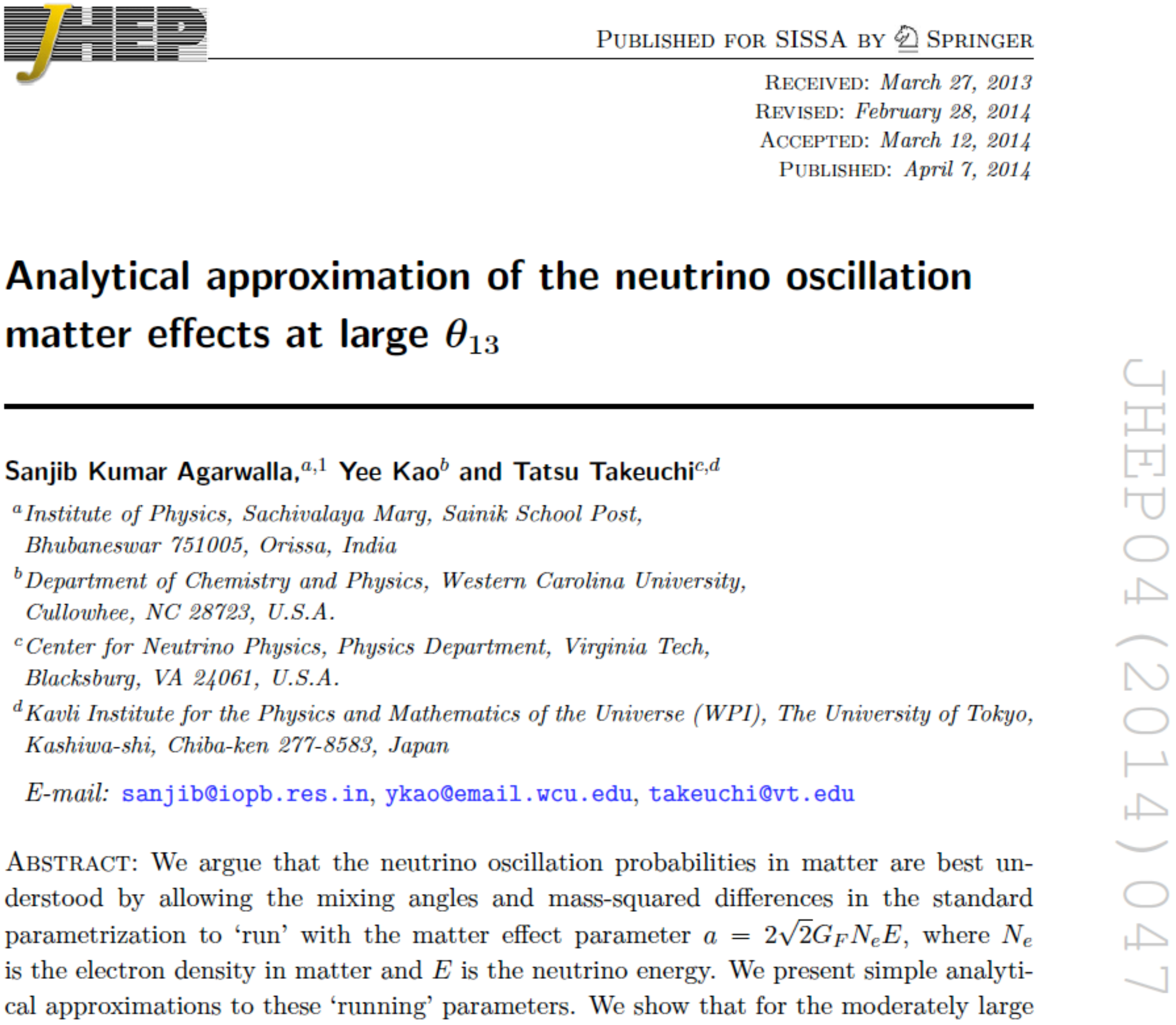
Measure θ_{23} precisely, Establish deviation from maximality at higher C.L. Then look for Octant

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

Analytical Understanding of Neutrino Oscillation Probability



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Analytical approximation of the neutrino oscillation matter effects at large θ_{13}

Sanjib Kumar Agarwalla,[a,1] **Yee Kao**[b] **and Tatsu Takeuchi**[c,d]

[a] *Institute of Physics, Sachivalaya Marg, Sainik School Post,*
Bhubaneswar 751005, Orissa, India
[b] *Department of Chemistry and Physics, Western Carolina University,*
Cullowhee, NC 28723, U.S.A.
[c] *Center for Neutrino Physics, Physics Department, Virginia Tech,*
Blacksburg, VA 24061, U.S.A.
[d] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo,*
Kashiwa-shi, Chiba-ken 277-8583, Japan

E-mail: sanjib@iopb.res.in, ykao@email.wcu.edu, takeuchi@vt.edu

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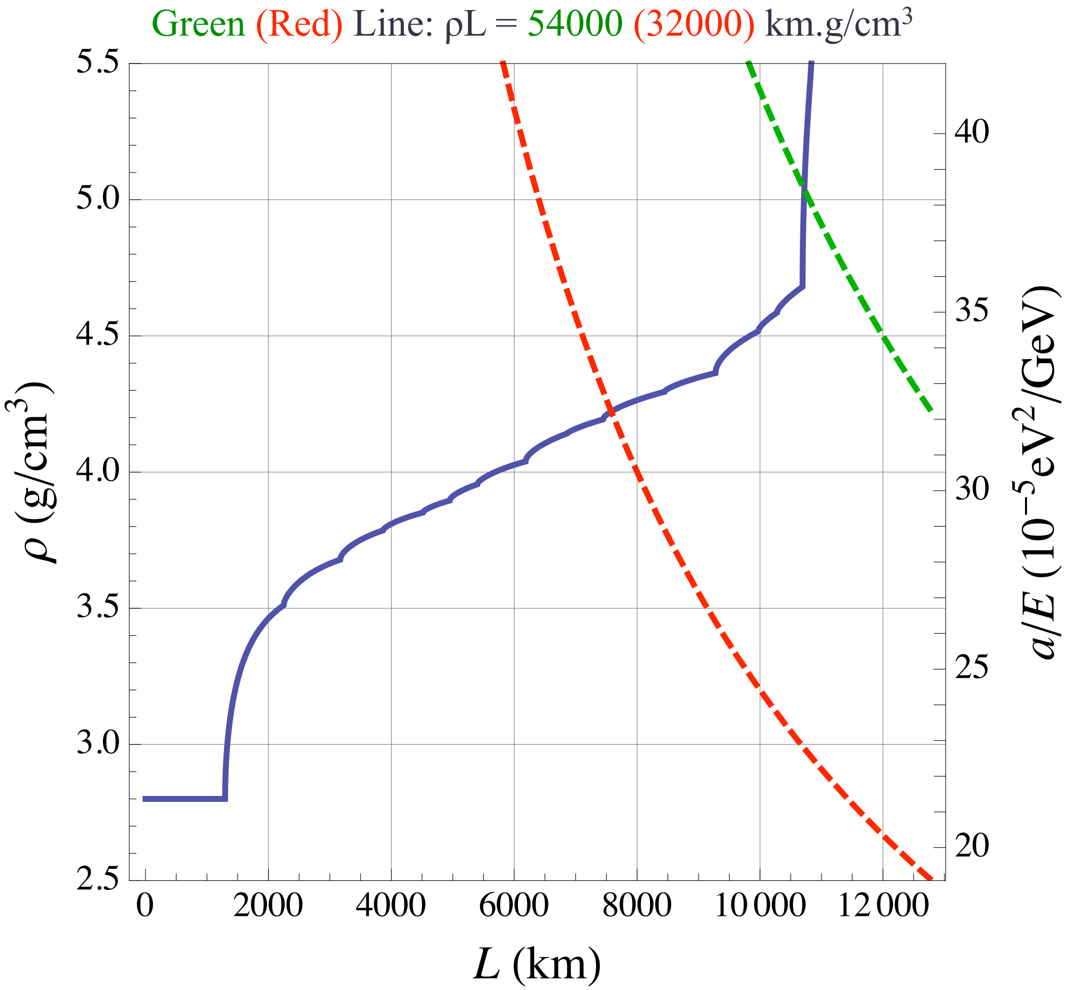
ABSTRACT: We argue that the neutrino oscillation probabilities in matter are best understood by allowing the mixing angles and mass-squared differences in the standard parametrization to 'run' with the matter effect parameter $a = 2\sqrt{2}G_F N_e E$, where N_e is the electron density in matter and E is the neutrino energy. We present simple analytical approximations to these 'running' parameters. We show that for the moderately large

Matter Effect Parameter a

$$a = 2\sqrt{2}G_F N_e E \quad = 7.63\times10^{-5}(\mathrm{eV}^2)\left(\frac{\rho}{\mathrm{g/cm}^3}\right)\left(\frac{E}{\mathrm{GeV}}\right)$$



Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

- Matter effects play an important role
- Mixing angles and and mass-squared differences run with the matter effect parameter ‘a’
- We present simple analytical approximations to these running parameters using the Jacobi method
- We show that for large θ_{13}, the running of θ_{23} and δ_{CP} can be neglected, simplifying the probability expression
- We need to rotate only θ_{12} and θ_{13}

Our Approach

Use the expressions for the vacuum oscillation probabilities as it is, but make the following replacements:

$$\theta_{12} \to \theta'_{12}, \quad \theta_{13} \to \theta'_{13}, \quad \delta m^2_{jk} \to \lambda_j - \lambda_k$$

where

$$\tan 2\theta'_{12} = \frac{(\delta m^2_{21}/c^2_{13})\sin 2\theta_{12}}{(\delta m^2_{21}/c^2_{13})\cos 2\theta_{12} - a}, \qquad \tan 2\theta'_{13} = \frac{(\delta m^2_{31} - \delta m^2_{21} s^2_{12})\sin 2\theta_{13}}{(\delta m^2_{31} - \delta m^2_{21} s^2_{12})\cos 2\theta_{13} - a},$$

$$\lambda_1 = \lambda'_- \qquad \lambda'_\pm = \frac{(\delta m^2_{21} + a c^2_{13}) \pm \sqrt{(\delta m^2_{21} - a c^2_{13})^2 + 4 a c^2_{13} s^2_{12} \delta m^2_{21}}}{2}$$

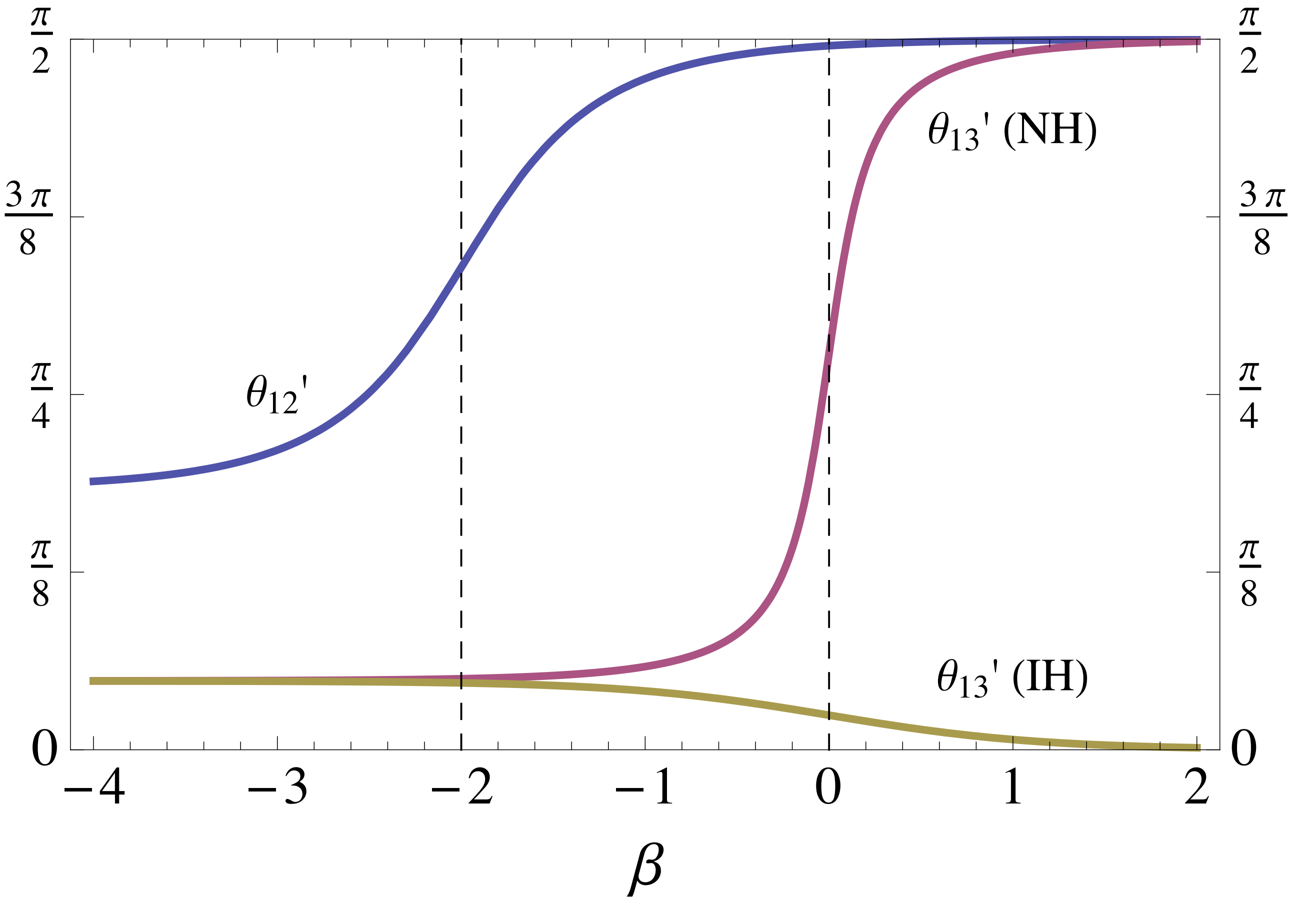
$$\lambda_2 = \lambda''_\mp$$

$$\lambda_3 = \lambda''_\pm \qquad \lambda''_\pm = \frac{\left[\lambda'_+ + (\delta m^2_{31} + a s^2_{13})\right] \pm \sqrt{\left[\lambda'_+ - (\delta m^2_{31} + a s^2_{13})\right]^2 + 4 a^2 s'^2_{12} c^2_{13} s^2_{13}}}{2}$$

upper (lower) sign is for the normal (inverted) hierarchy

Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

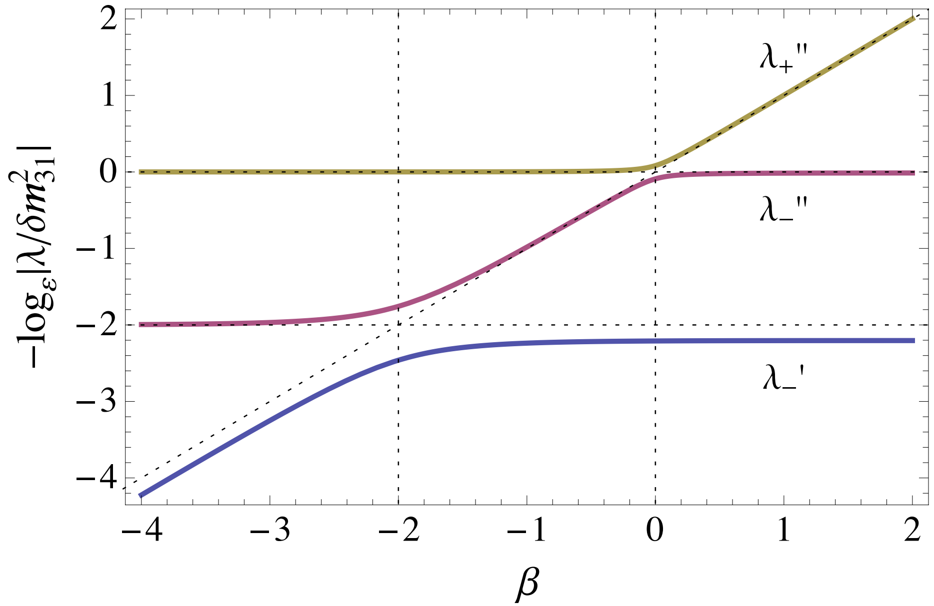
a-dependence of effective mixing angles



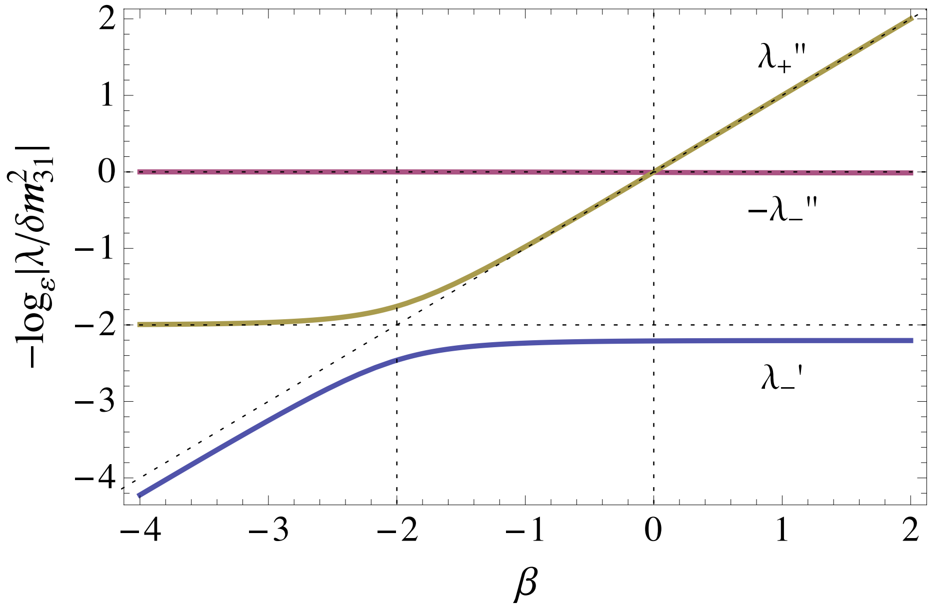
$$\frac{a}{|\delta m_{31}^2|} = \varepsilon^{-\beta}, \qquad \varepsilon = \sqrt{\frac{\delta m_{21}^2}{|\delta m_{31}^2|}} \approx 0.17$$

Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

a-dependence of effective mass-squared differences



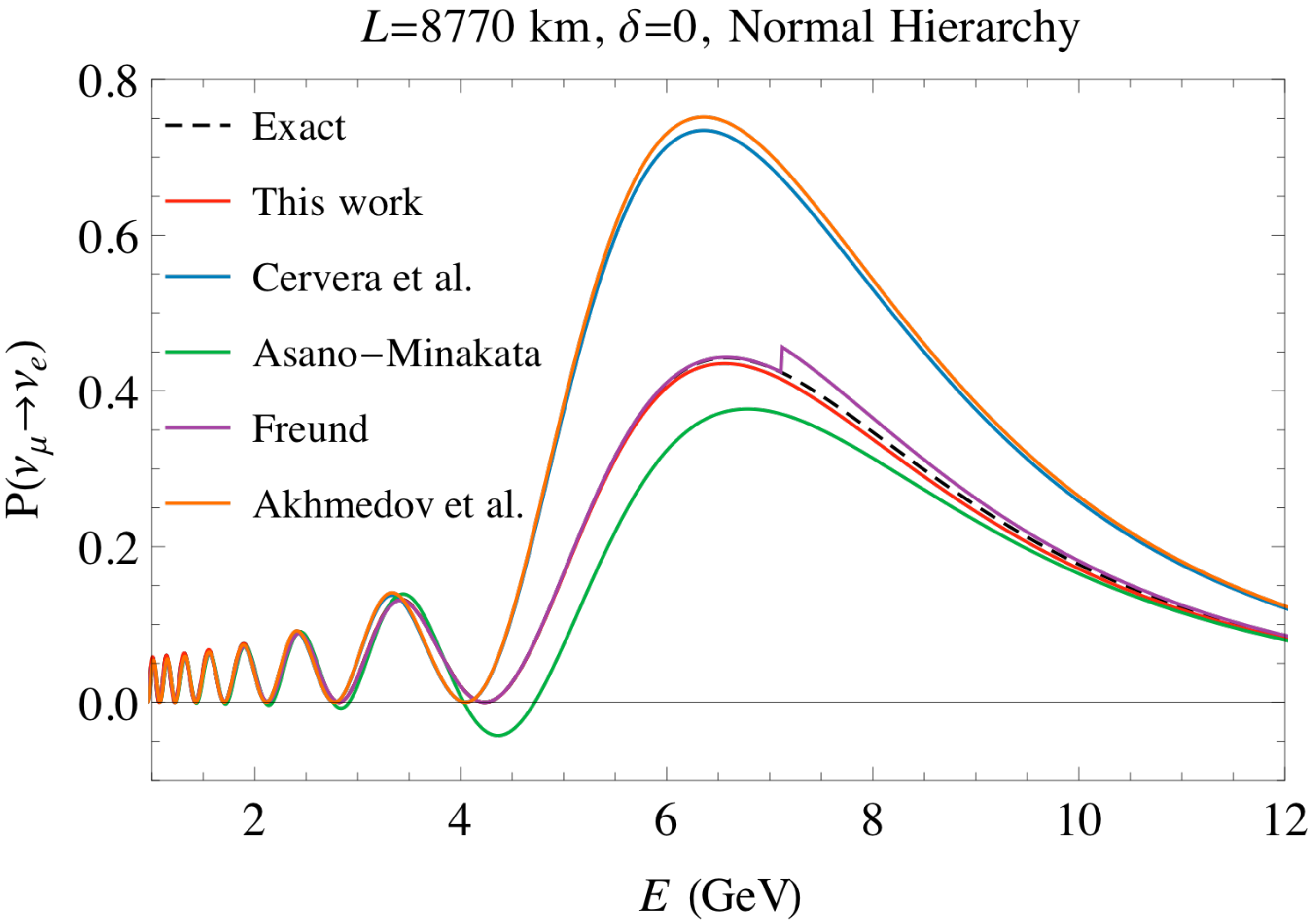
Normal Hierarchy



Inverted Hierarchy

Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

Accuracy of Our Method and Comparison with Existing Literature



Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

Other analytical expressions suffer in accuracy due to their reliance on expansion in θ_{13}, or in simplicity when higher order terms in θ_{13} included

Our method gives accurate probability for all channels, baselines and energies

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

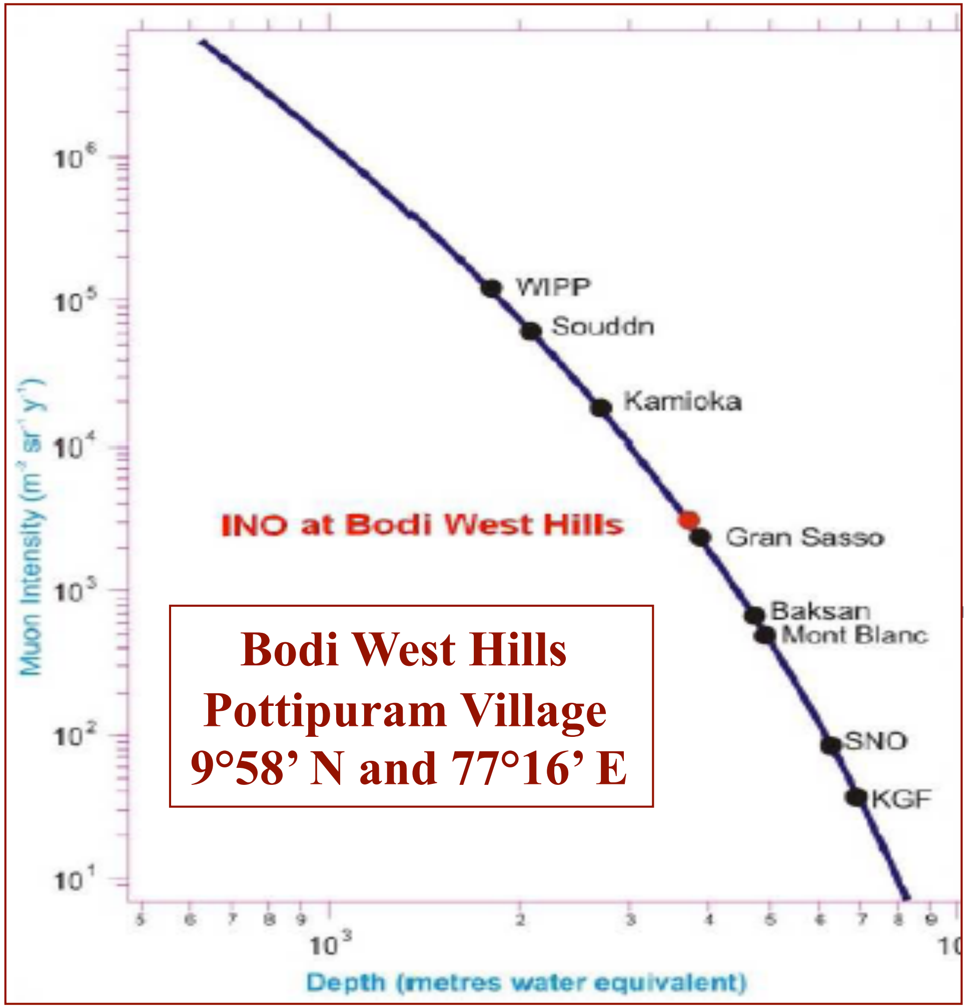
One of the largest basic science projects in India in terms of man power & cost as well

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*
- ***INO project was discussed and approved by the Atomic Energy Commission***
- *Regarding Final approval: Clearance from the Cabinet expected soon*
- *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



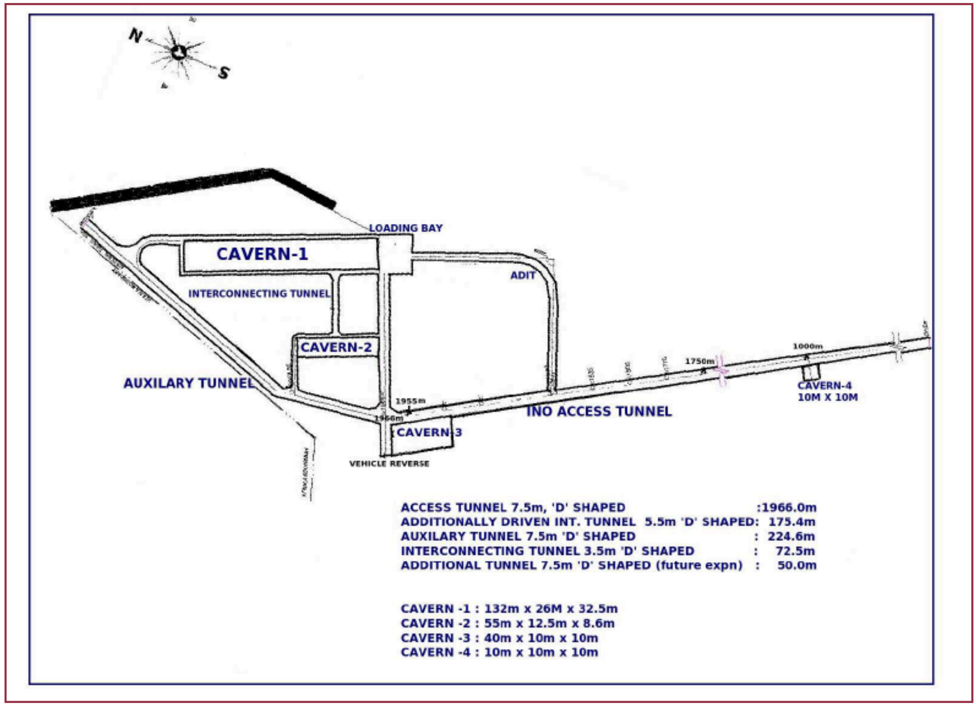
Bodi West Hills
Pottipuram Village
9°58' N and 77°16' E

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

Madurai has an International Airport

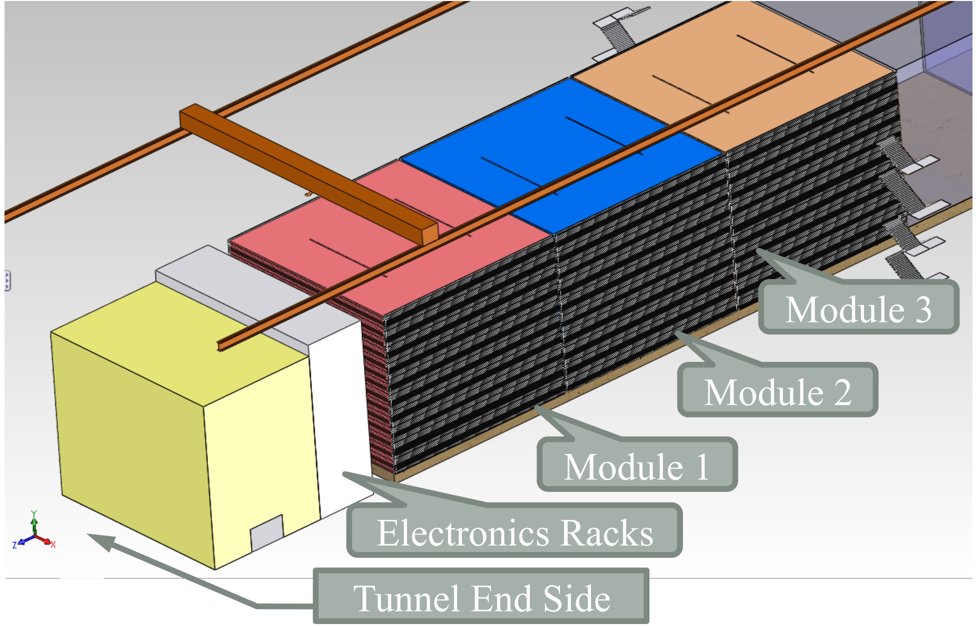
Approved projects under INO

- *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*



ACCESS TUNNEL 7.5m, 'D' SHAPED :1966.0m
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m 'D' SHAPED: 175.4m
AUXILARY TUNNEL 7.5m 'D' SHAPED : 224.6m
INTERCONNECTING TUNNEL 3.5m 'D' SHAPED : 72.5m
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (future expn) : 50.0m

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m



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?

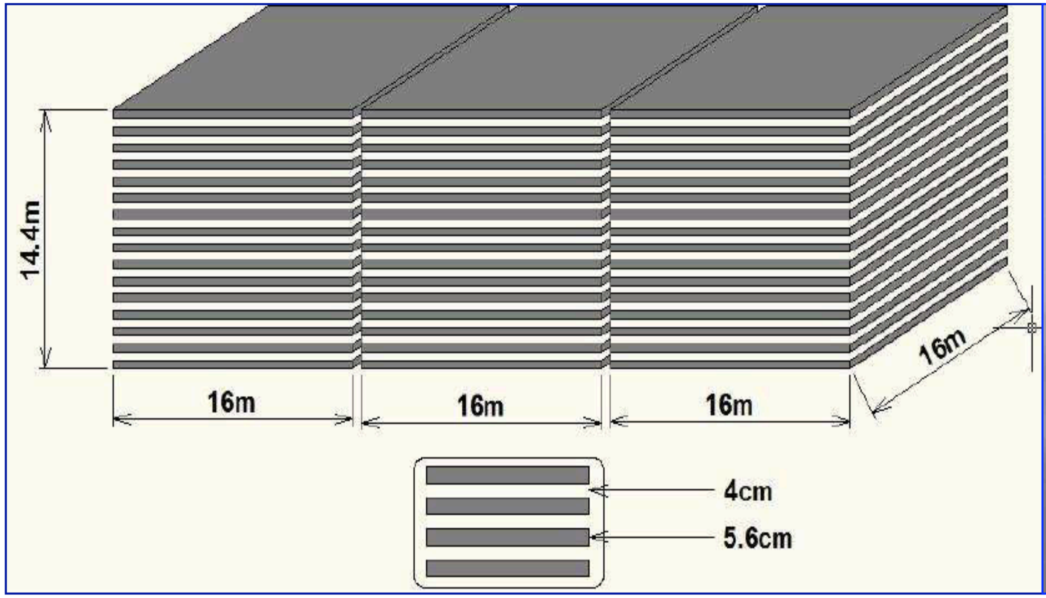
- ***Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately***
- ***Improved precision of atmospheric oscillation parameters***
- ***Determine neutrino mass hierarchy using matter effects via charge discrimination***
- ***Measure the deviation of 2-3 mixing angle from its maximal 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***

Detector Characteristics

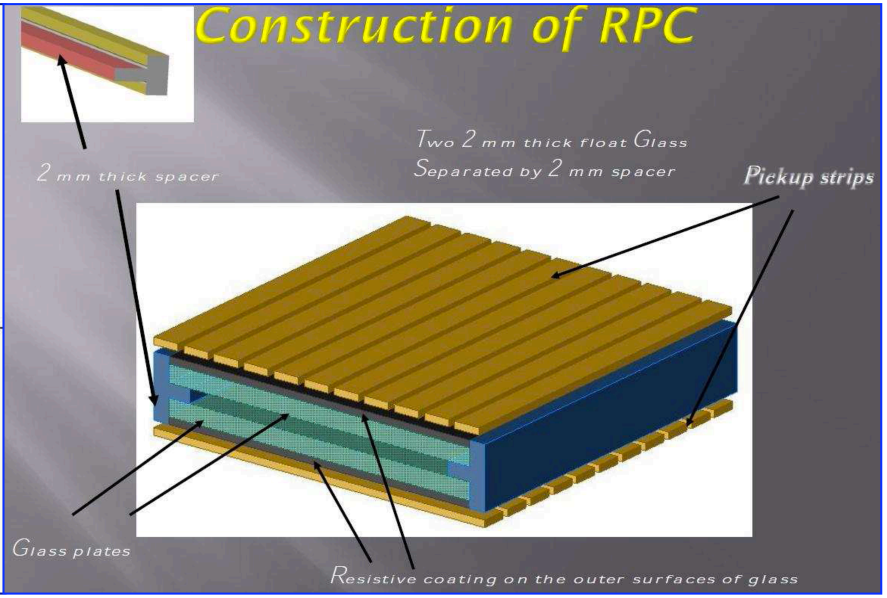
- ***Should have large target mass (50 – 100 kt)***
- ***Good tracking and Energy resolution (tracking calorimeter)***
- ***Good directionality for up/down discrimination (nano-second time resolution)***
- ***Charge identification (need to have uniform, homogeneous magnetic field)***
- ***Ease of construction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

Our choice

Magnetized iron (target mass): ICAL



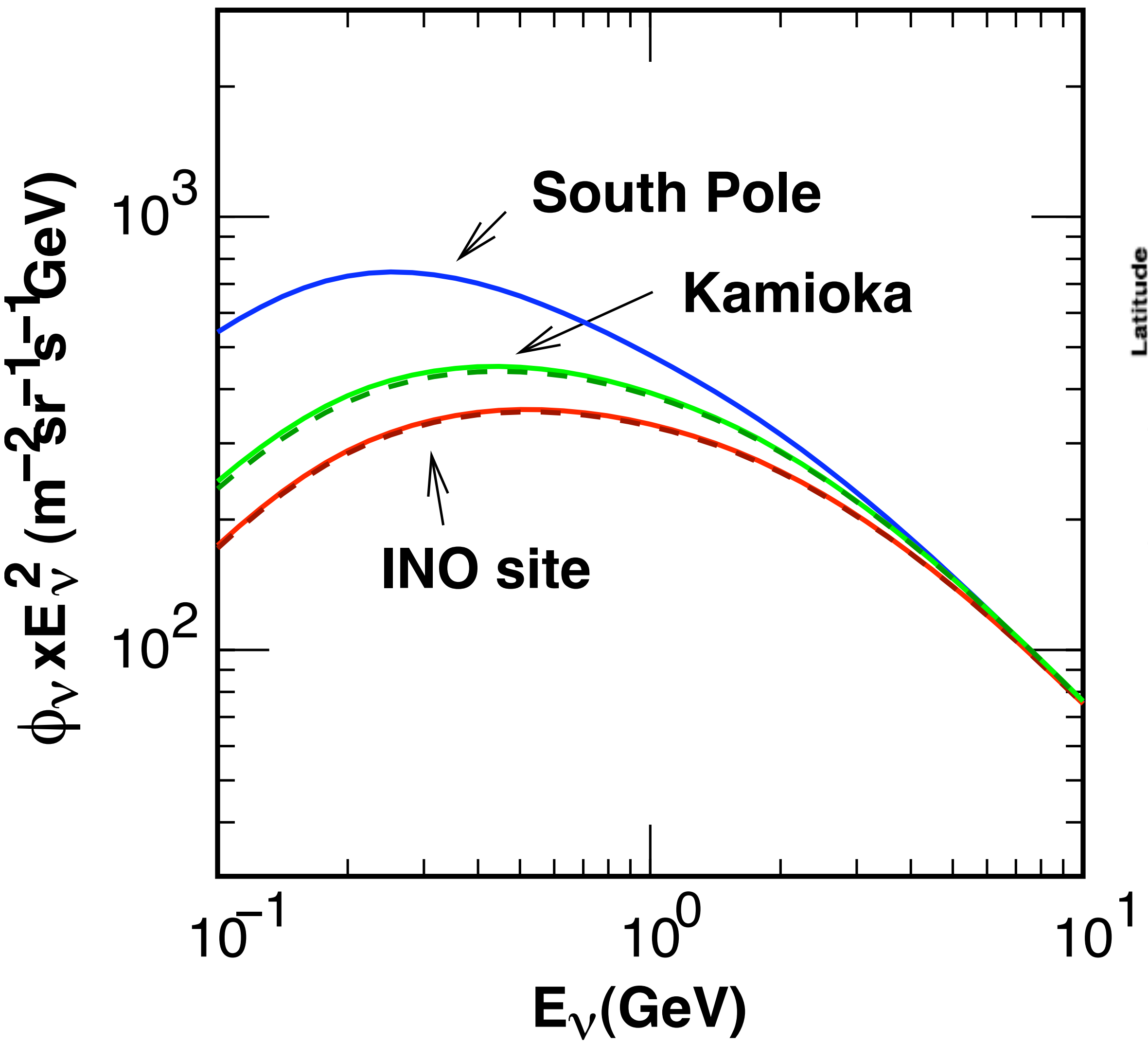
RPC (active detector element)

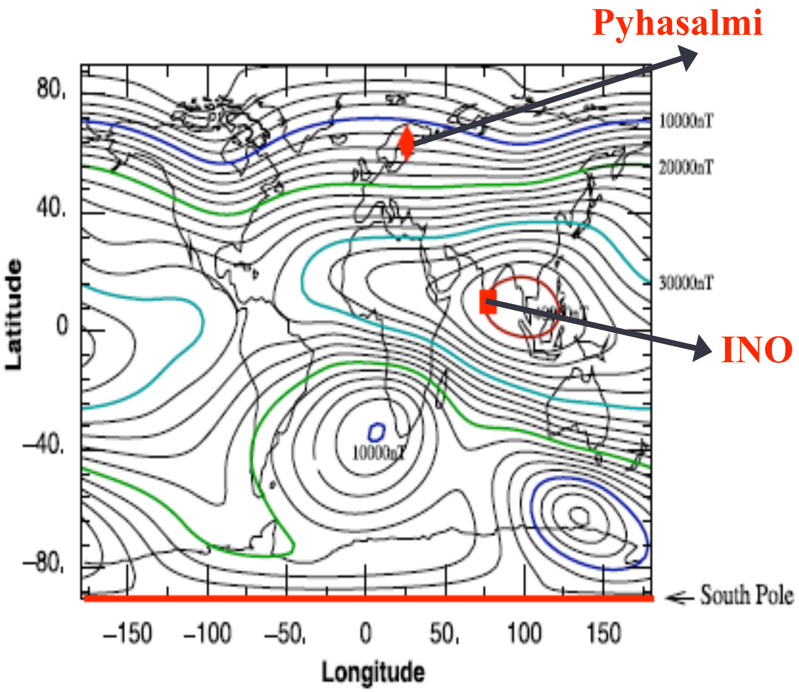


Specifications of the ICAL Detector

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





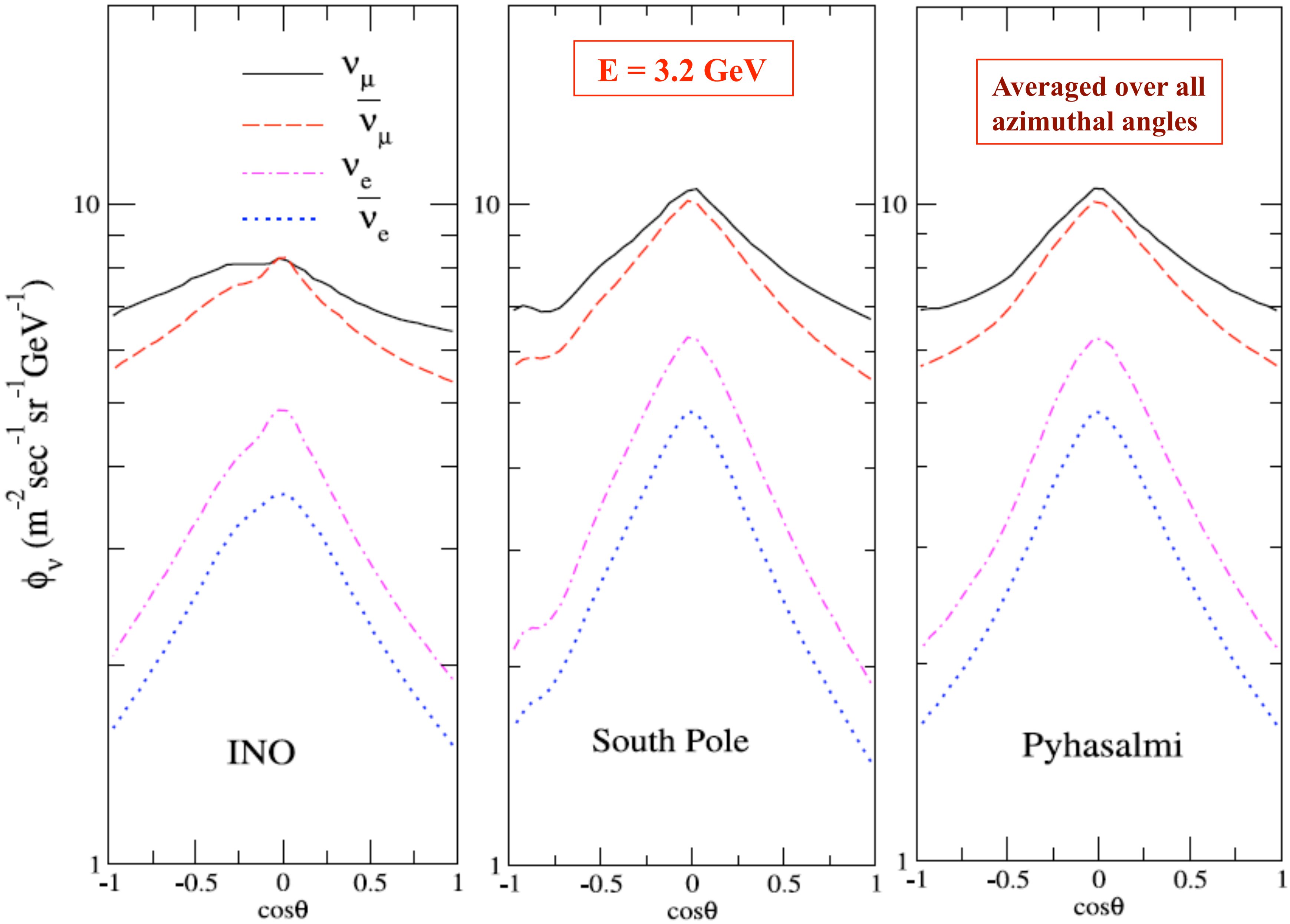
Horizontal component of the geomagnetic field

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

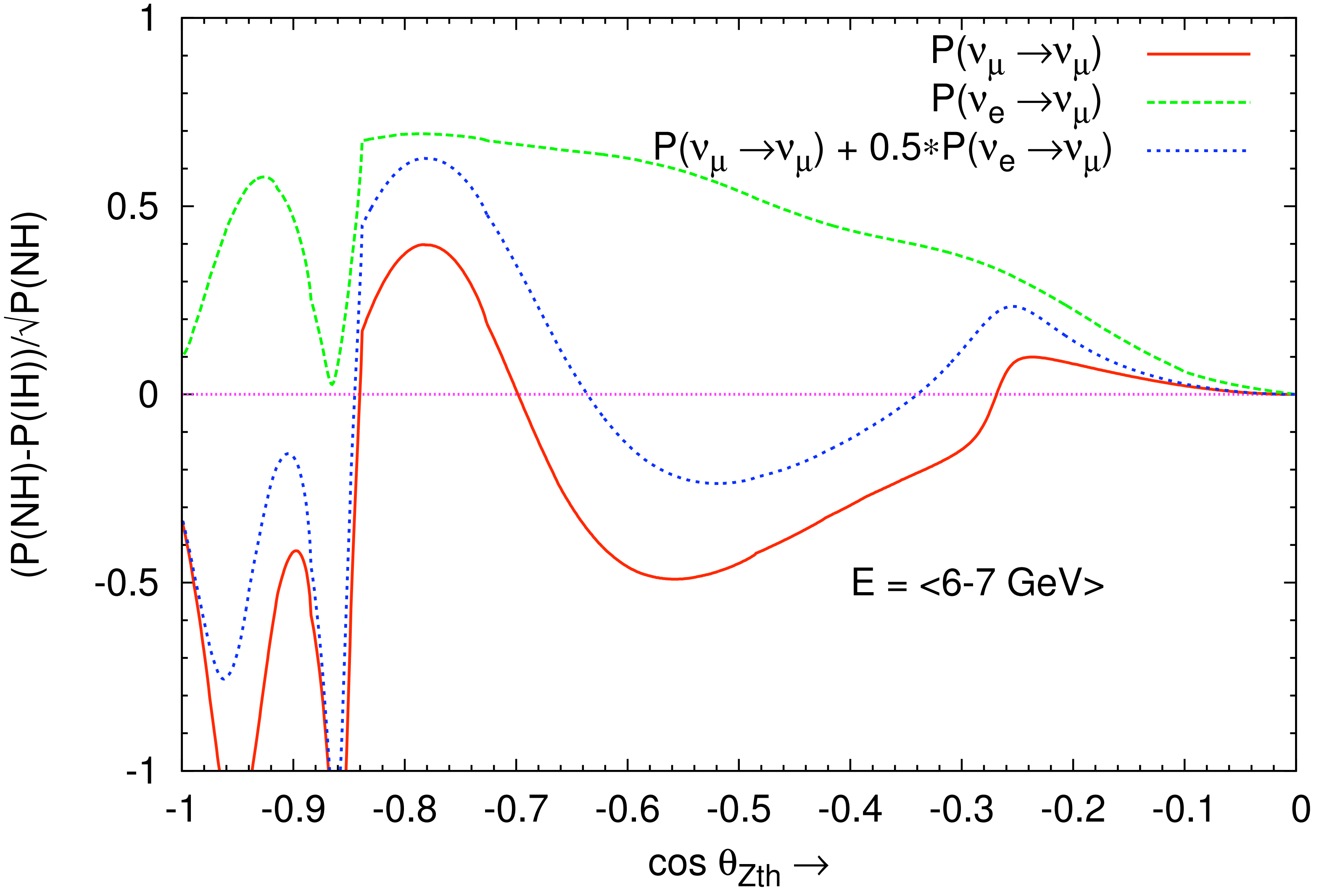
Athar, Honda, Kajita, Kasahara, Midorikawa, arXiv:1210.5154 [hep-ph]

Atmospheric Neutrino Flux



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

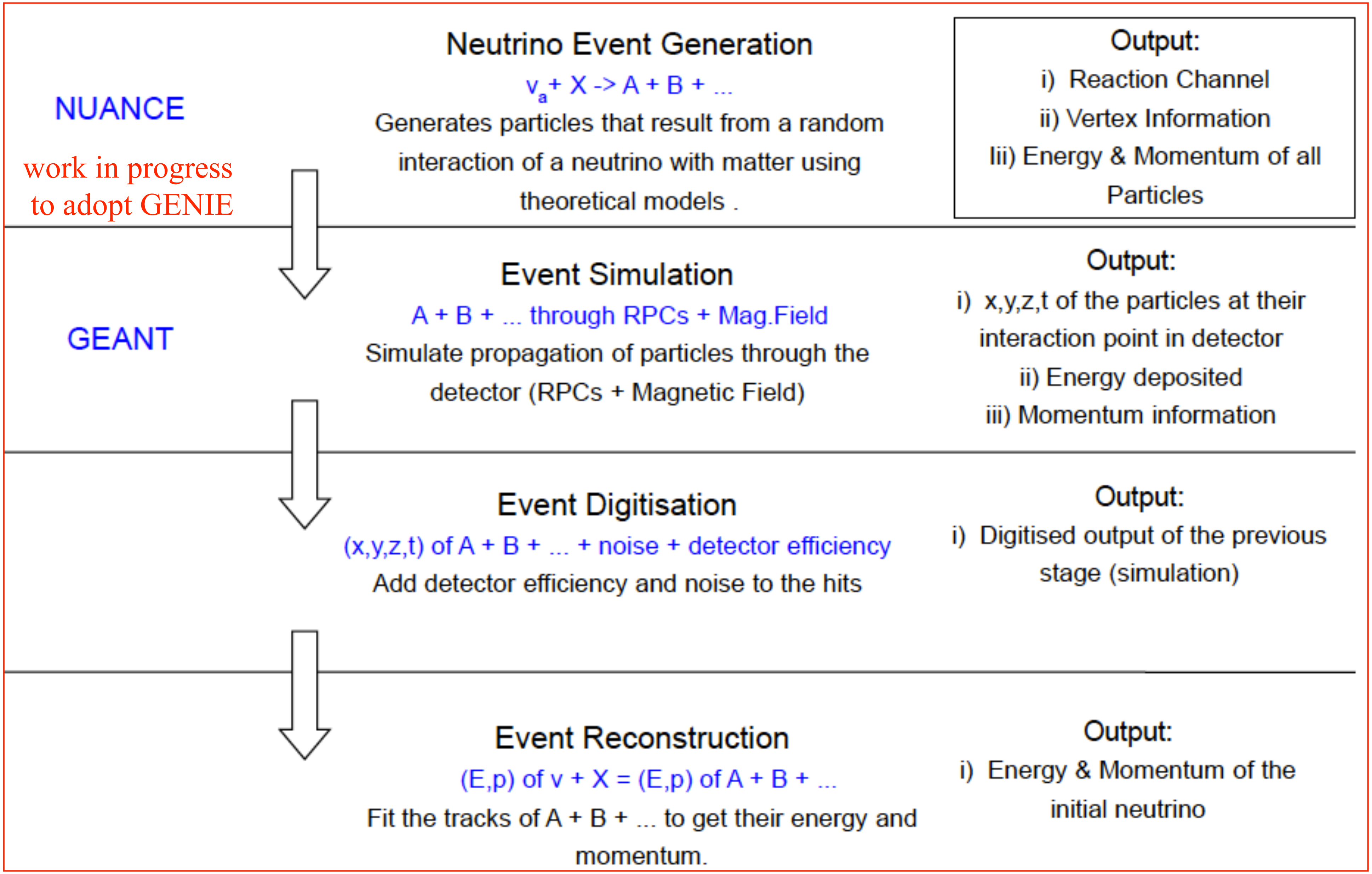
Atmospheric Conspiracy



Presence of different flavors dilutes the MH effect in oscillation

Agarwalla, Chatterjee, Khatun, work in progress (INO Collaboration)

Overview of Simulation Framework



NUANCE

work in progress
to adopt GENIE

Neutrino Event Generation

v_a+ X -> A + B + ...

Generates particles that result from a random interaction of a neutrino with matter using theoretical models .

Output:
- i) Reaction Channel
- ii) Vertex Information
- Iii) Energy & Momentum of all Particles

GEANT

Event Simulation

A + B + ... through RPCs + Mag.Field

Simulate propagation of particles through the detector (RPCs + Magnetic Field)

Output:
- i) x,y,z,t of the particles at their interaction point in detector
- ii) Energy deposited
- iii) Momentum information

Event Digitisation

(x,y,z,t) of A + B + ... + noise + detector efficiency

Add detector efficiency and noise to the hits

Output:
- i) Digitised output of the previous stage (simulation)

Event Reconstruction

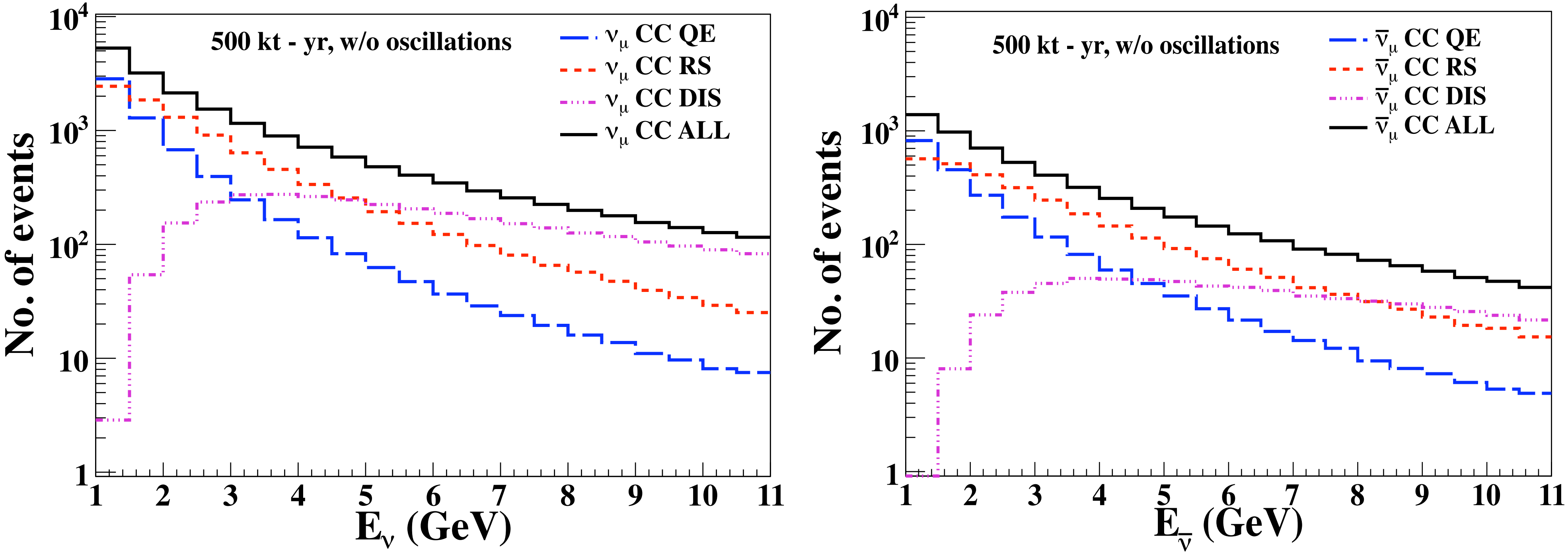
(E,p) of v + X = (E,p) of A + B + ...

Fit the tracks of A + B + ... to get their energy and momentum.

Output:
- i) Energy & Momentum of the initial neutrino

Simulation work is under progress in full swing!

Events in Various Channels

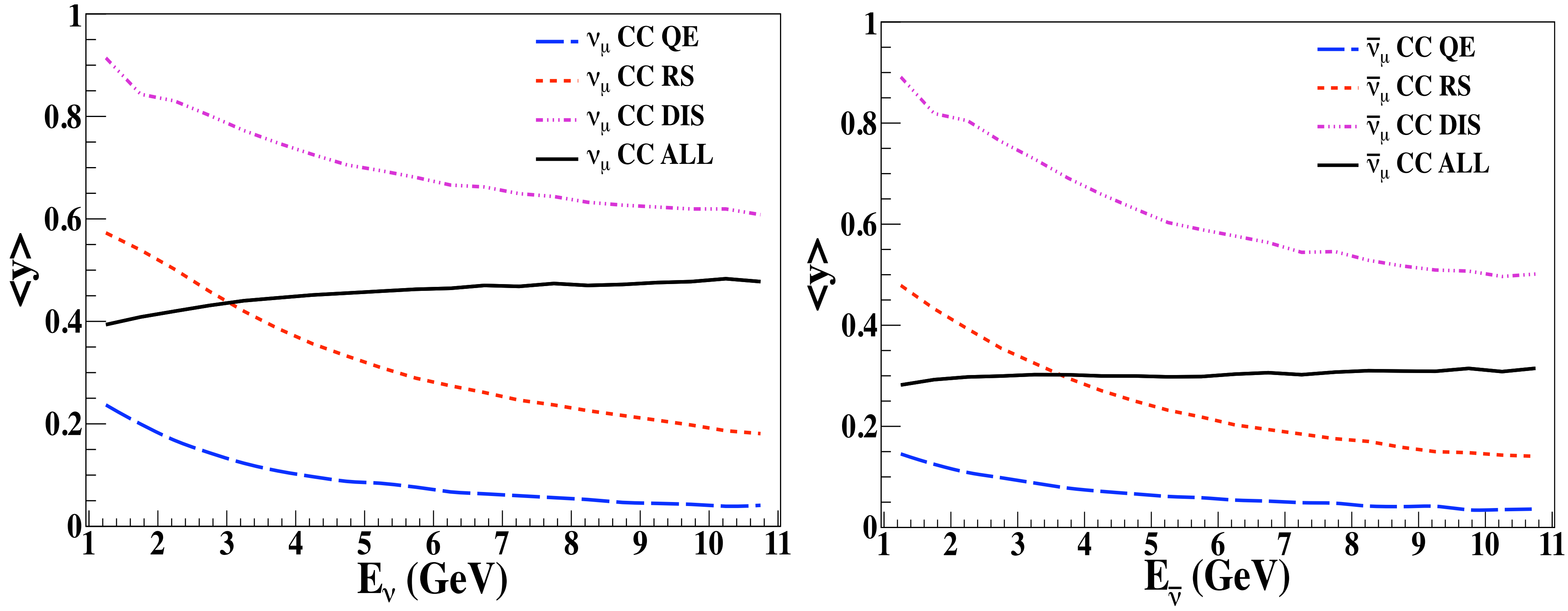


Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

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

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

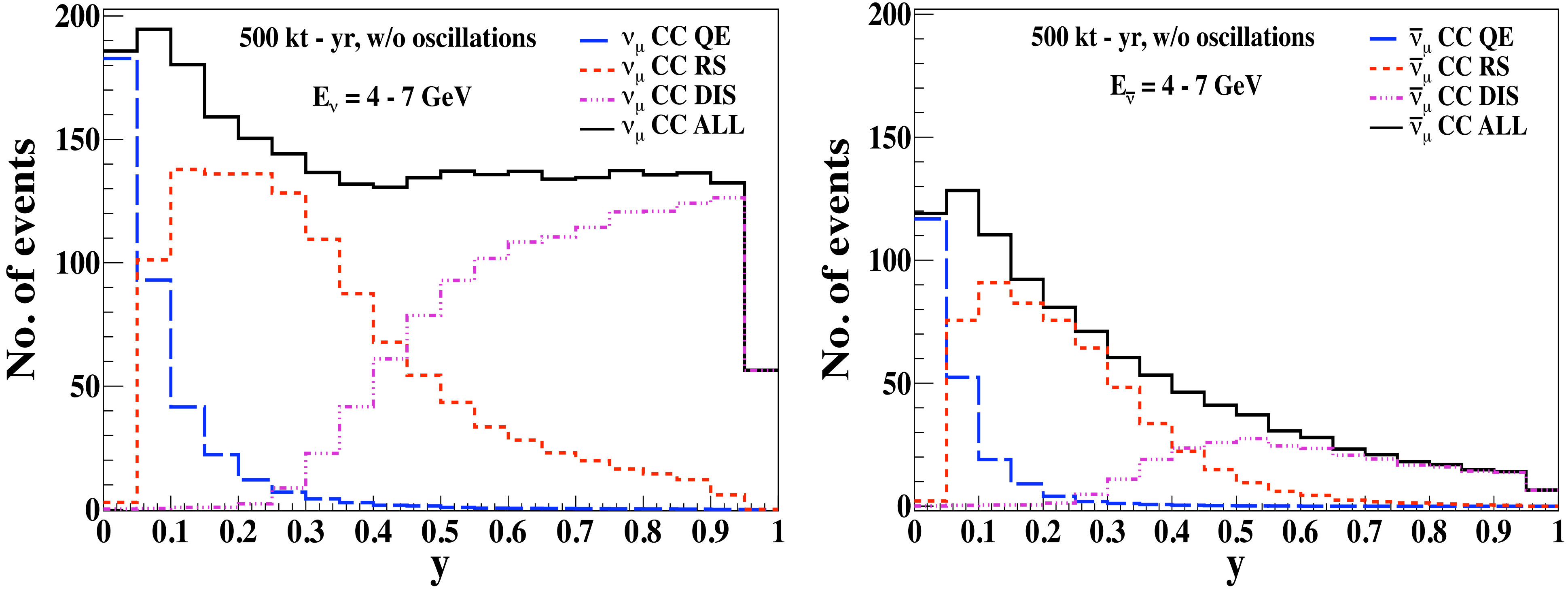


Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Average Inelasticity in the deep-inelastic events is significant

Crucial for mass hierarchy identification

Distribution of Inelasticities in Events

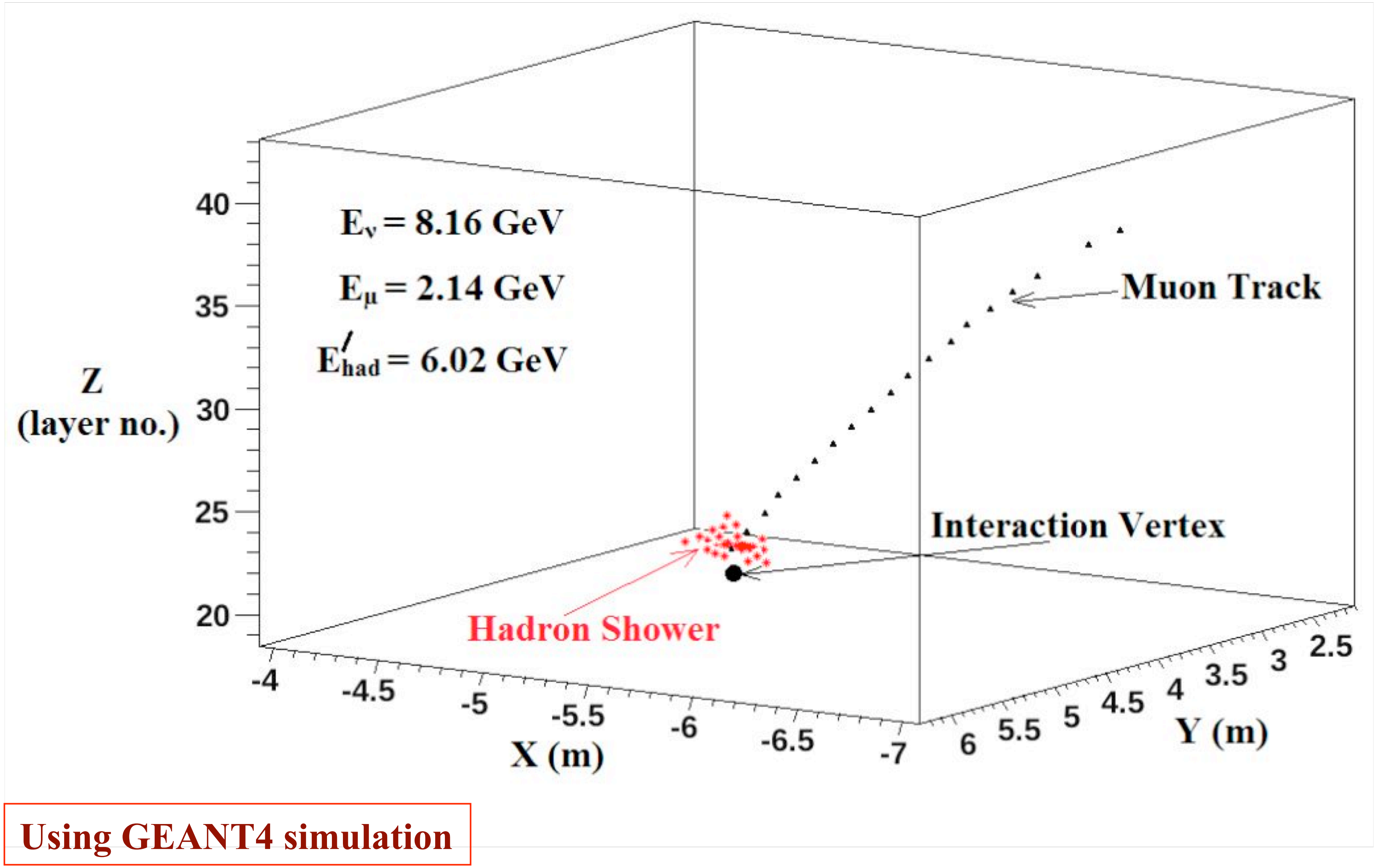


Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Inelasticities in individual events have a wide distribution

Important to measure inelasticity in individual events

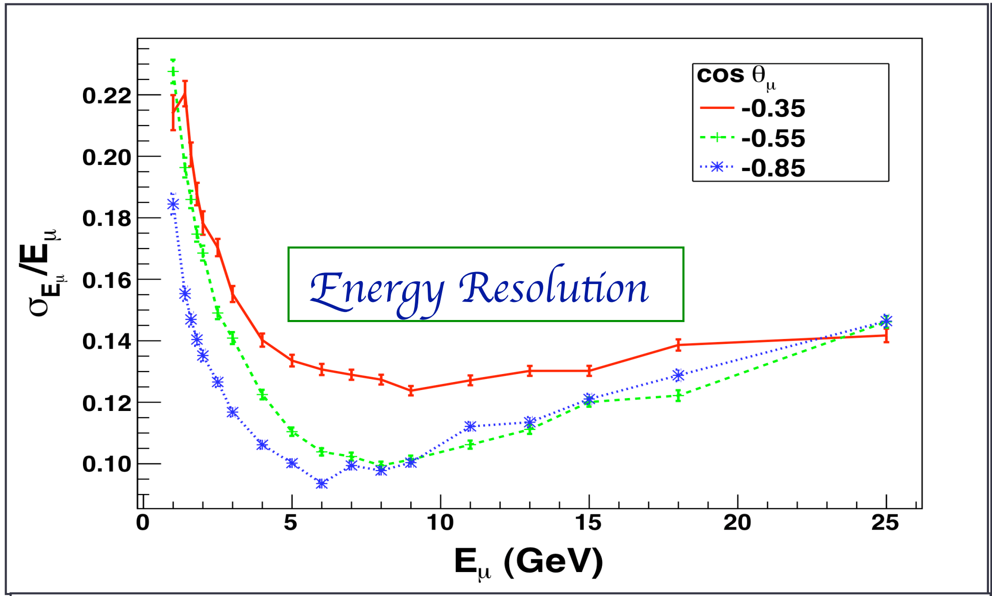
Event Display Inside the ICAL Detector

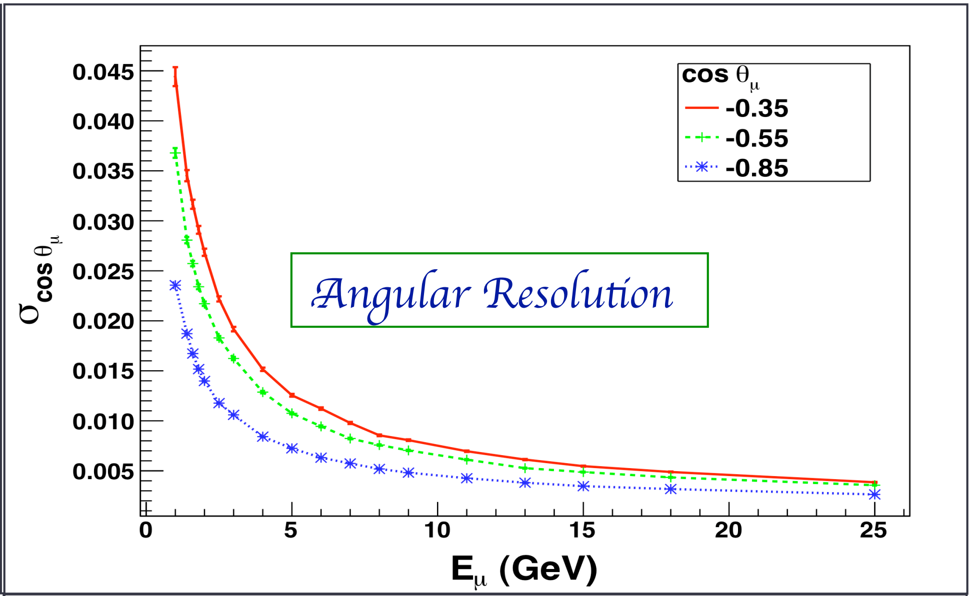


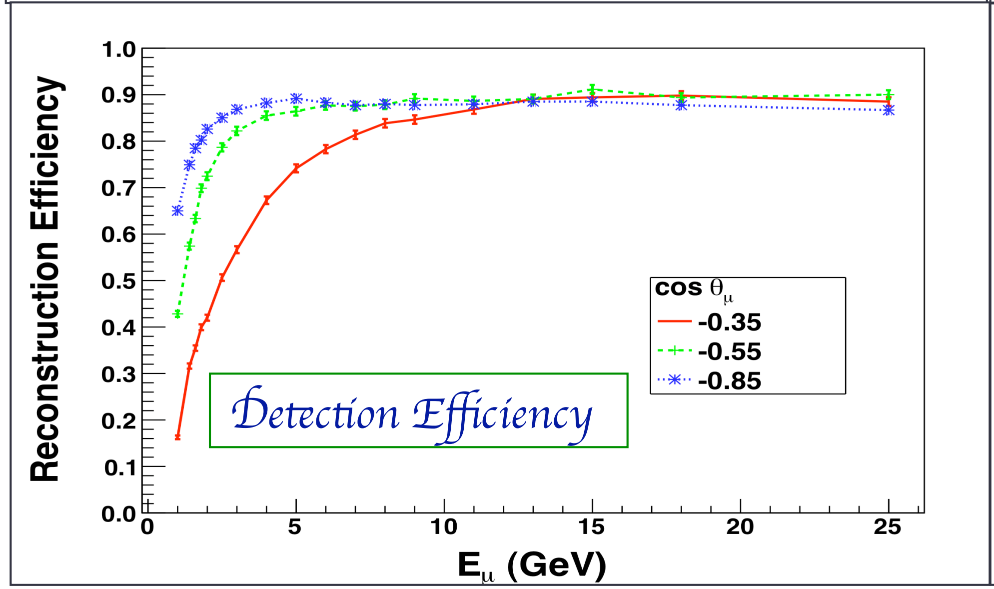
Using GEANT4 simulation

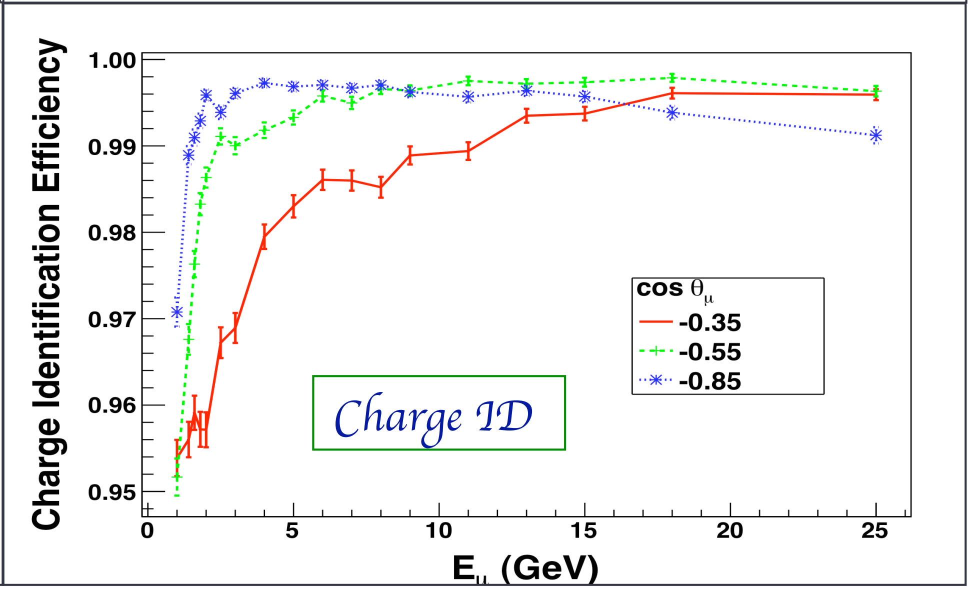
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Muon Efficiencies and Resolutions



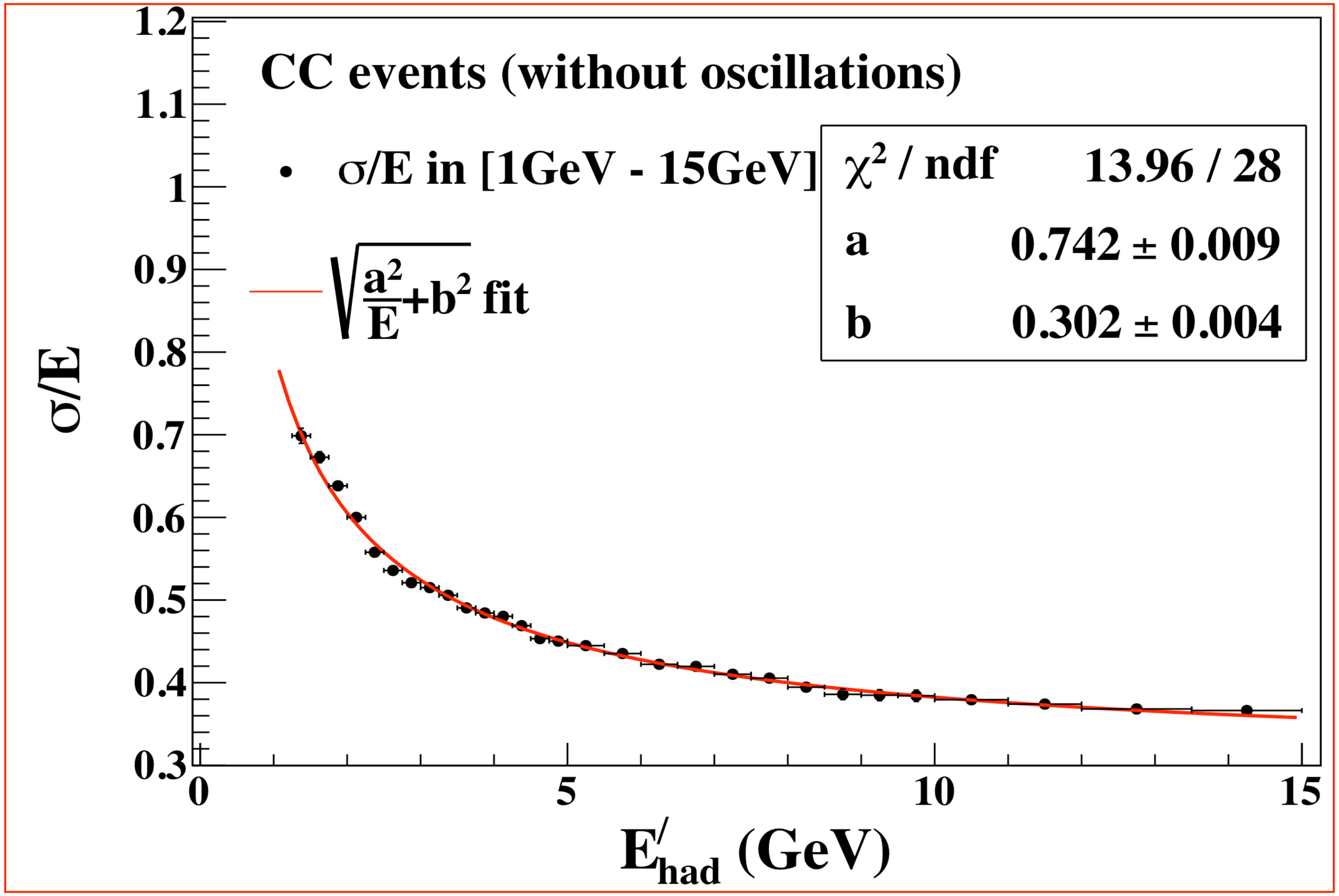






Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore etal., arXiv:1405.7243 [physics.ins-det]

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

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

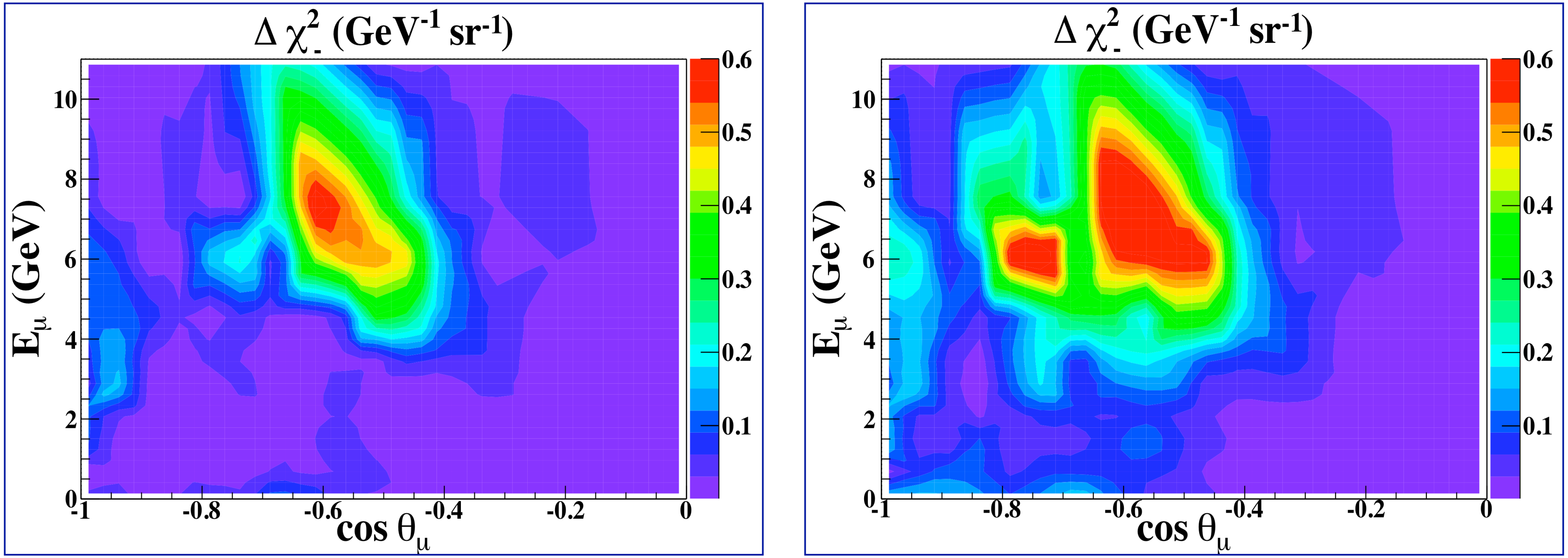
Observable	Range	Bin width	Total bins	
E_μ (GeV)	$[1, 4)$	0.5	6	10
	$[4, 7)$	1	3	
	$[7, 11)$	4	1	
$\cos\theta_\mu$	$[-1.0, -0.4)$	0.05	12	21
	$[-0.4, 0.0)$	0.1	4	
	$[0.0, 1.0]$	0.2	5	
$E'_{\rm had}$ (GeV)	$[0, 2)$	1	2	4
	$[2, 4)$	2	1	
	$[4, 15)$	11	1	

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

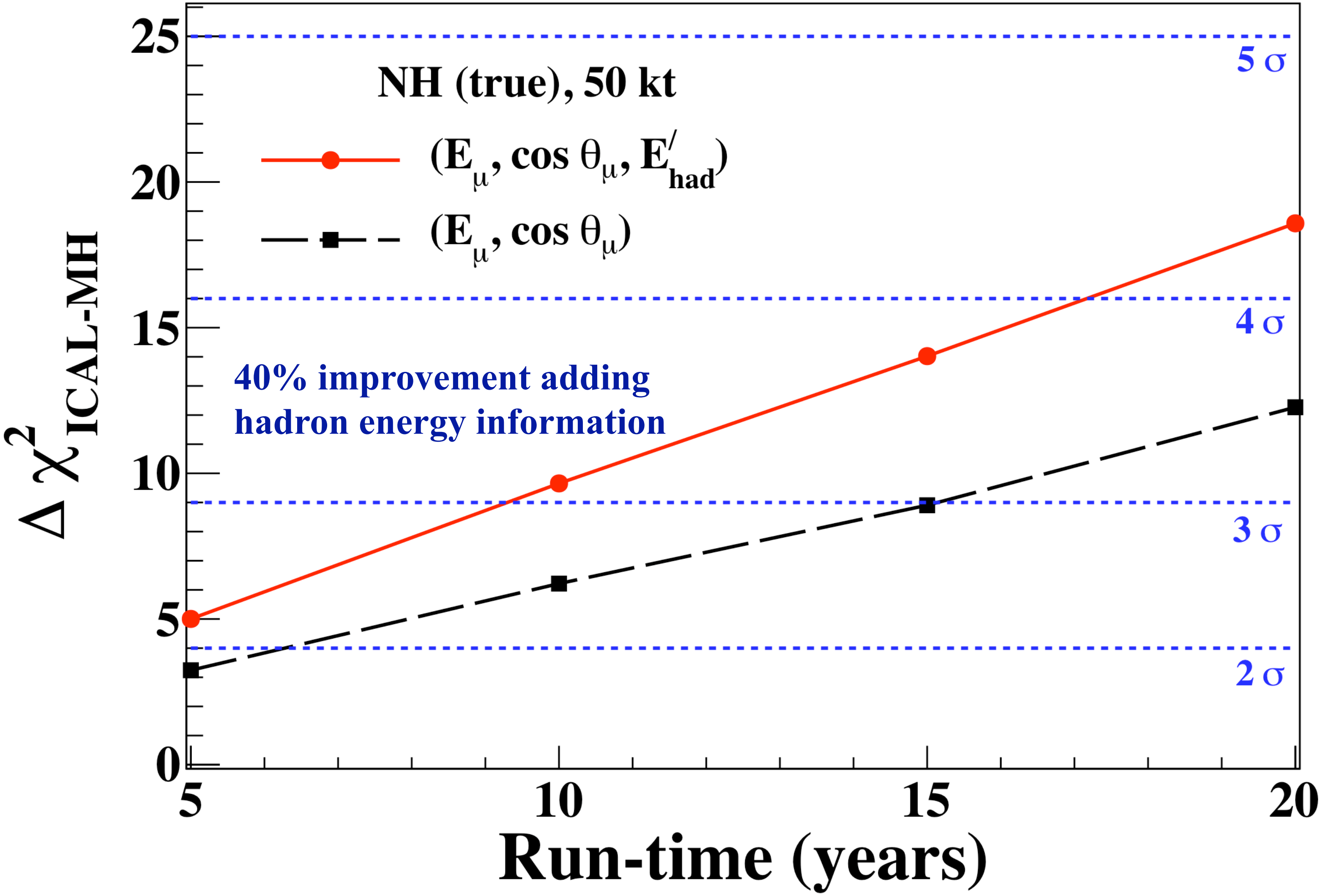


Hadron energy information not used

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

Identifying Neutrino Mass Hierarchy with ICAL

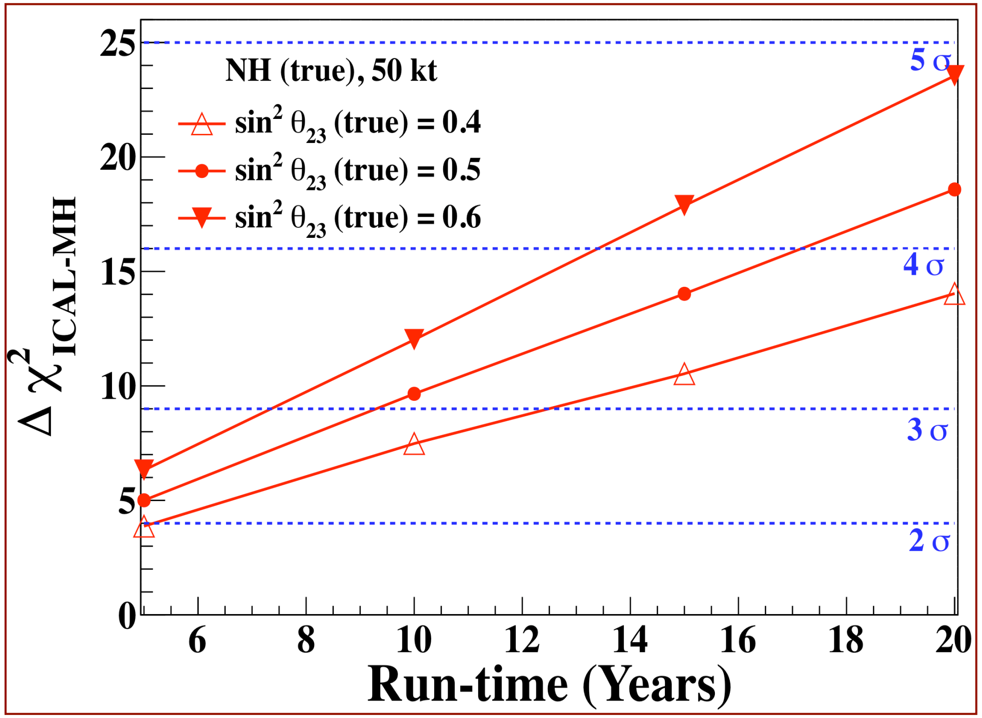


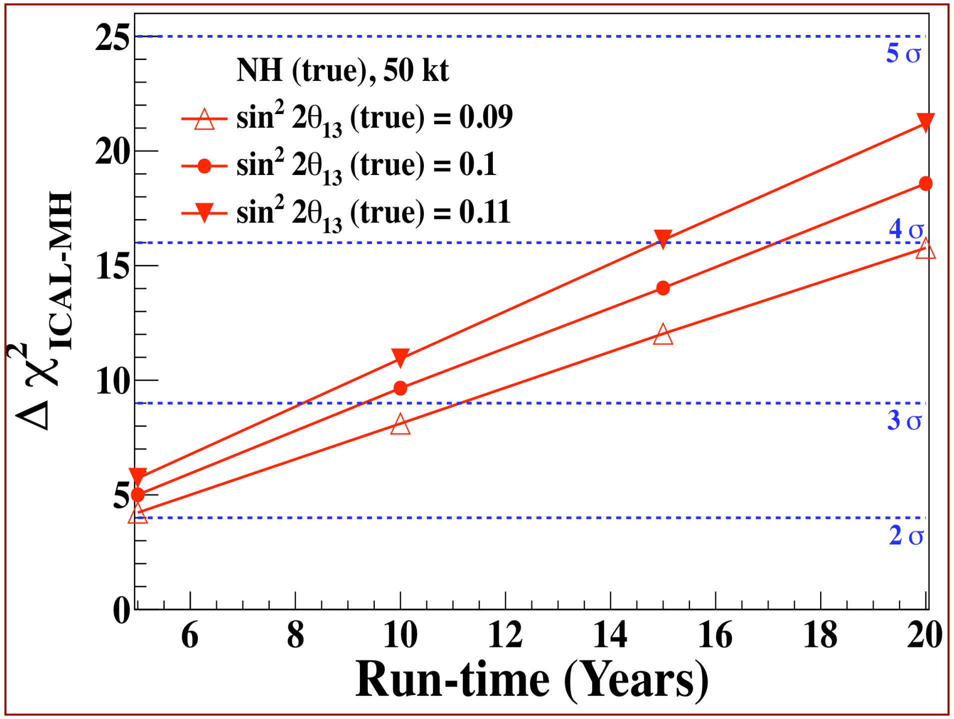
Median Sensitivity

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

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

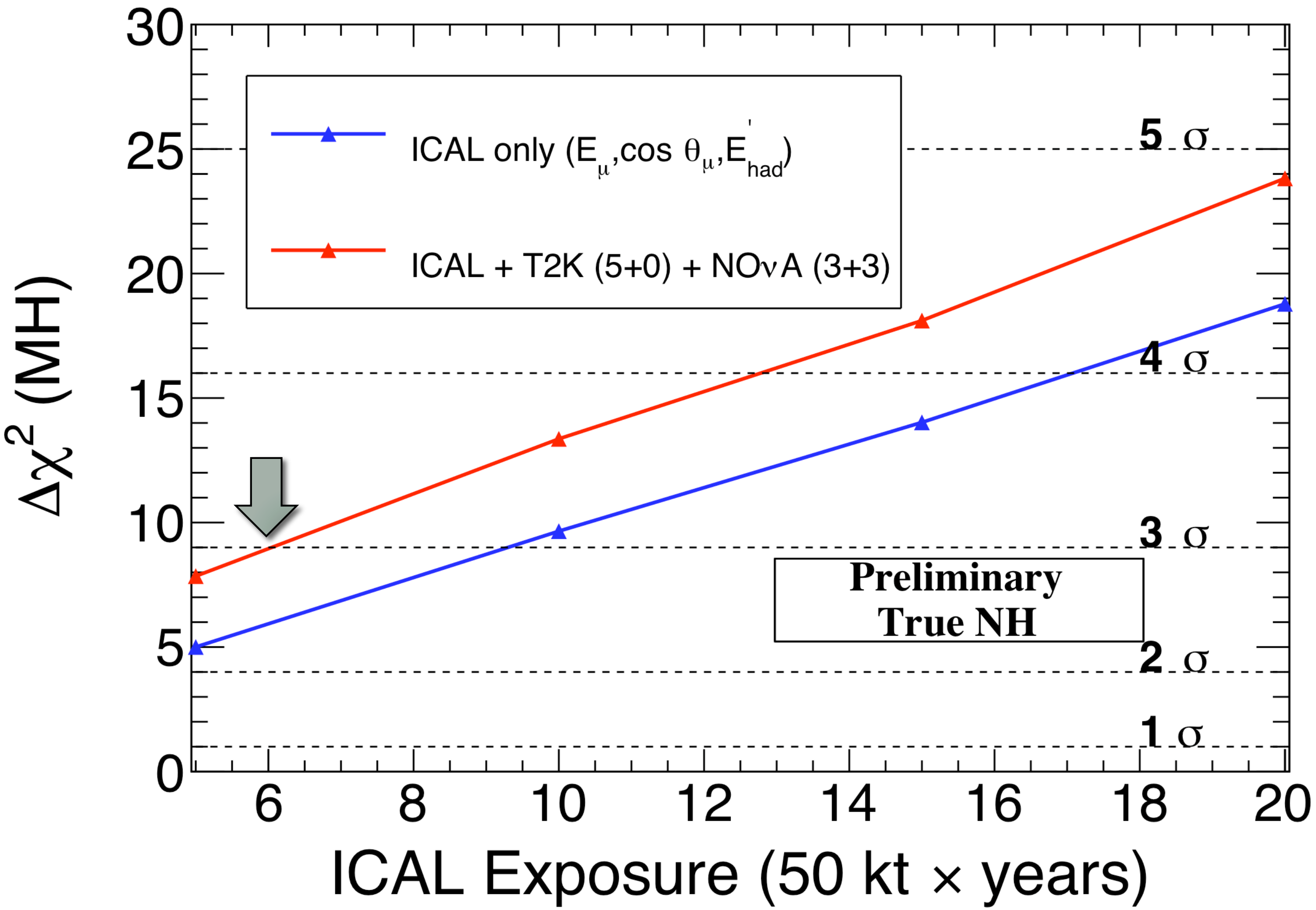




Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

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

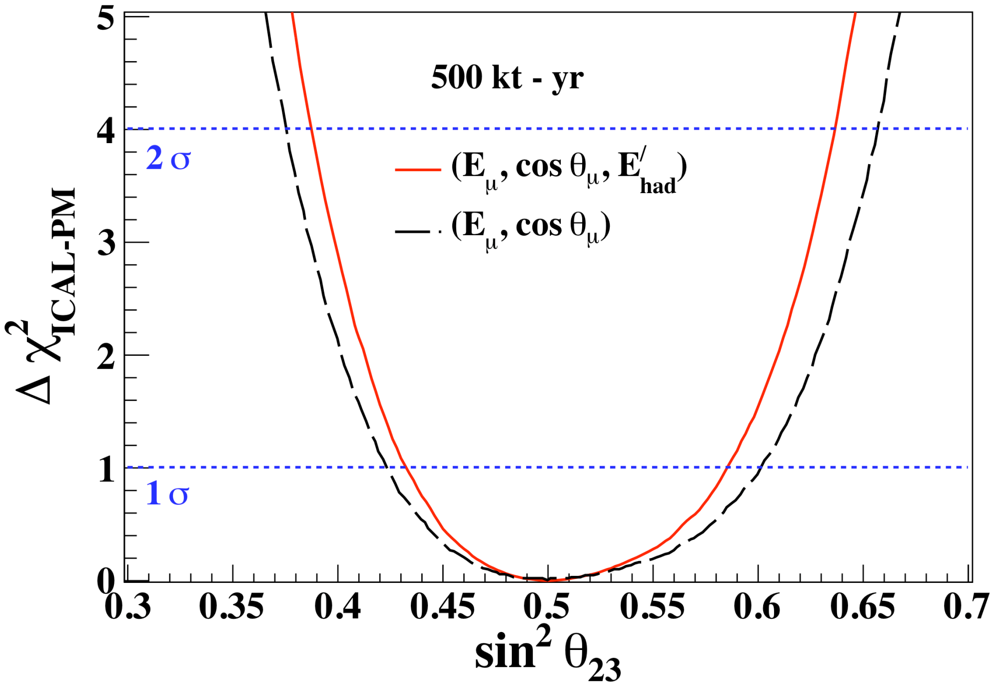
MH Discovery with ICAL+T2K+NOνA



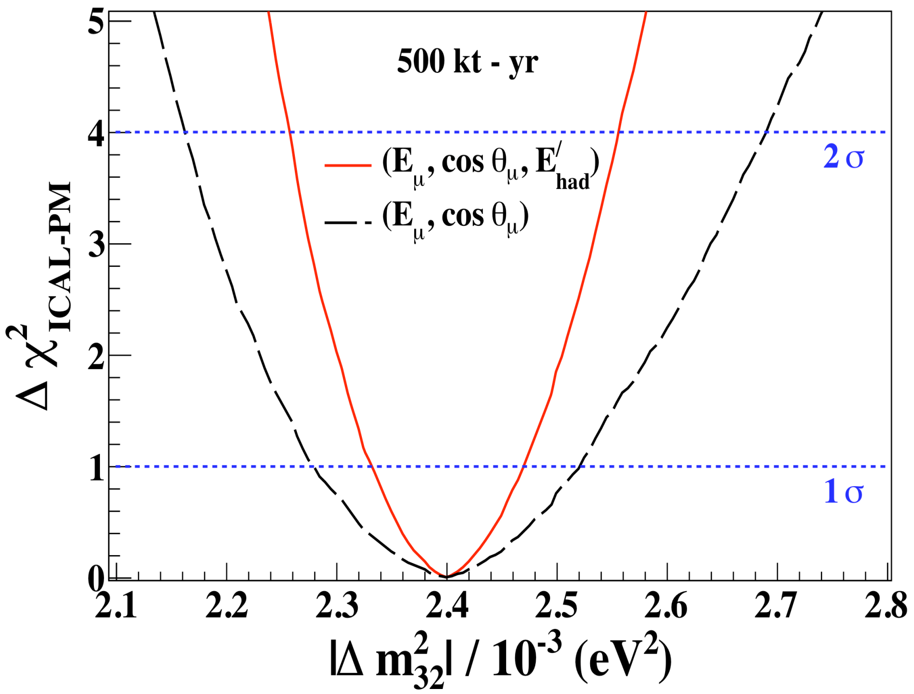
Devi, Thakore, Agarwalla, Dighe, work in progress (INO Collaboration)

3σ median sensitivity can be achieved in 6 years

Precision of Atmospheric Oscillation Parameters



Relative 1σ precision: 12%

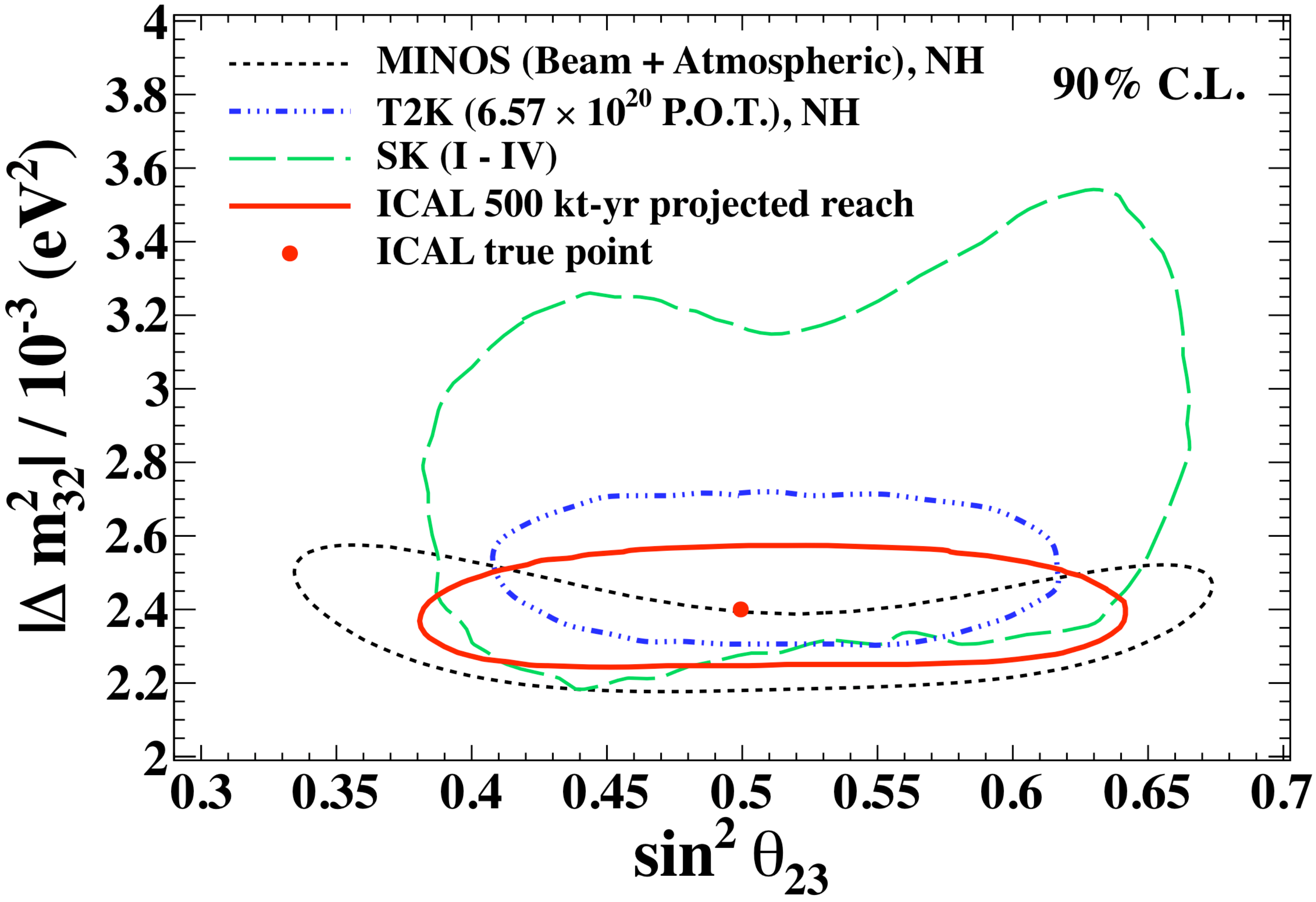


Relative 1σ precision: 2.9%

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

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

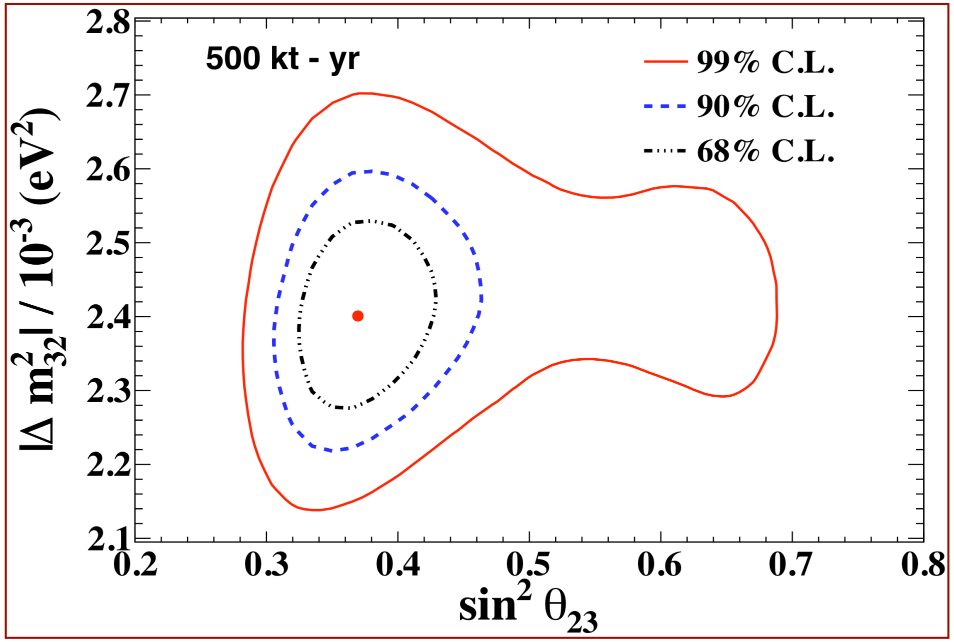
Precision Measurement of Atmospheric Parameters

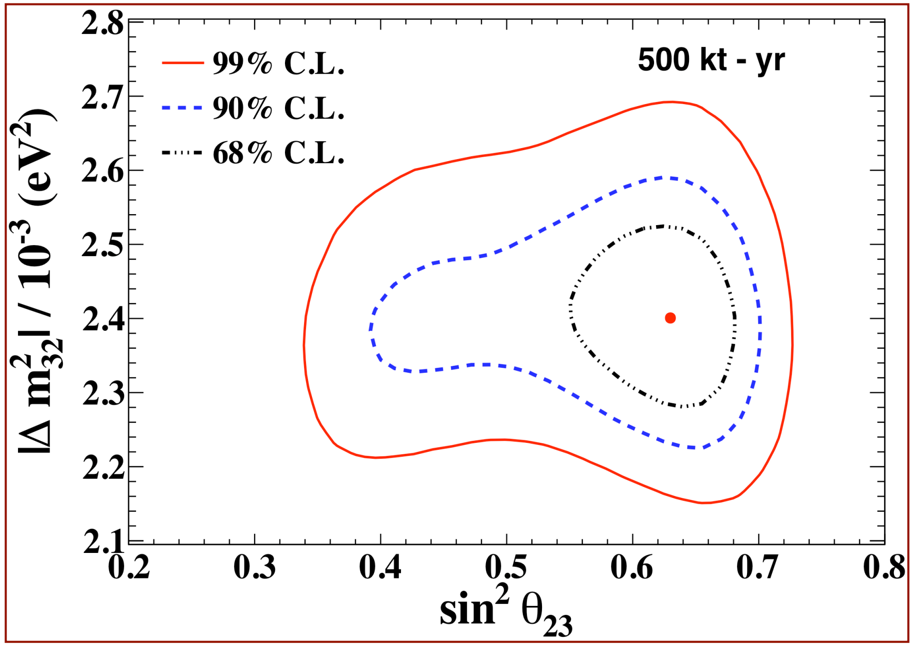


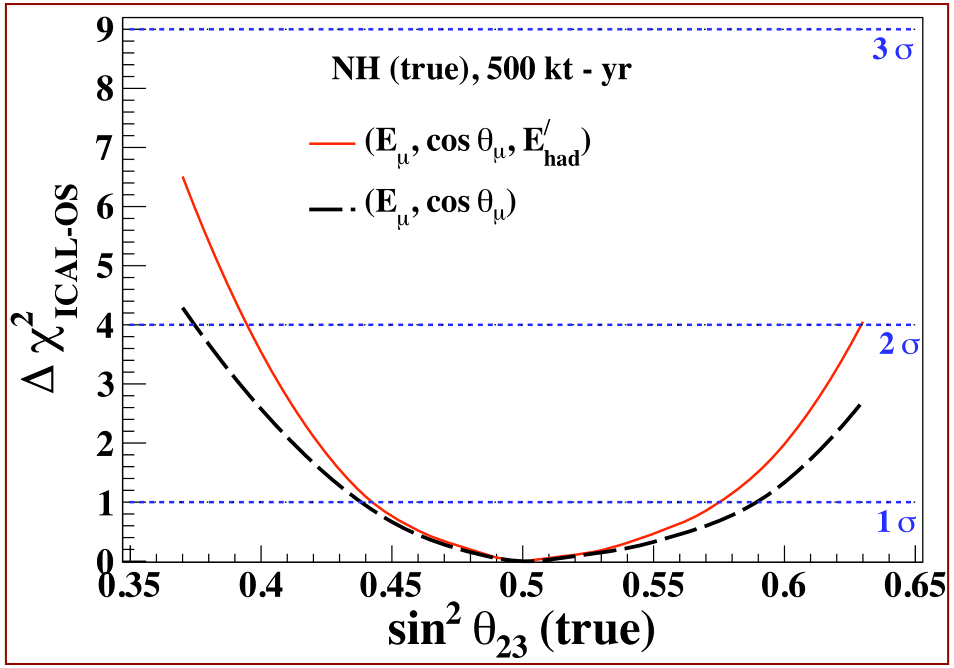
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

ICAL's expected precision on atmospheric mass splitting is far superior 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
(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**

- **DPR for Detector and DAQ system is ready**

- **Will start industrial production of RPCs and associated front-end electronics soon**

- **Full project approved by Indian Atomic Energy Commission. Waiting for approval from Prime Minister's cabinet committee to start construction**

Concluding Remarks

Recent discovery of θ_{13} signifies an important breakthrough in establishing the standard three flavor oscillation picture of neutrinos

It has opened up exciting possibilities for current & future oscillation experiments

At present, we have:

$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.799 \rightarrow 0.844 & 0.515 \rightarrow 0.581 & 0.129 \rightarrow 0.173 \\ 0.212 \rightarrow 0.527 & 0.426 \rightarrow 0.707 & 0.598 \rightarrow 0.805 \\ 0.233 \rightarrow 0.538 & 0.450 \rightarrow 0.722 & 0.573 \rightarrow 0.787 \end{pmatrix}$$

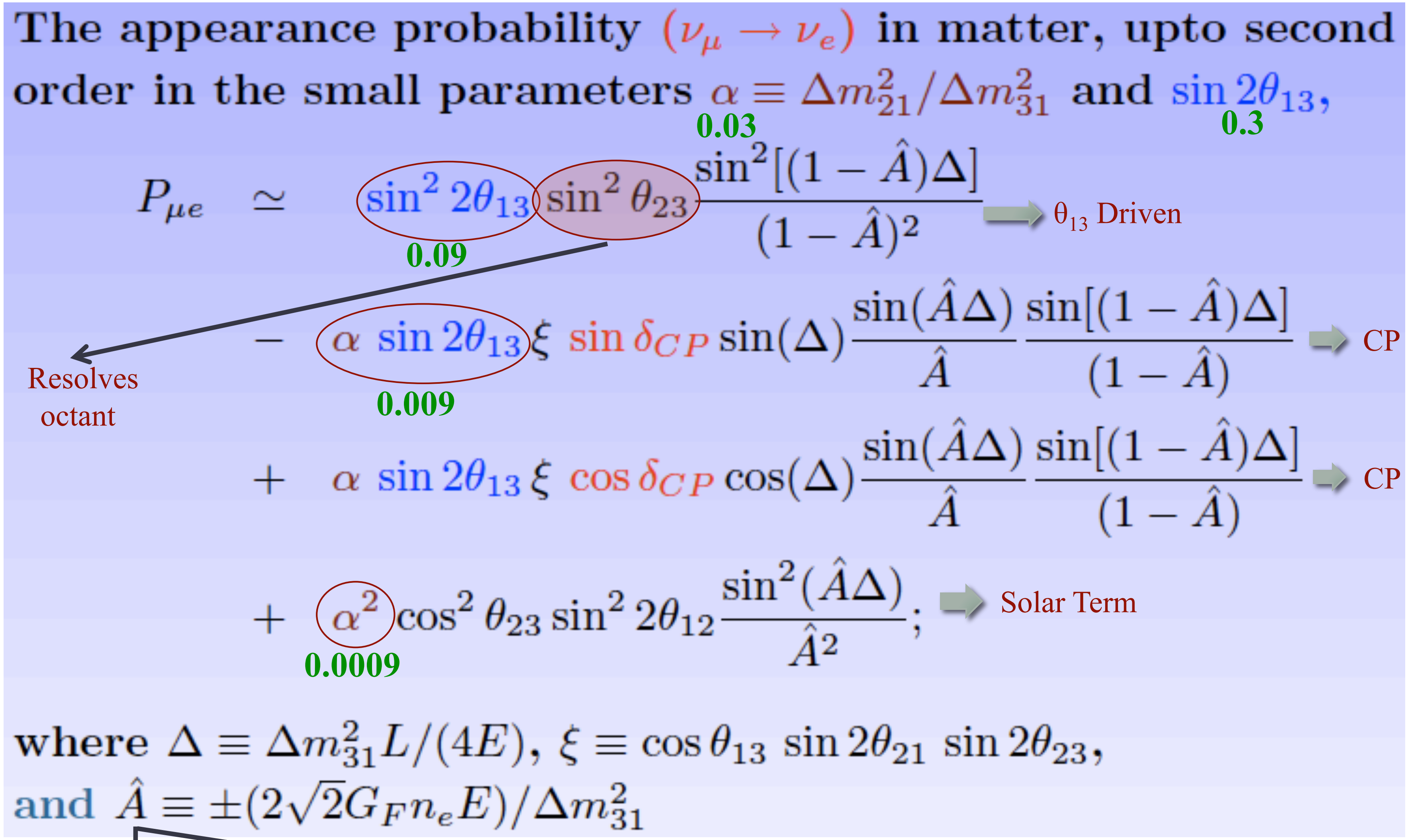
Satisfactory progress in last 15 years but still very far from the 'dream' precision:

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

!! Let us work together and achieve it !!

Thank you!

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)

$$P_{\mu e} \simeq \underbrace{\sin^2 2\theta_{13}}_{0.09} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

→ θ_{13} Driven

Resolves octant

$$- \underbrace{\alpha \sin 2\theta_{13}}_{0.009} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ 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

$$+ \underbrace{\alpha^2}_{0.0009} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

→ 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?