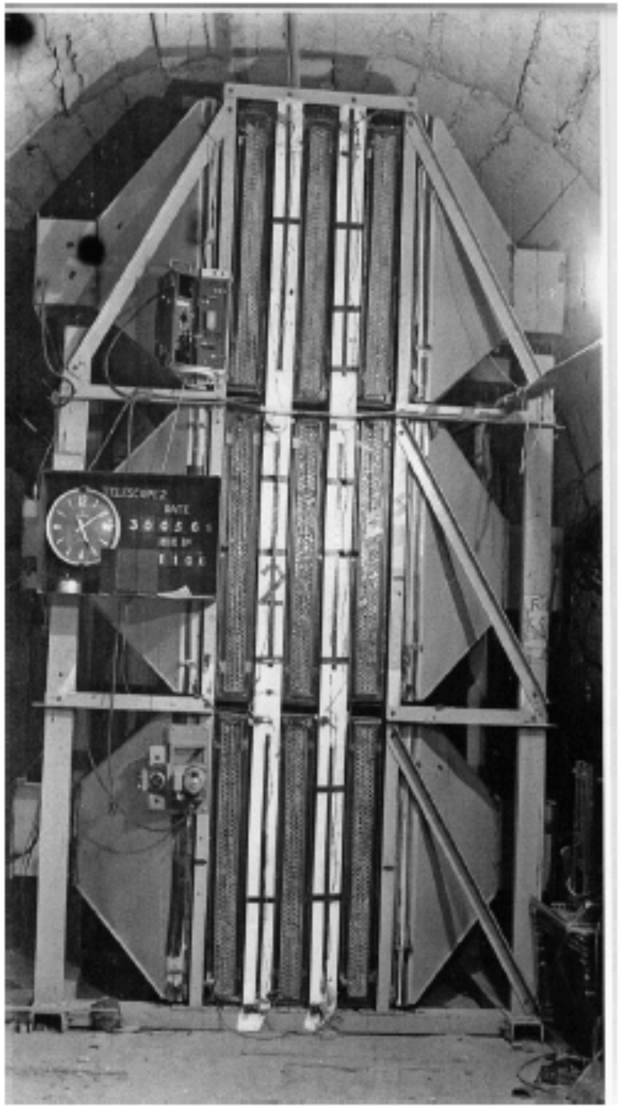
India-based Neutrino Observatory: Present Status and Physics Reach

Sanjib Kumar Agarwalla

sanjib@iopb.res.in

Institute of Physics, Bhubaneswar, India



Detector in
Kolar Gold Fields

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters 18, (1965) 196
(15th Aug 1965)

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

PRL 15, (1965) 429
(30th Aug 1965)

An Indian Initiative to build a world-class underground laboratory to pursue non-accelerator based high energy and nuclear physics research

The initial goal of INO is to study fundamental properties of neutrinos

For more updates visit: http://www.ino.tifr.res.in/ino/

You can join us at: https://www.facebook.com/ino.neutrino

The INO Collaboration

- INO Collaborating Institutions

Collaborating Institutions:

- AMU
- BARC
- BHU
- CU
- DU
- HNBGU
- HPU
- HRI
- IGCAR
- IITB
- IITG
- IITM
- IMSc
- IOP
- JU
- KU
- MU
- NBU
- PRL
- PU
- SINP
- SMIT
- SU
- TIFR
- UoH
- VECC

+IISER (Mohali), American College , Tezpur Univ, CKU (Gulbarga)

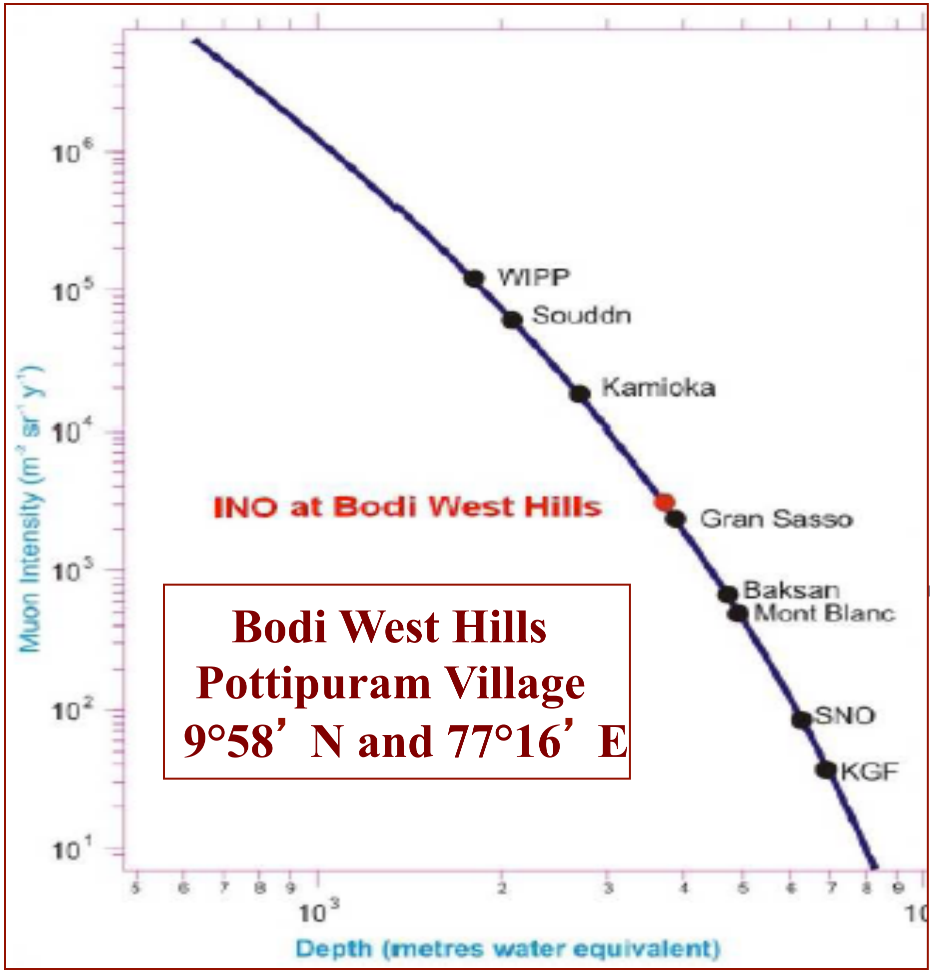
Participants of the INO Collaboration meeting at Madurai Kamaraj University (22-23 March 2018)

~28 institutions (national labs, Universities, IITs) participating

Nearly 100 Scientists from 28 Research Institutes, IITs, & Universities all over India

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

Coordinates of INO

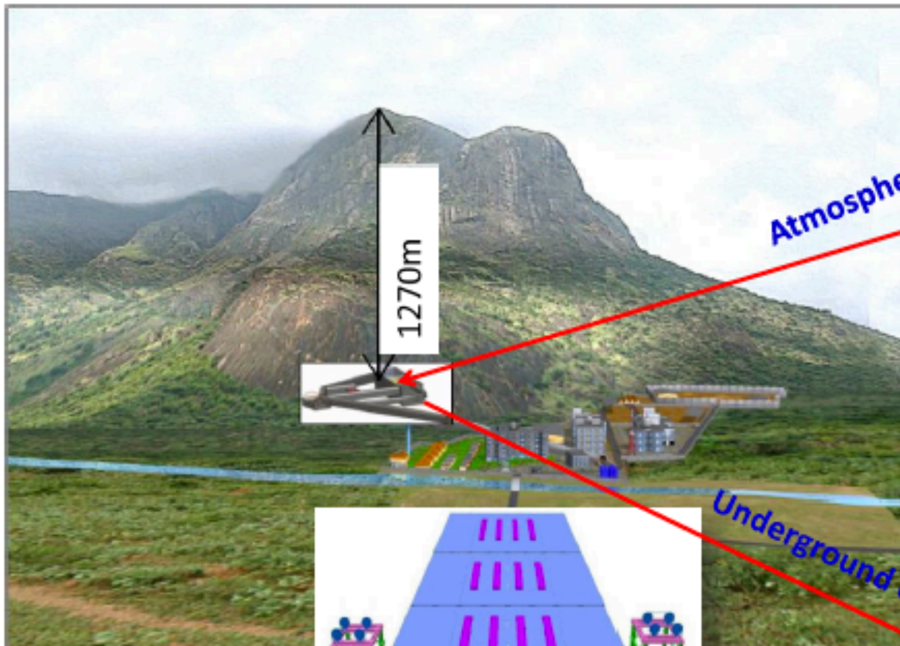


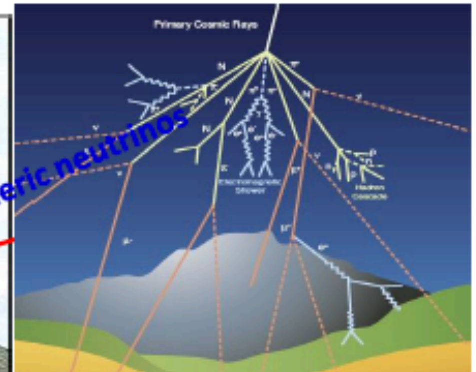
Bodi West Hills
Pottipuram Village
9°58’ N and 77°16’ E

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

Madurai has an International Airport

India based Neutrino Observatory at Pottipuram (Theni)

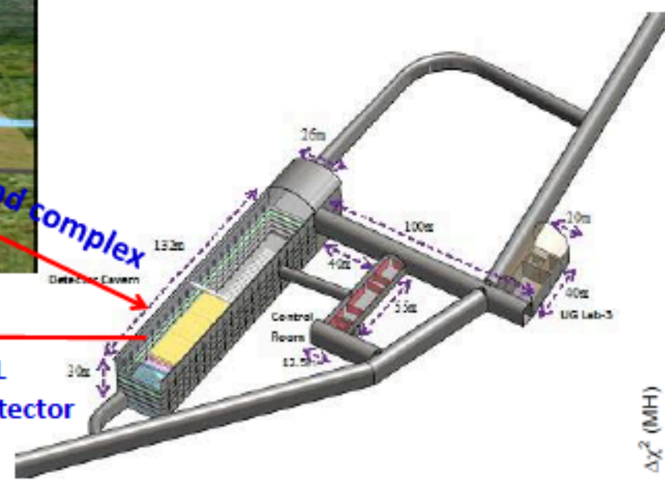




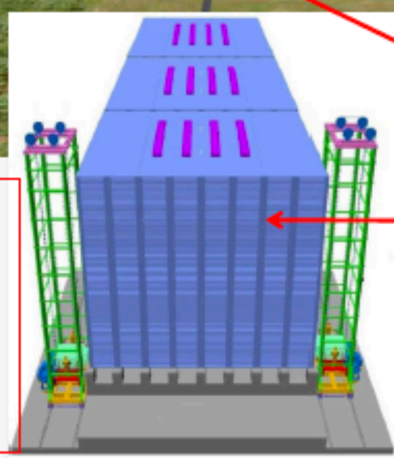
Atmospheric neutrinos

Collaboration of ~28 institutions (research centres, Universities, IITs)

Underground complex

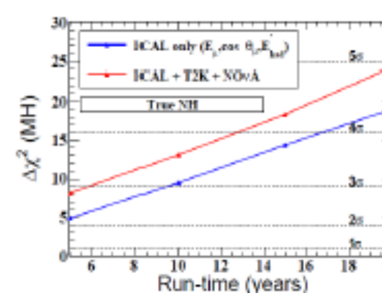


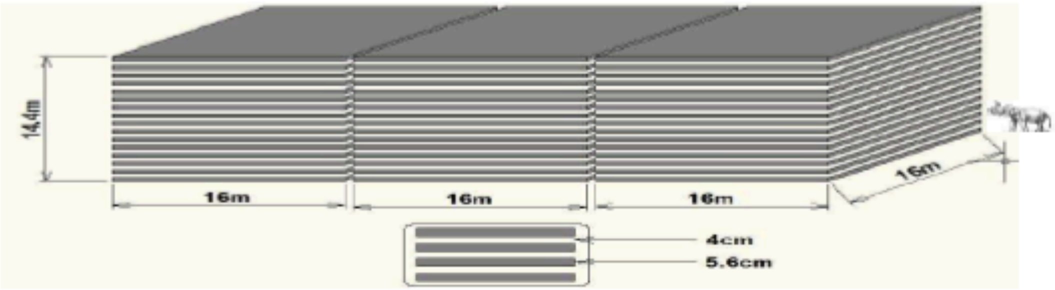
Will be largest electromagnet in the world – 51,000 tons. ~30000 glass RPCs (×3 world total)

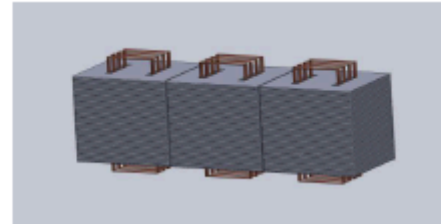


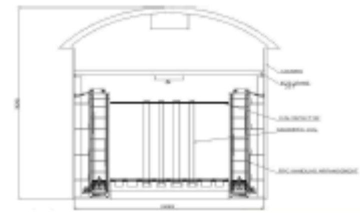
51 kton ICAL neutrino detector

Mass ordering of ν



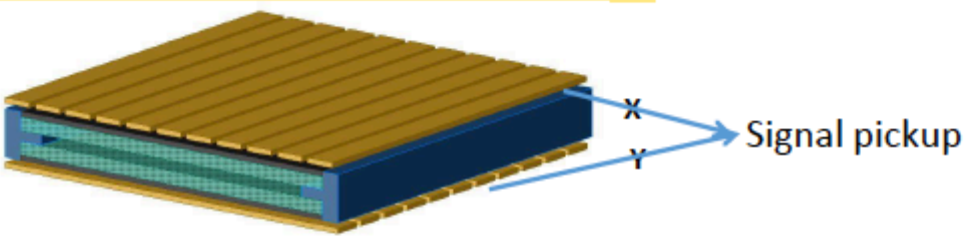




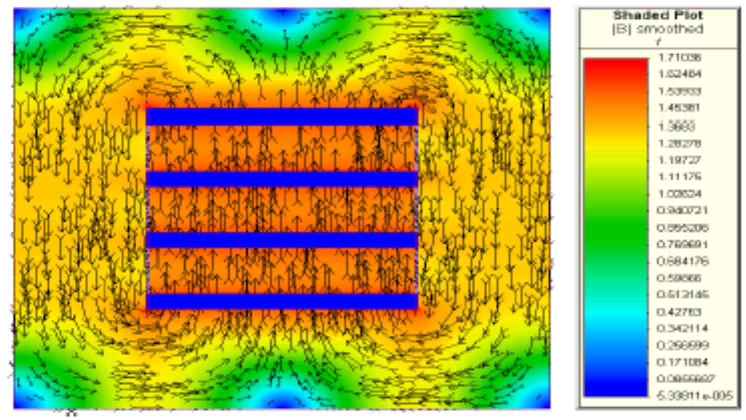


51 kt world's largest electromagnet

3 modules × 17 kton
Each with 150 layers Fe+RPC
B-field > 1 Tesla (90%)



Glass RPC for detecting charged particles
~30,000 RPCs required, ~ 3.8 M channels



B-field for 60 kA-turns, typical low C steel

Observe atmospheric neutrinos and antineutrinos separately over a wide range of energies & baselines using 50 kt magnetized Iron Calorimeter (ICAL) detector

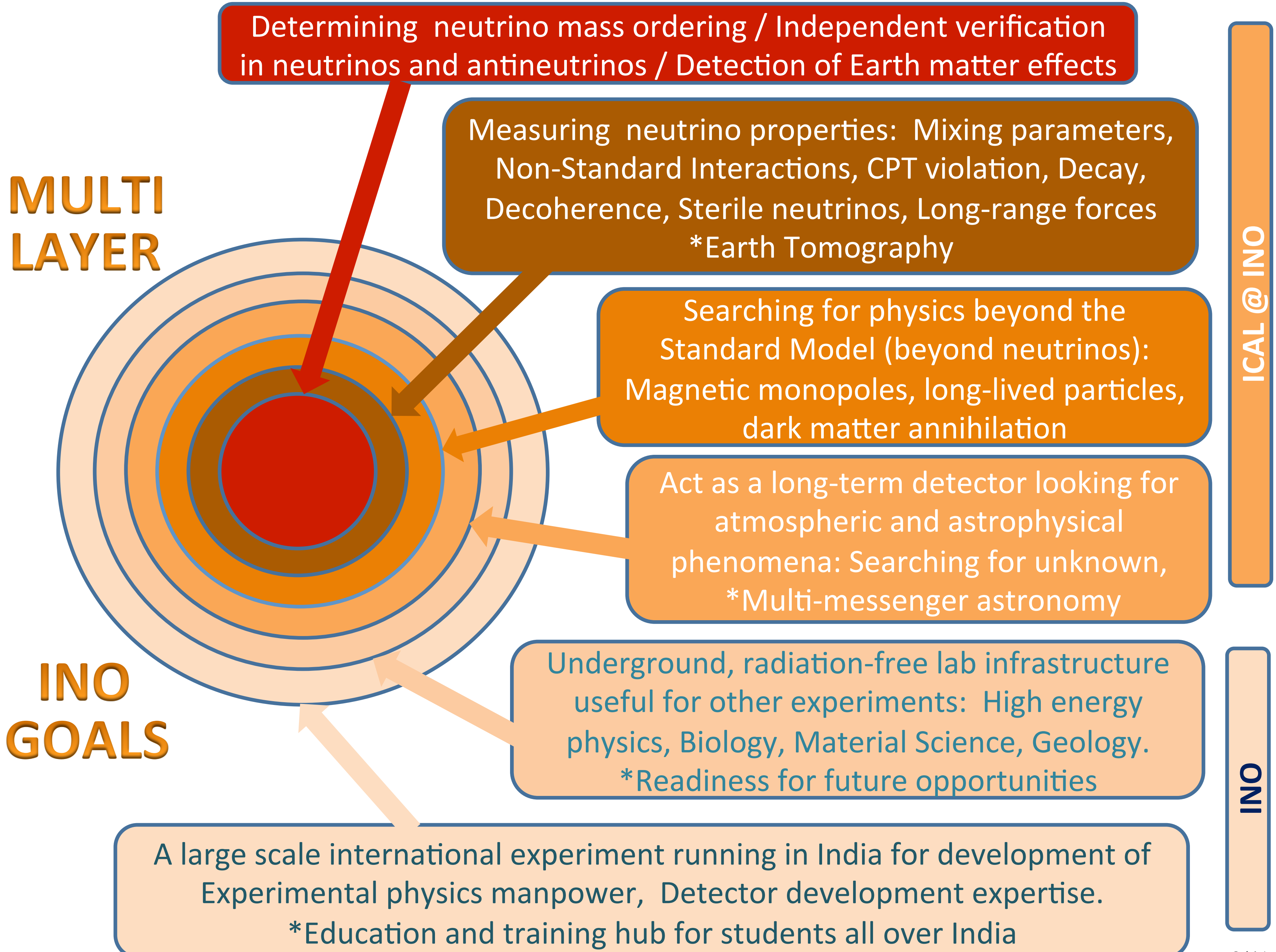
Determining the Neutrino Mass Hierarchy with Atmospheric Neutrinos

S. T. Petcov[a] and T. Schwetz[b]

Scuola Internazionale Superiore di Studi Avanzati
Via Beirut 2–4, I–34014 Trieste, Italy

Abstract

The possibility to determine the type of neutrino mass hierarchy by studying atmospheric neutrino oscillations with a detector capable to distinguish between neutrino and antineutrino events, such as magnetized iron calorimeters, is considered. We discuss how the ability to distinguish between the neutrino mass spectrum with normal and inverted hierarchy depends on detector characteristics like neutrino energy and direction resolutions or charge miss-identification, and on the systematical uncertainties related to the atmospheric neutrino fluxes. We show also how the neutrino mass hierarchy determination depends on the true values of θ_{13} and θ_{23}, as well as on the type of the true hierarchy. We find that for μ-like events, an accurate reconstruction of the energy and direction of the neutrino greatly improves the sensitivity to the type of neutrino mass spectrum. For $\sin^2 2\theta_{13} \cong 0.1$ and a precision of 5% in the reconstruction of the neutrino energy and 5° in the neutrino direction, the type of neutrino mass hierarchy can be identified at the 2σ C.L. with approximately 200 events. For resolutions of 15% for the neutrino energy and 15° for the neutrino direction roughly one order of magnitude larger event numbers are required. For a detector capable to distinguish between ν_e and $\bar{\nu}_e$ induced events the requirements on energy and direction resolutions are, in general, less demanding than for a detector with muon charge identification.


Determining neutrino mass ordering / Independent verification in neutrinos and antineutrinos / Detection of Earth matter effects
Measuring neutrino properties: Mixing parameters, Non-Standard Interactions, CPT violation, Decay, Decoherence, Sterile neutrinos, Long-range forces *Earth Tomography
MULTI LAYER
Searching for physics beyond the Standard Model (beyond neutrinos): Magnetic monopoles, long-lived particles, dark matter annihilation
Act as a long-term detector looking for atmospheric and astrophysical phenomena: Searching for unknown, *Multi-messenger astronomy
ICAL @ INO
INO GOALS
Underground, radiation-free lab infrastructure useful for other experiments: High energy physics, Biology, Material Science, Geology. *Readiness for future opportunities
INO
A large scale international experiment running in India for development of Experimental physics manpower, Detector development expertise. *Education and training hub for students all over India

INO – A Long Journey ….

- MoU between 6 Department of Atomic Energy (DAE) Institutions signed in 2002
- INO Report submitted to the Chairman DAE in 2006
- Detailed Project Report on INO Site by Tamil Nadu Electricity Board (TNEB) in 2010
- MoEFCC – Govt. of India Environmental Clearance (EC) for Pottipuram Site in 2010
- DPR to DAE (2012), Full Financial Sanction by Central Cabinet, GoI in Jan. 2015
- PILs in Madurai bench of Madras HC, NGT SZ at Chennai in 2015
- Fresh EC from MoEF in March, 2018. Again PIL by NGO in NGT Delhi
- NGT dismisses appeal to quash EC for INO on 2nd November 2018
- NGO has filed appeal in the Supreme Court on 22-12-2018
- Awaiting clearances from National Board of Wildlife, Madurai Town Planning Authority for Civil construction at the Site, and finally TN Pollution Control Board

INO – Present Status

- Prime Minister's office, Cabinet Secretary monitoring progress to get these clearances post 12/2017

- Strong outreach efforts are underway to counter misinformation spread by NGOs, Politicians, some sections of Media and Press

- Overwhelming support for INO from the International Neutrino Community. Benefits of having INO are highlighted by Prof. Jogesh Chandra Pati, Prof. Takaaki Kajita, Prof. Art McDonald, Prof. Francis Halzen, Prof. Ramnath Cowsik, Prof. Subir Sarkar, and by several INO students through YouTube videos and letters were written to the PM and the CM of Tamil Nadu requesting to remove the bottlenecks so that we can start the construction

https://www.youtube.com/watch?v=cPATEhMG6zg

https://www.youtube.com/watch?v=LOuD28r48Mc

INO – Present Status

- A massive outreach effort was launched through the IICHEP, Madurai involving several INO members, students, and members of the Tamil Nadu Science Forum

- During 15th to 29th July 2018: meetings were held in 17 (14) colleges in Madurai (Theni); press conferences in Theni, Madurai (covered by newspapers and local TV channels); visits by 5 groups to mini-ICAL at IICHEP; summer projects by students (~ 30) at IICHEP; on 2-9-2018 at IIT-Madras ~ 350 attendees (~ 80% students)

- 85 ton magnetized mini-ICAL (4m × 4m × 11 layers of Fe) commissioned in May 2018 at the transit campus of IICHEP, Madurai to study the performance of magnets, RPCs over a long period

- Plan to have Cosmic Muon Veto Detector (CMVD) for mini-ICAL using extruded Plastic Scintillator to be given at no cost by Fermilab and rest by INO

- 600 ton engineering module likely at BARC-Vizag in Andhra Pradesh

- R&D is going on to explore the possibilities to have this engineering module at a shallow depth of 30 to 100 metres

Activities related to mini-ICAL

Plate machining Job

Spacers and Pins

Copper Conductor Spool

Magnet Components (Core & Coil) BARC group

Conductor bending machine

Conductor straightening machine

Coil fabrication


Glass RPC gap at St. Gobain
Closed loop gas system
Analog
Mixed
Digital
FEE hybrids to ICs
DAQ card with FPGA, HPTDC
±5 kV DC-DC HV card
8 channel FEE board
Trigger and Calibtation system

Assembly of mini-ICAL

Pillars for magnet, G10 boards for Cu coils

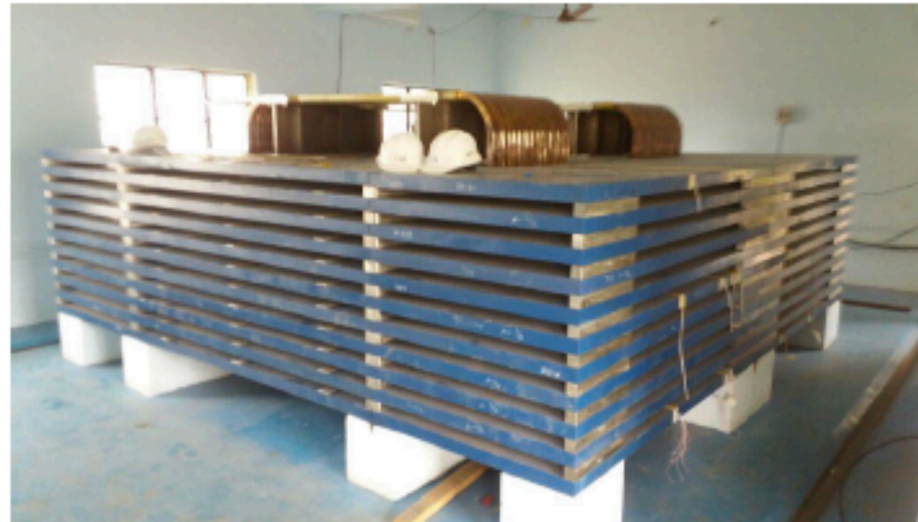
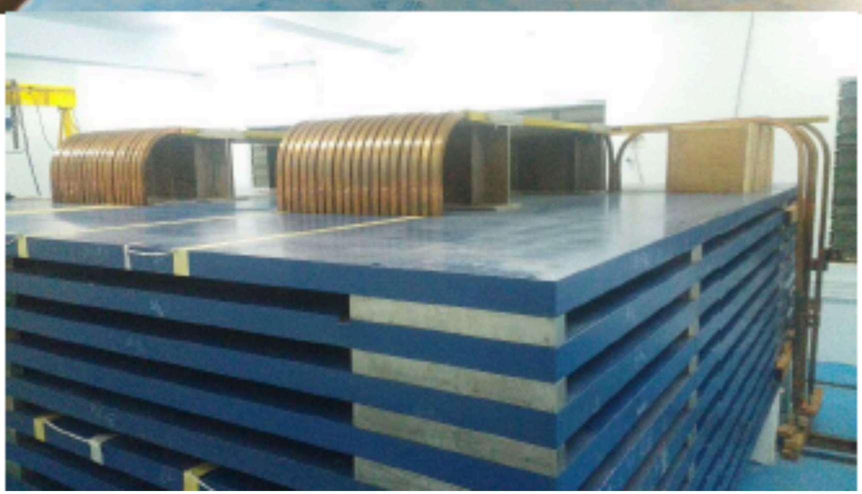
OFHC Cu “U” and “C” sections

Magnet assembly in progress

Assembly of iron plates of mini-ICAL magnet

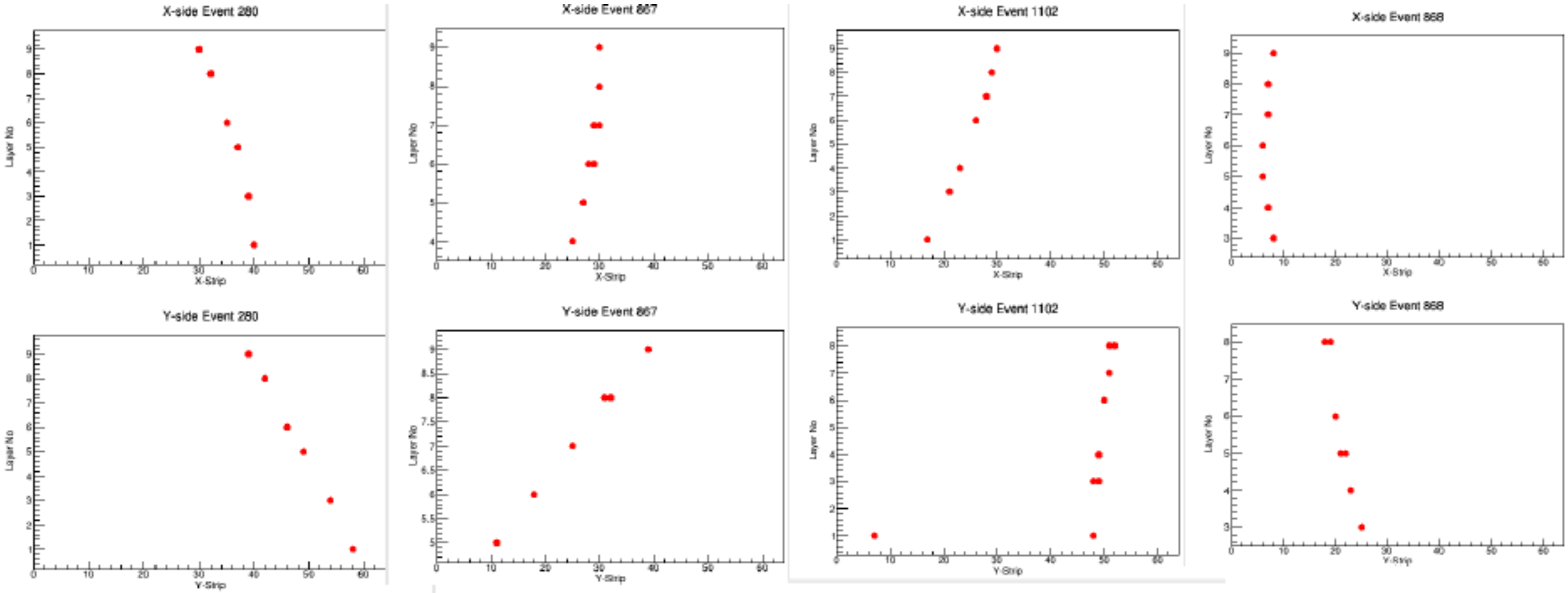
Cu Coil Brazing

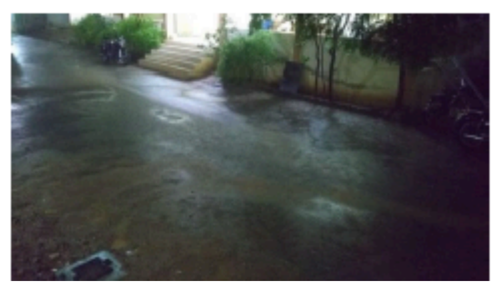
mini-ICAL Assembled


First cosmic muons seen in mini-ICAL on 8-5-2018 with 6 RPCs on edge

Uncorrelated X-Y hit data

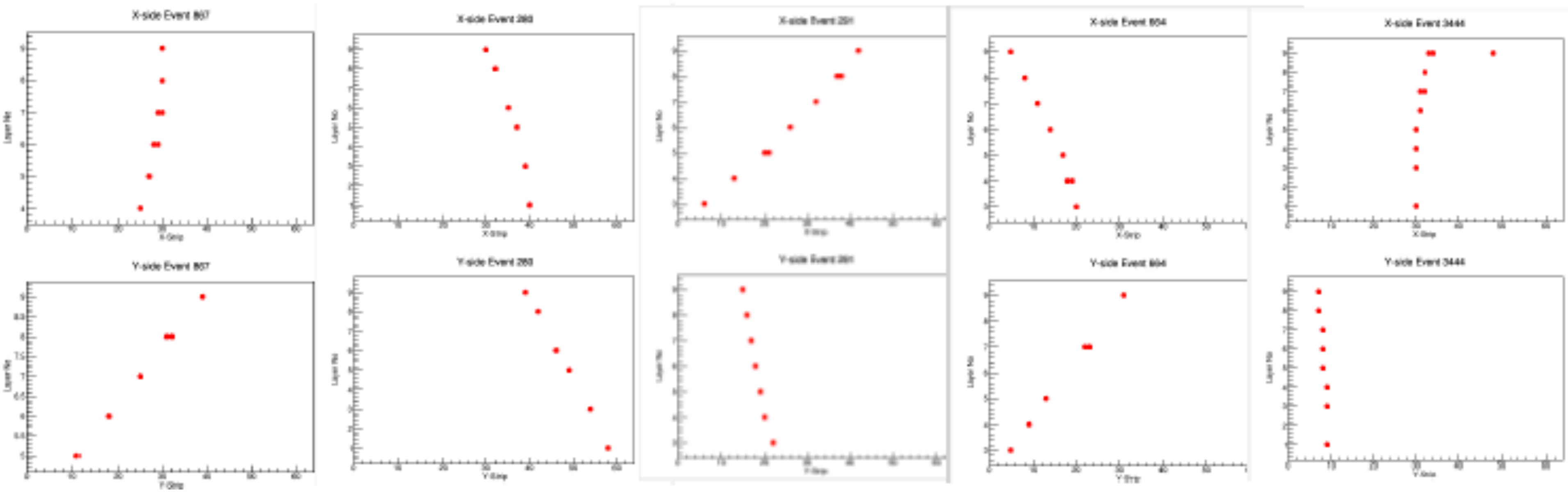




8 RPCs at centre of mini-ICAL on 23-5-2018

I = 900 A $\Rightarrow$ B ~ 1.4 Tesla

Offset corrected X-Y hit data



Muon tracks in mini-ICAL detector

Opposite curvatures in bending (X-) plane due to opposite electric charges of down-going muons

INO Graduate Training Program (GTP) Students and Outreach activities at IICHEP, Madurai






A compact cosmic muon veto detector and possible use with the Iron Calorimeter detector for neutrinos

Neha,[a,b] S. Mohanraj,[a,b,1] A. Kumar,[a,b] T. Dey,[a,b] G. Majumder,[b] R. Shinde,[b] P. Verma,[b] B. Satyanarayana[b] and V.M. Datar[b]

[a]Homi Bhabha National Institute, Anushaktinagar, Mumbai-400094, India

[b]Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai-400005, India

E-mail: neha_005@tifr.res.in

Abstract: The motivation for a cosmic muon veto (CMV) detector is to explore the possibility of locating the proposed large Iron Calorimeter (ICAL) detector at the India based Neutrino Observatory (INO) at a shallow depth. An initial effort in that direction, through the assembly and testing of a ~1 m × 1 m × 0.3 m plastic scintillator based detector, is described. The plan for making a CMV detector for a smaller prototype mini-ICAL is also outlined.

Keywords: Cosmic, veto, calorimeter, scintillator.

JINST 12 (2017) no.11, T11002

Simulation of muon-induced neutral particle background for a shallow depth Iron Calorimeter detector

Neha Panchal,[a,b,1] G. Majumder[b] and V.M. Datar[b]

[a]Homi Bhabha National Institute, Anushaktinagar, Mumbai-400094, India

[b]Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai-400005, India

E-mail: neha.dl0525@gmail.com

Abstract: The Iron Calorimeter (ICAL) detector at the India based Neutrino Observatory (INO) is planned to be set up in an underground cavern with a rock overburden of more than 1 km. This overburden reduces the cosmic muon flux by a factor of 10^6 with respect to that at the sea level. In this paper, we examine the possibility of a 100 m shallow depth ICAL (SICAL) detector. The cosmic muons would have to be detected in a veto detector with an efficiency of 99.99% in order to have the same level of muon background leaking undetected through the veto detector as at the 1 km depth underground site. However, an additional background arises from interactions of cosmic muons with the rock. Since the neutral particles produced in such interactions can pass through the veto detector without any interaction, they can possibly mimic neutrino events in the ICAL. In this paper, the results of a GEANT4 based simulation study to estimate the background signals due to muon induced interactions with the rock for the SICAL is presented.

Keywords: neutrino, cosmic muons, veto detector

ArXiv ePrint: 1234.56789

JINST 14 (2019) no.02, P02032

India-USA Collaboration

Dr. Sekhar Basu and Rick Perry

APRIL 16, 2018

U.S. Department of Energy and Indian Department of Atomic Energy Signed Agreement for Neutrino Physics Collaboration

Opens the door for jointly advancing LBNF-DUNE and INO projects

Physics Whitepaper of ICAL @ INO

INO/ICAL/PHY/NOTE/2015-01
ArXiv:1505.07380 [physics.ins-det]

Pramana - J Phys (2017) 88 : 79
doi:10.1007/s12043-017-1373-4

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

The ICAL Collaboration

Atmospheric neutrino experiments (wide range of E & L)

(Magnetized Iron Calorimeter @ India-based Neutrino Observatory)

Category 1:

$$(\nu_\mu \rightarrow \nu_\mu) + (\nu_e \rightarrow \nu_\mu) = \text{observable } \mu^-$$

Category 2:

$$(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_\mu) + (\text{anti-}\nu_e \rightarrow \text{anti-}\nu_\mu) = \text{observable } \mu^+$$

Excellent Charge-Identification: μ^- and μ^+ are separately detected

Electron detection not possible with present design

Oscillation Probabilities with One Mass Scale Dominance

take $\Delta m^2_{21} = 0$

$A = 2\sqrt{2}G_F N_e E_\nu$

$$P^{approx}_{\mu\mu} = 1 - \sin^2\theta^M_{13}\sin^2 2\theta_{23}\sin^2\frac{[(\Delta m^2_{31} + A) - (\Delta m^2_{31})^M]L}{8E_\nu} - \cos^2\theta^M_{13}\sin^2 2\theta_{23}\sin^2\frac{[(\Delta m^2_{31} + A) + (\Delta m^2_{31})^M]L}{8E_\nu} - \sin^2 2\theta^M_{13}\sin^4\theta_{23}\sin^2\frac{(\Delta m^2_{31})^M L}{4E_\nu},$$

$$P^{approx}_{e\mu} = \sin^2 2\theta^M_{13}\sin^2\theta_{23}\sin^2\frac{(\Delta m^2_{31})^M L}{4E_\nu}$$

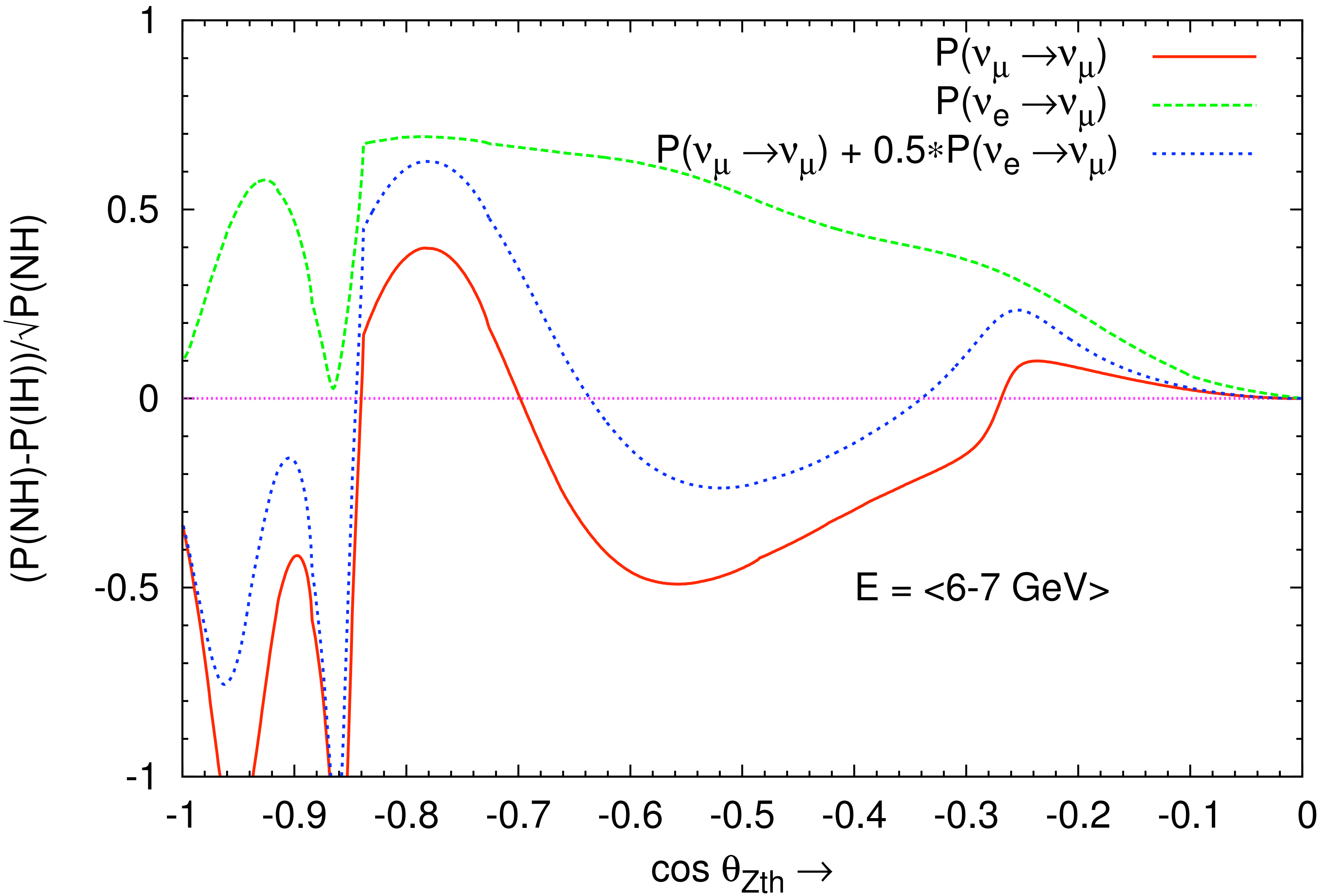
where

$$(\Delta m^2_{31})^M = \left((\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + \Delta m^2_{31}\sin^2 2\theta_{13}\right)^{1/2},$$

$$\sin^2 2\theta^M_{13} = \frac{\Delta m^2_{31}\sin^2 2\theta_{13}}{\left((\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + \Delta m^2_{31}\sin^2 2\theta_{13}\right)}.$$

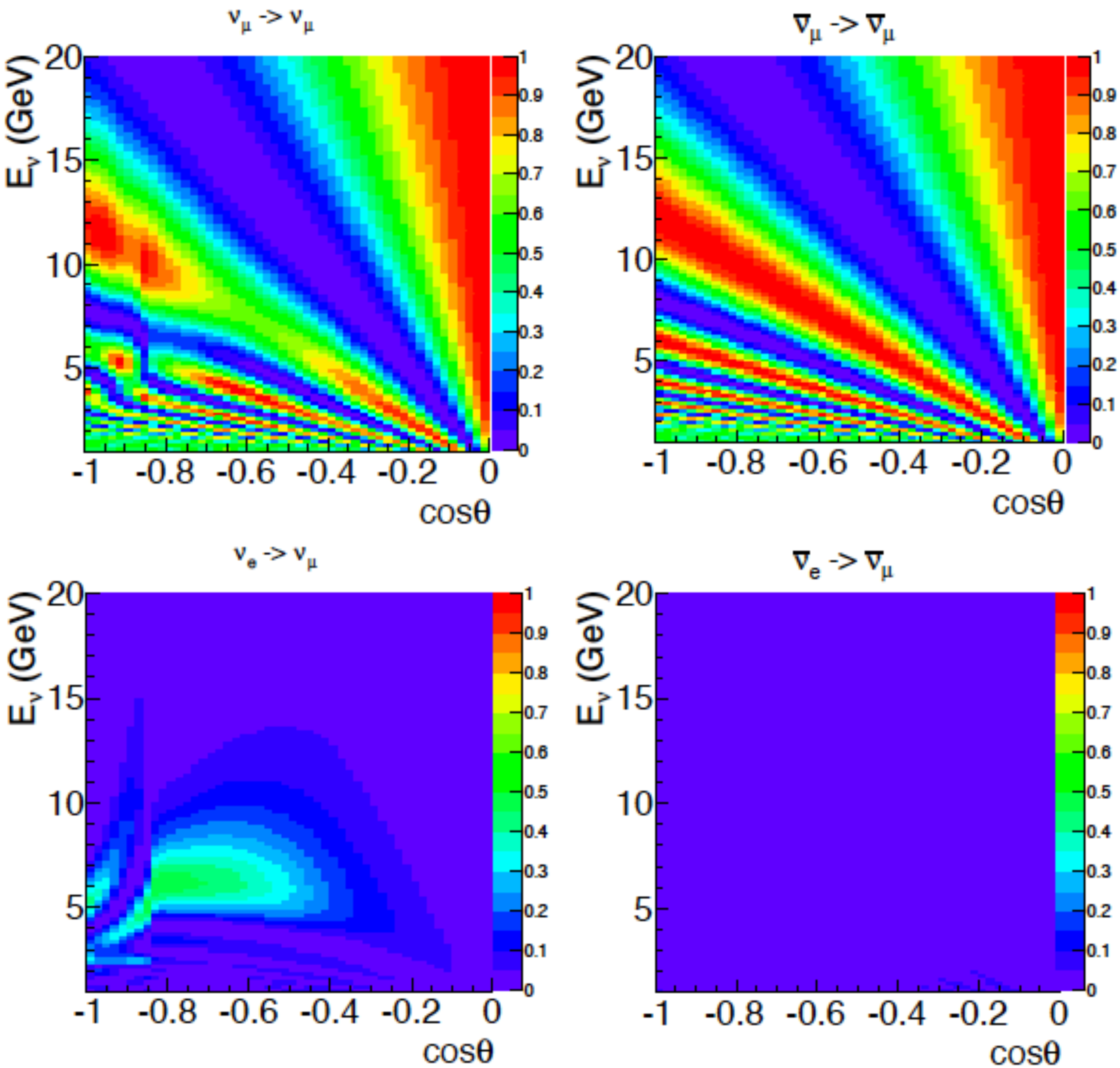
Choubey, Roy, hep-ph/0509197v2

- If θ_{13} would have been zero, there is no Earth matter effect
- No discrimination between NH and IH
- Large θ_{13} is a good news for MH



Presence of different flavors dilutes the MH effect in oscillation

Neutrino Mass Hierarchy Signature



Neutrino Oscillograms

These plots are for NH

For IH, the neutrino & anti-neutrino patterns are exchanged

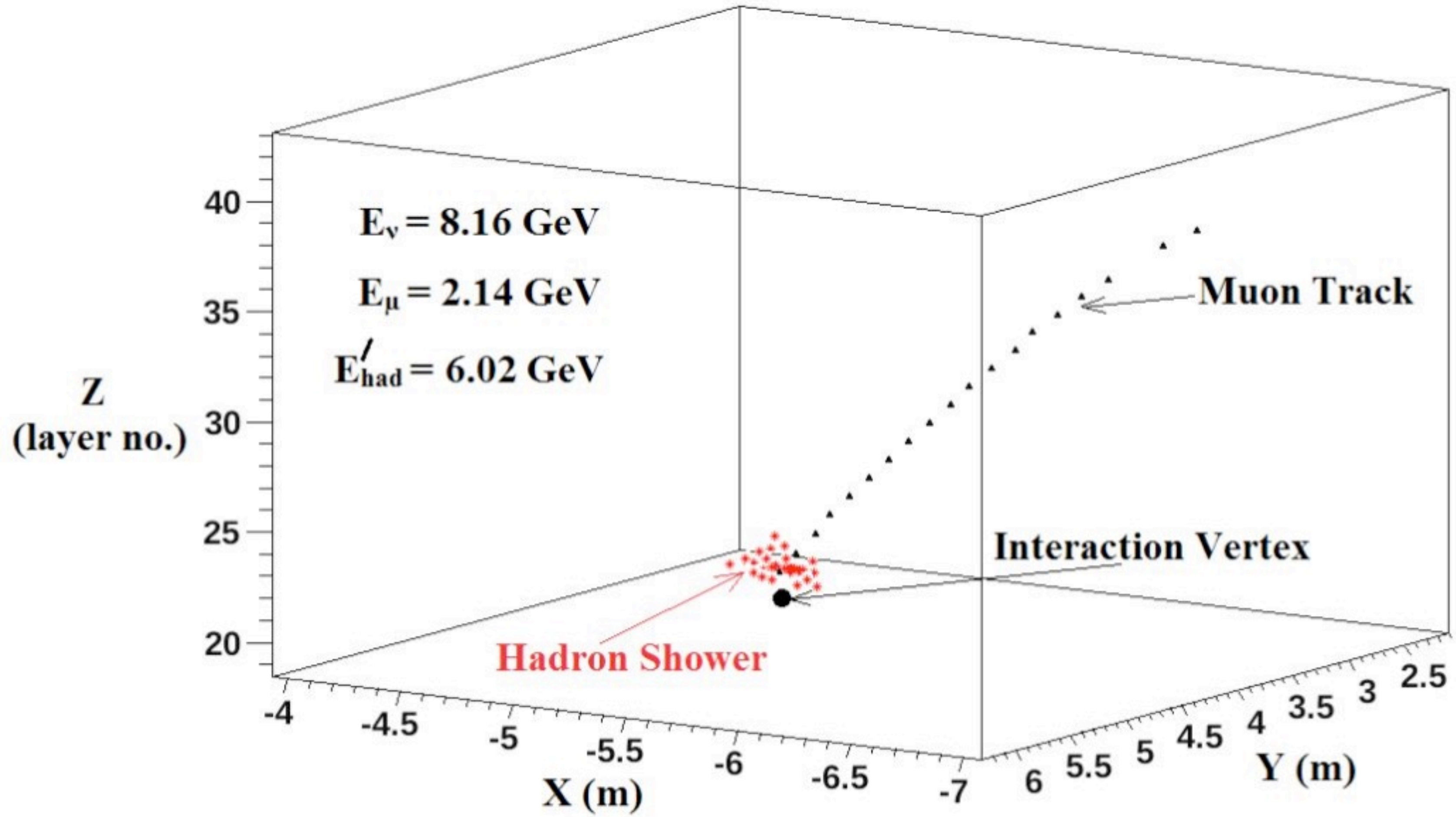
Crucial for MSW effect:

Energy:
2 GeV to 8 GeV

Baseline:
2000 km to 8000 km

Qian, Vogel, arXiv:1505.01891v3 [hep-ex]

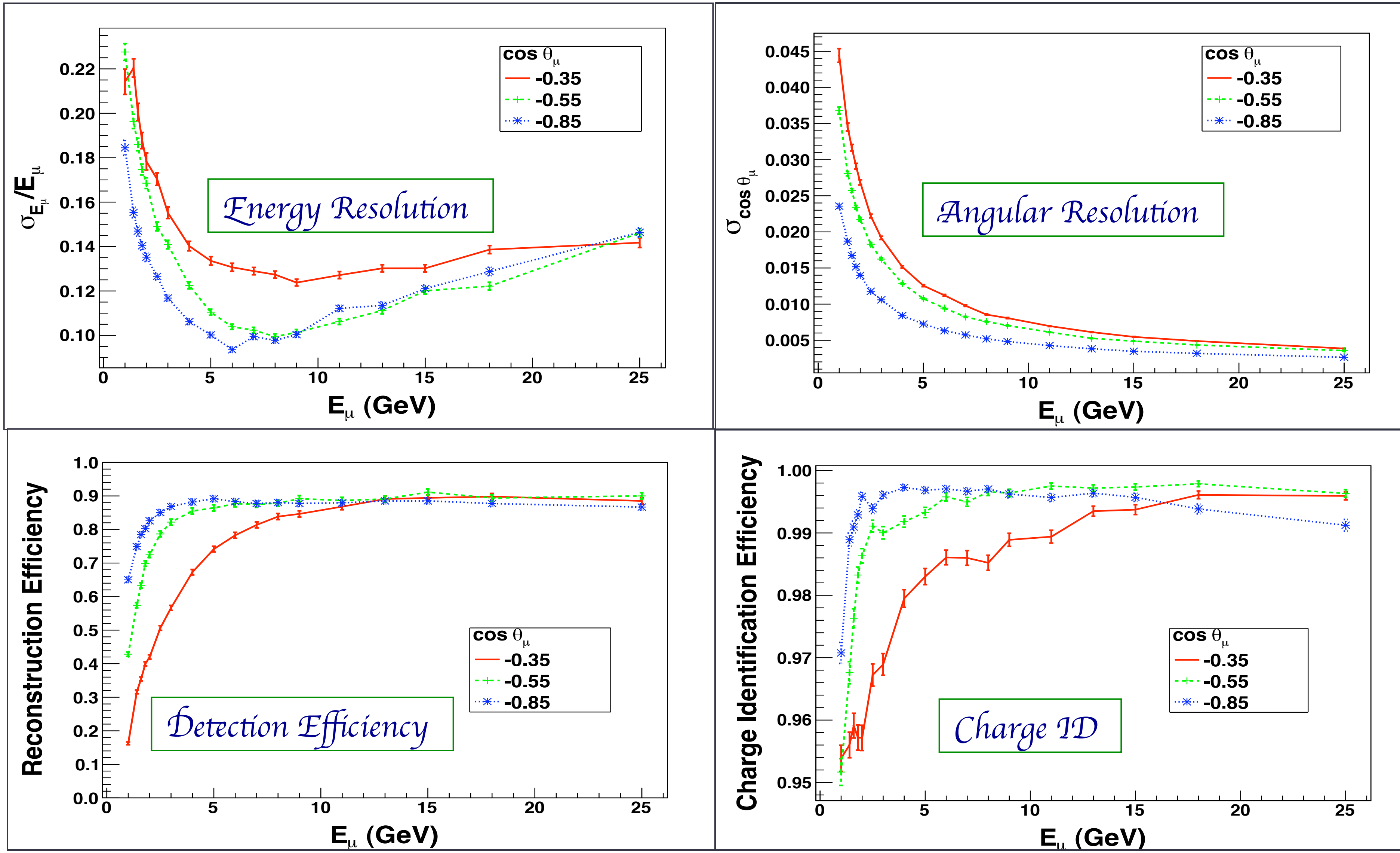
Event Display Inside the ICAL Detector



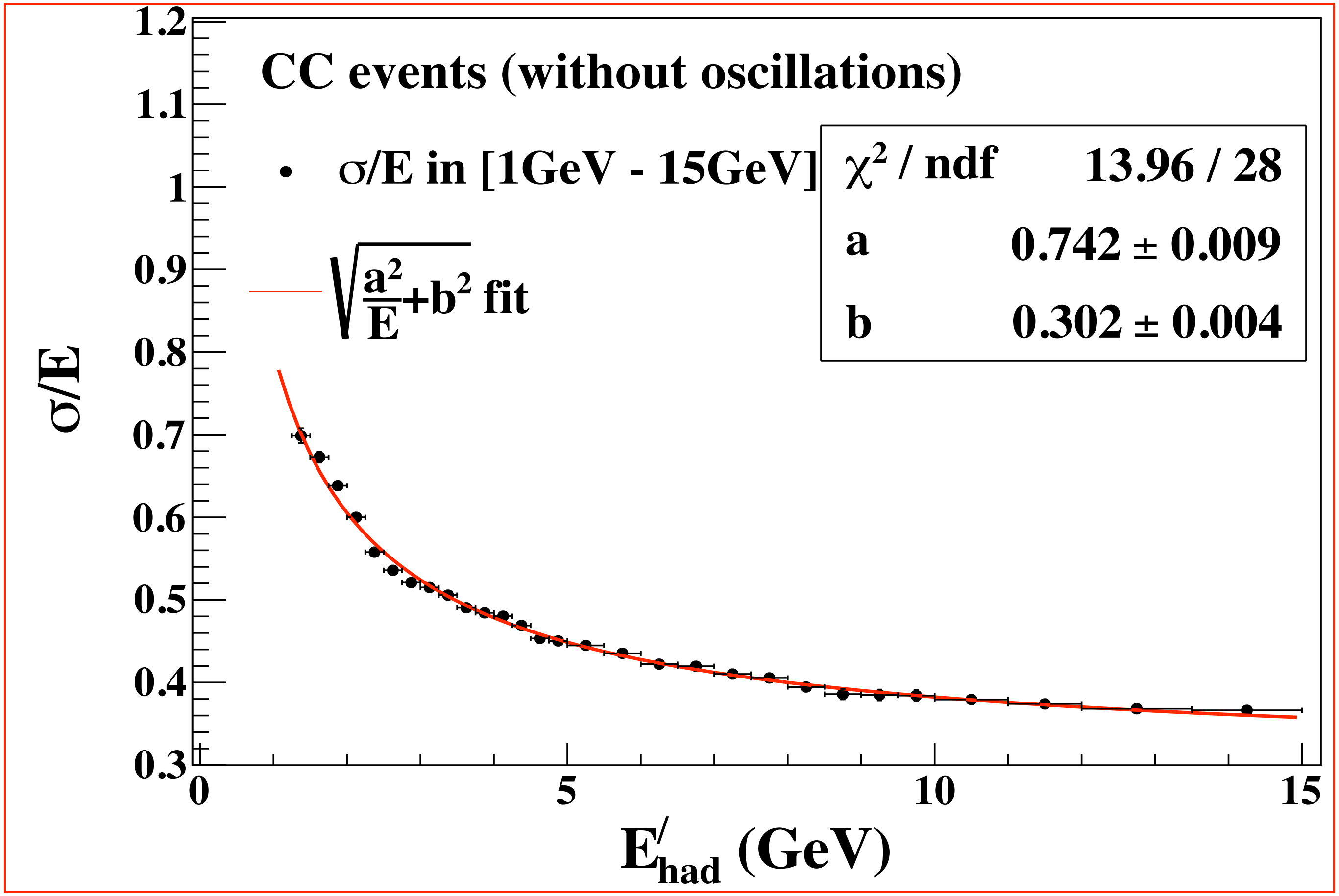
Using GEANT4 simulation

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., JINST 9 (2014) P07001



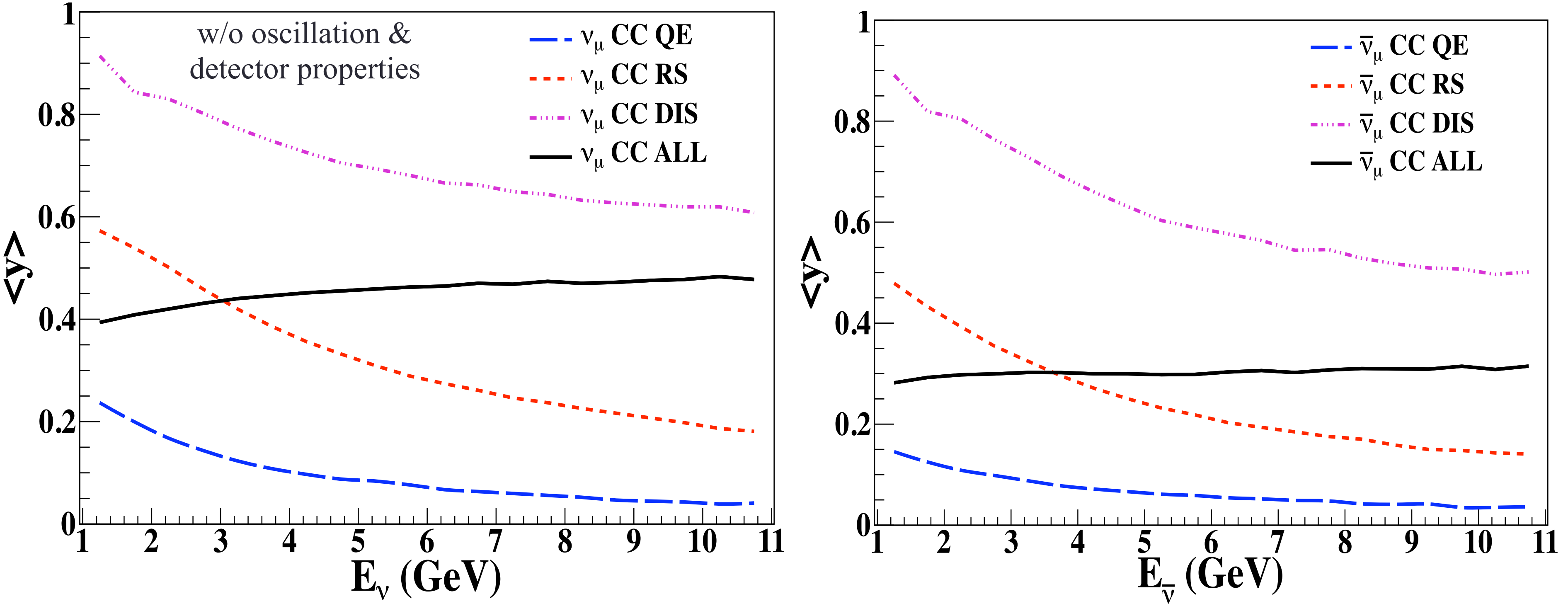
$E'_h = E_\nu - E_\mu$ (from hadron hit calibration)

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

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

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

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

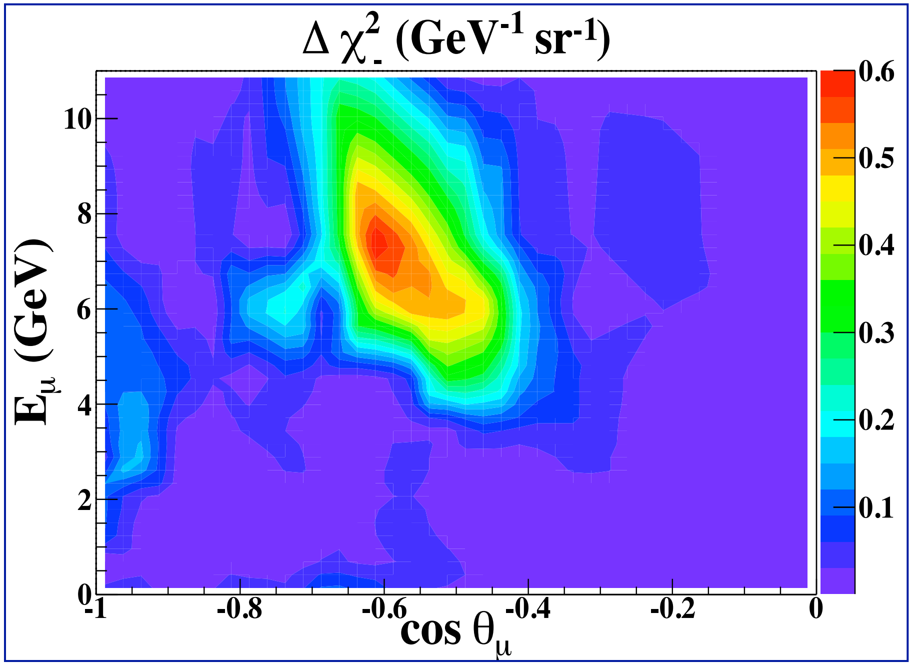
Observable	Range	Bin width	Total bins	
E_μ (GeV)	$[1, 4)$	0.5	6	10
	$[4, 7)$	1	3	
	$[7, 11)$	4	1	
$\cos\theta_\mu$	$[-1.0, -0.4)$	0.05	12	21
	$[-0.4, 0.0)$	0.1	4	
	$[0.0, 1.0]$	0.2	5	
$E'_{\rm had}$ (GeV)	$[0, 2)$	1	2	4
	$[2, 4)$	2	1	
	$[4, 15)$	11	1	

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

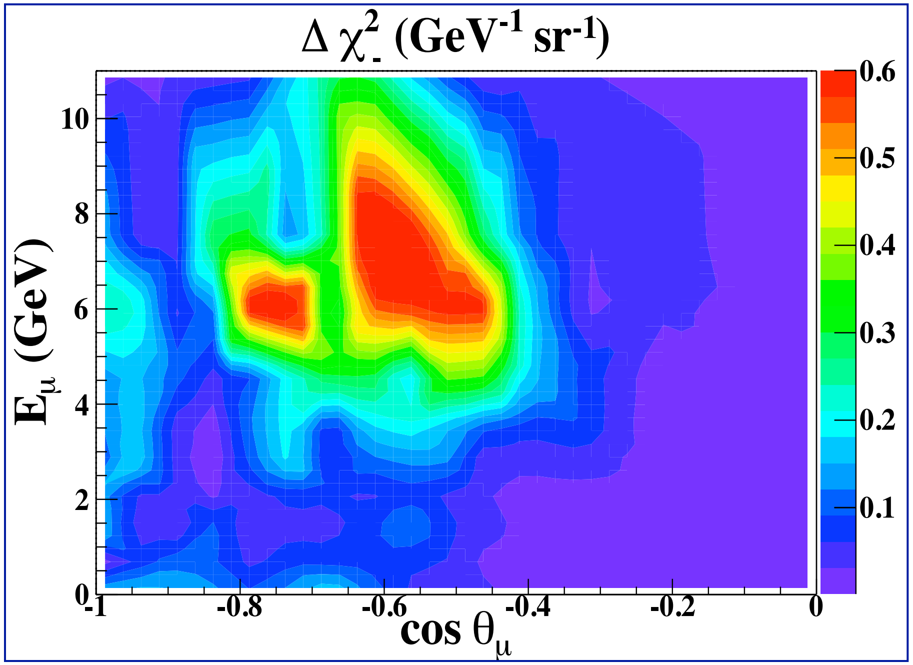
4) 5% uncertainty on the zenith angle dependence of the fluxes
5) Energy dependent tilt factor:
$\Phi_\delta(E) = \Phi_0(E)\,[E/E_0]^\delta \approx \Phi_0(E)\,[1+\delta \ln E/E_0]$
where $E_0 = 2$ GeV and
δ is the 1σ systematic error of 5%

Neutrino Mass Hierarchy Discrimination

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



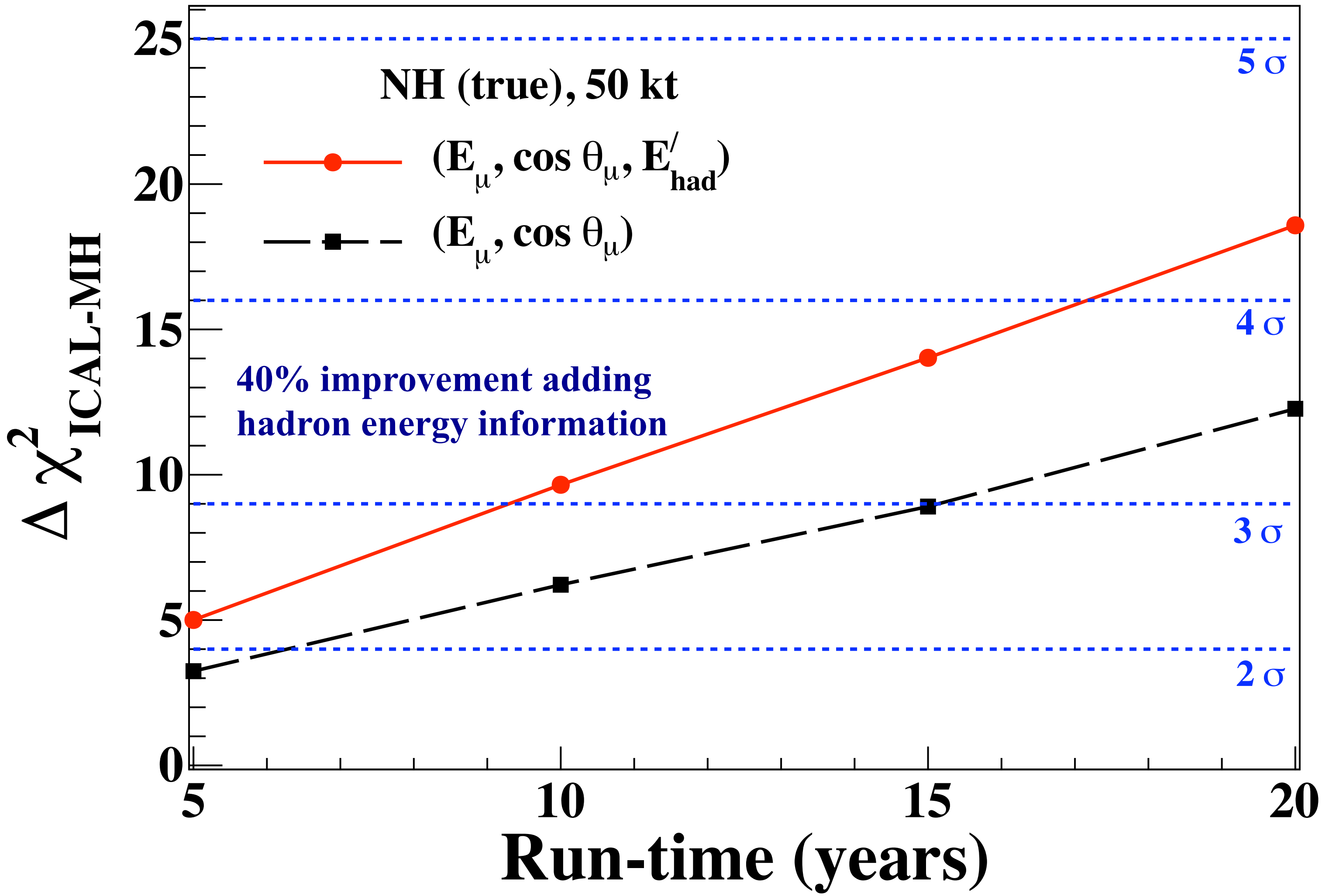
Hadron energy information not used



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

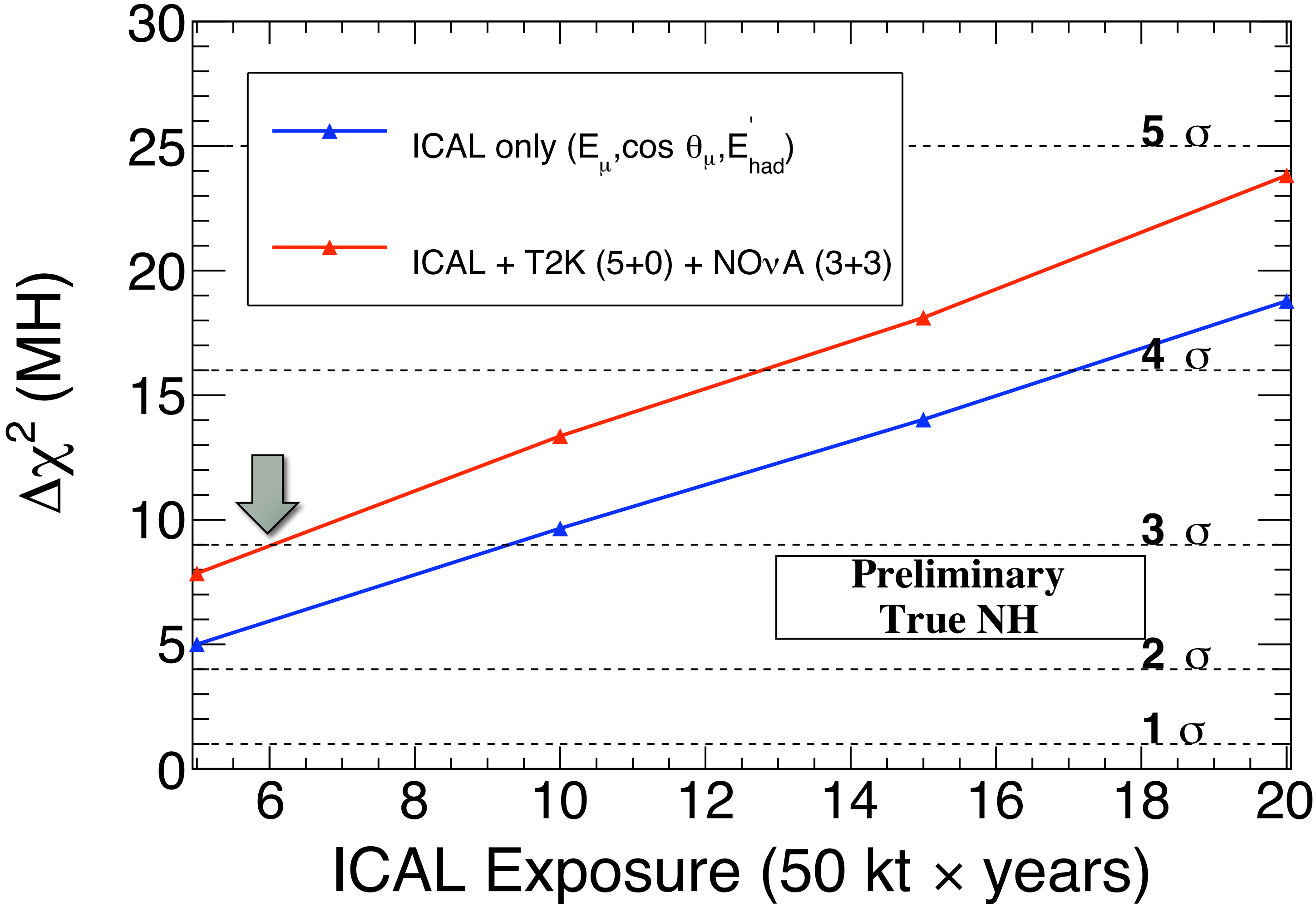


Median Sensitivity

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

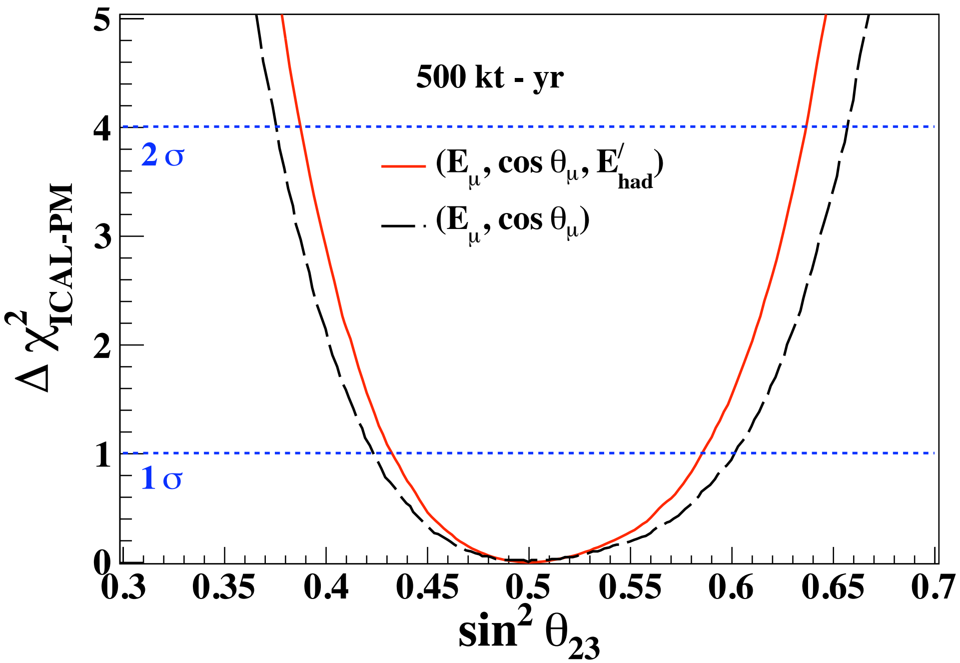
MH Discovery with ICAL+T2K+NOvA



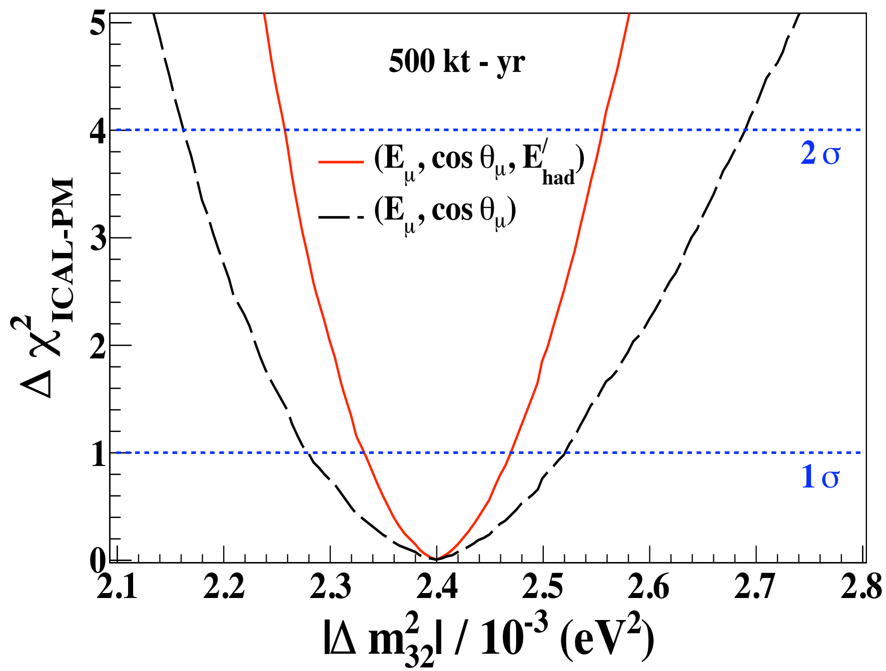
Agarwalla, Chatterjee, Thakore, work in progress (INO Collaboration)

3σ median sensitivity can be achieved in 6 years

Precision of Atmospheric Oscillation Parameters



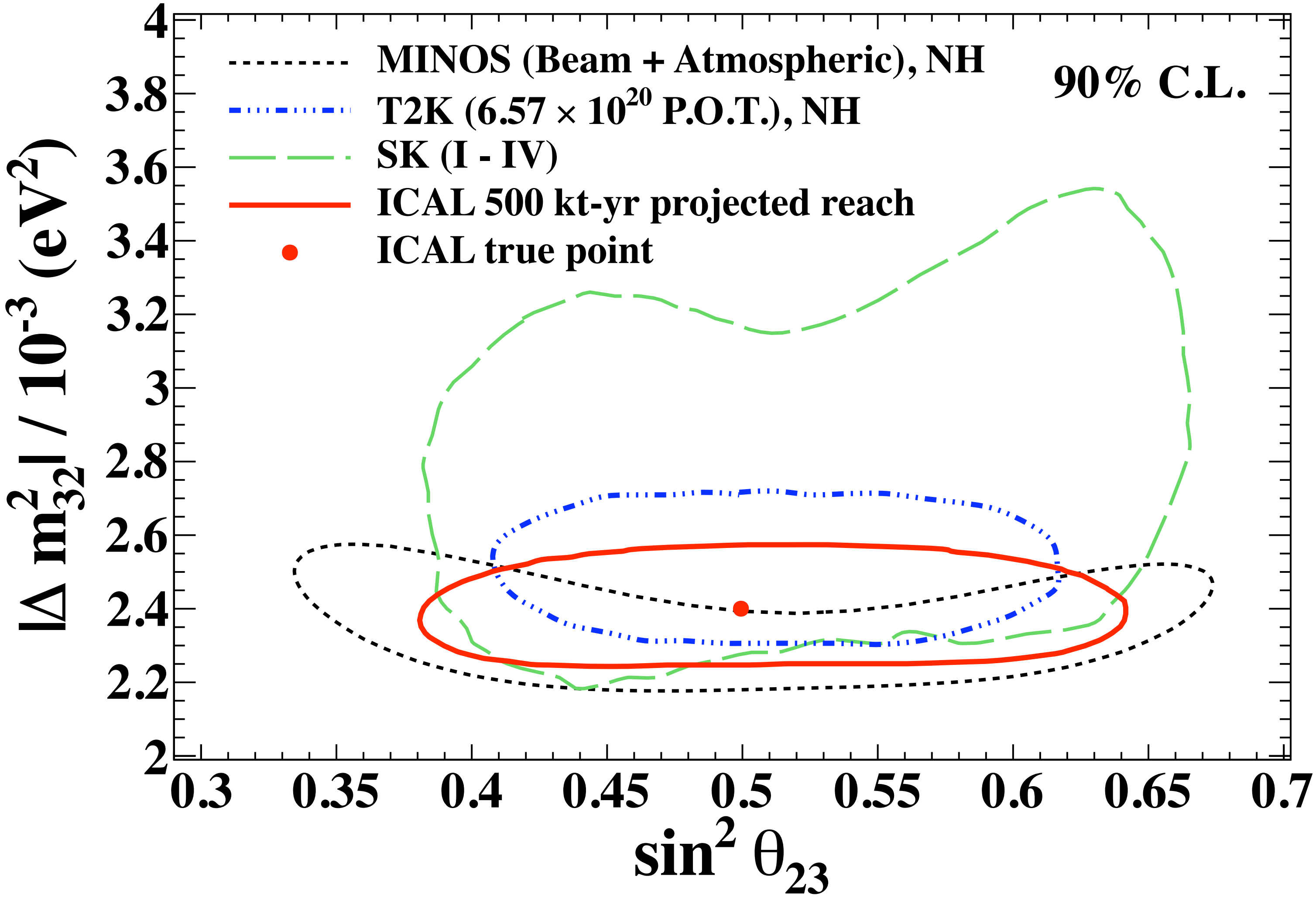
Relative 1σ precision: 12%



Relative 1σ precision: 2.9%

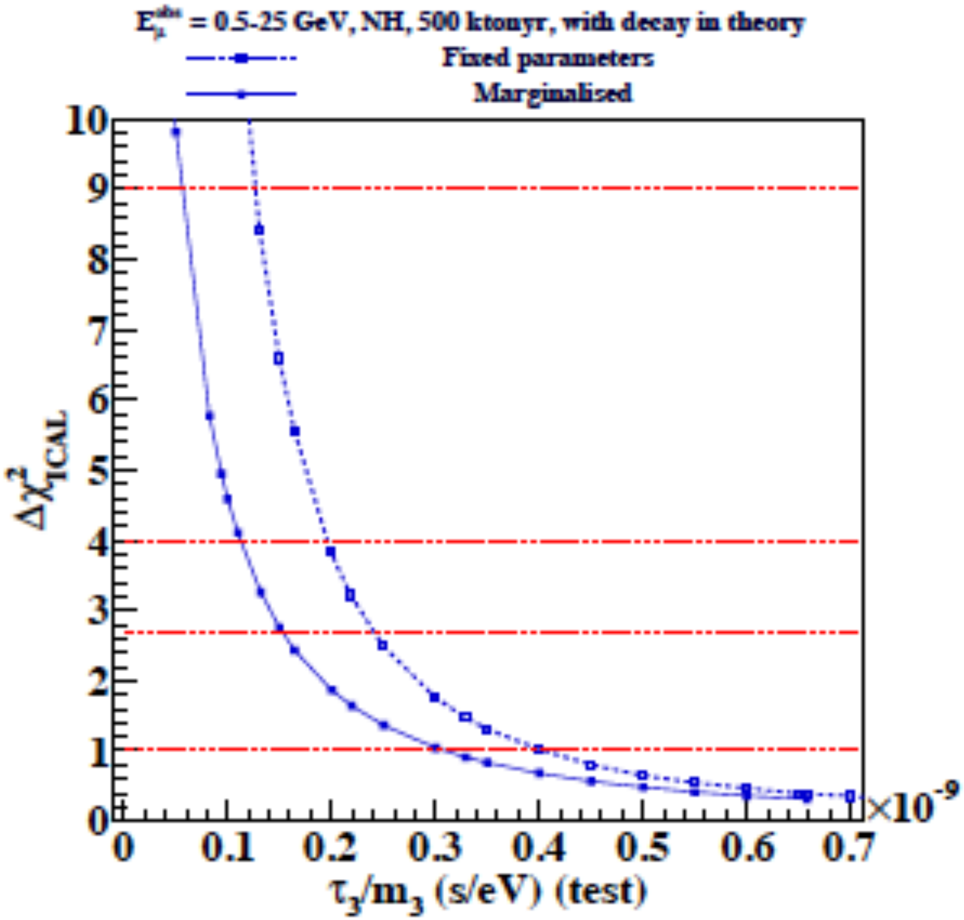
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

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



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

ICAL's expected precision on atmospheric mass splitting is better than Super-K



Analysis type	χ^2	α_3 (eV^2)	τ_3/m_3 (s/eV)
Fixed parameters	1	1.65×10^{-6}	3.99×10^{-10}
	2.71	2.73×10^{-6}	2.39×10^{-10}
	4	3.37×10^{-6}	1.96×10^{-10}
	9	5.19×10^{-6}	1.28×10^{-10}
Marginalised	1	2.13×10^{-6}	3.03×10^{-10}
	2.71	4.36×10^{-6}	1.51×10^{-10}
	4	5.89×10^{-6}	1.12×10^{-10}
	9	1.21×10^{-5}	5.66×10^{-11}

Invisible decay: $\nu_3 \rightarrow \nu_s + J$

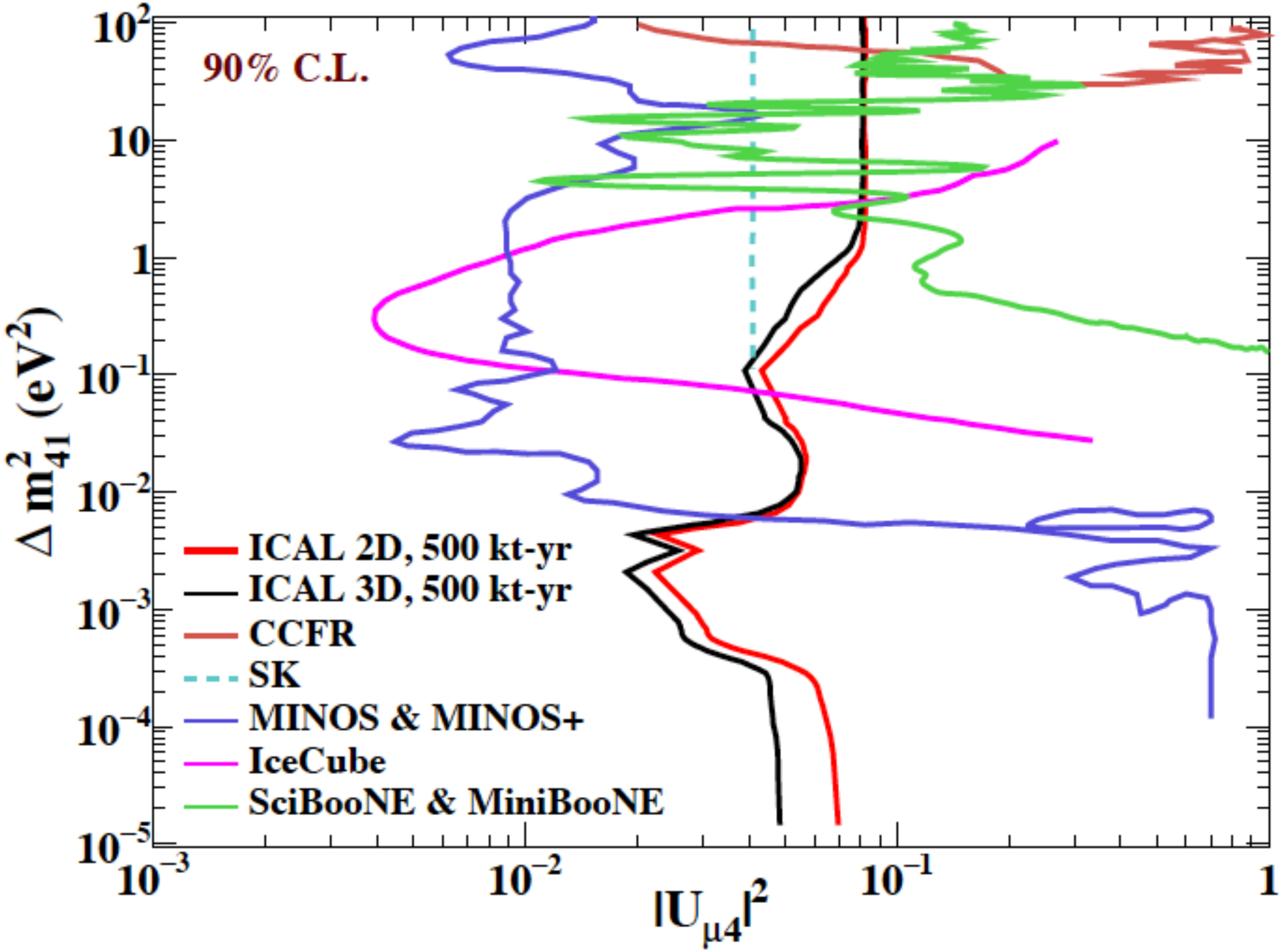
J (pseudo-scalar), ν_s (sterile neutrino)

Choubey, Goswami, Gupta, Lakshmi, Thakore, arXiv:1709.10376 [hep-ph] (INO Collaboration)

$$P_{\mu\mu}^{2G} = \left[\cos^2\theta_{23} + \sin^2\theta_{23}\exp(-m_3L/\tau_3E)\right]^2 - \sin^2 2\theta_{23}\exp(-m_3L/\tau_3E)\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

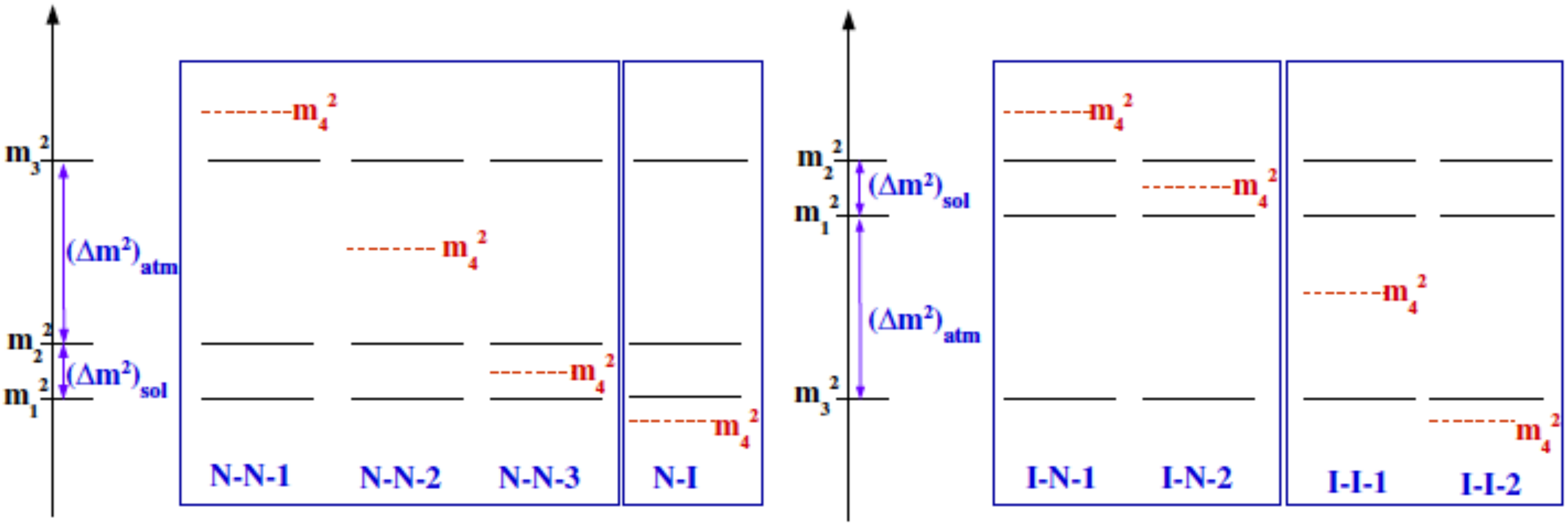
Super-K+MINOS: $\tau_3/m_3 > 2.9\times10^{-10}$ s/eV at 90% C.L.

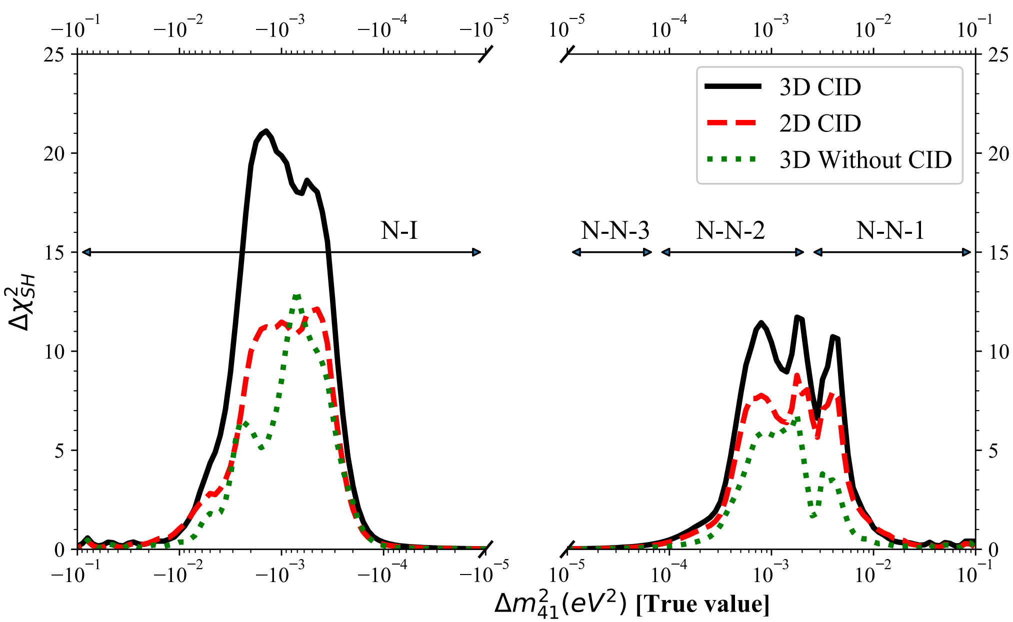
Gonzalez-Garcia, Maltoni, arXiv:0802.3699 [hep-ph]



Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph] (INO Collaboration)

Mass Ordering of Sterile Neutrino



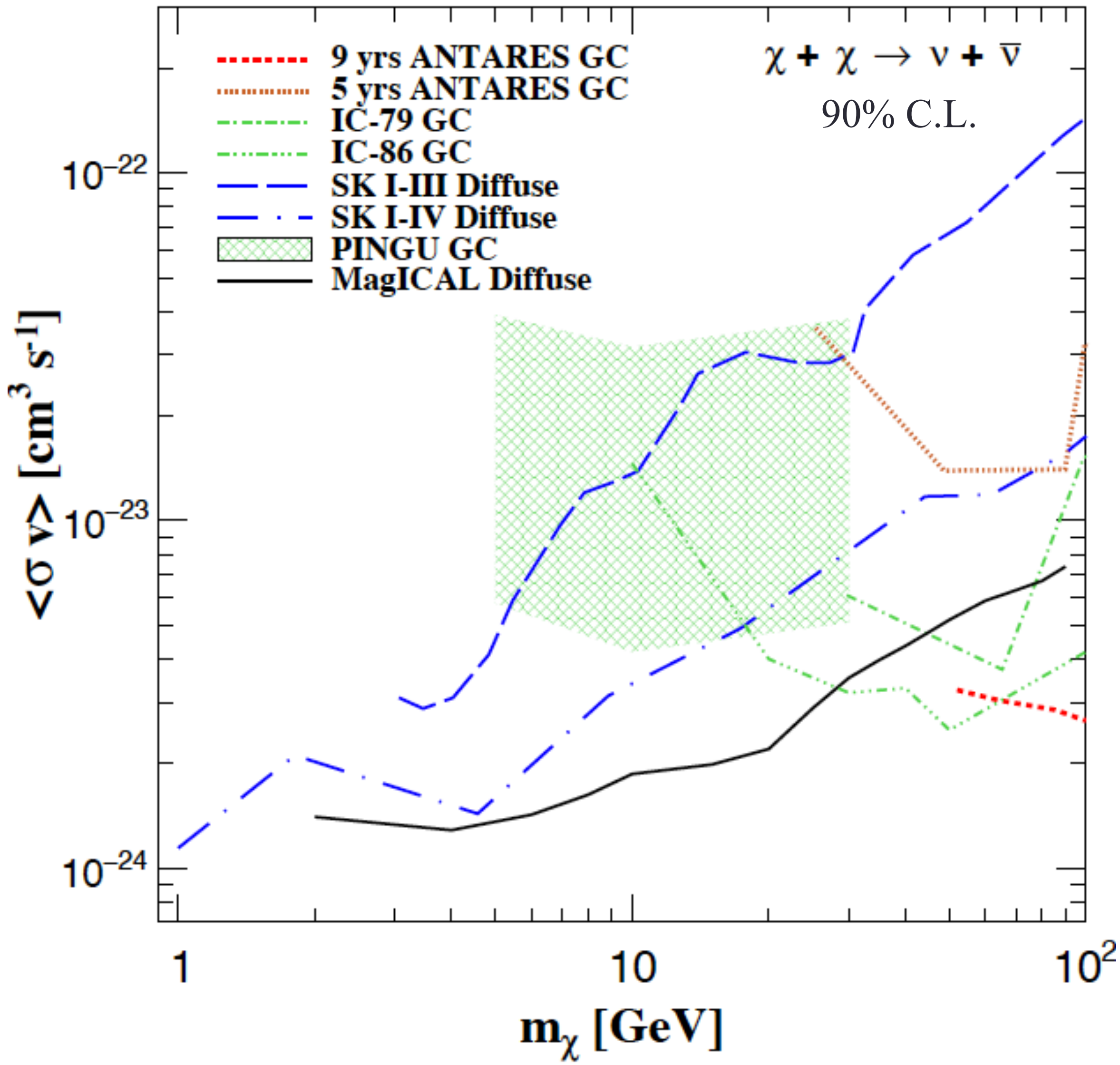


$$V_{es} = \sqrt{2} G_F (N_e - N_n/2) \quad \text{between } \nu_e \text{ and } \nu_s \,,$$
$$V_{\mu s} = V_{\tau s} = -\sqrt{2} G_F N_n/2 \quad \text{between } \nu_{\mu/\tau} \text{ and } \nu_s \,,$$

Addition of E'_h information improves sterile MH sensitivity by $\sim$ 40% for $\Delta m^2_{41} \sim (0.5 - 5) \times 10^{-3}$ eV^2

Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph] (INO Collaboration)

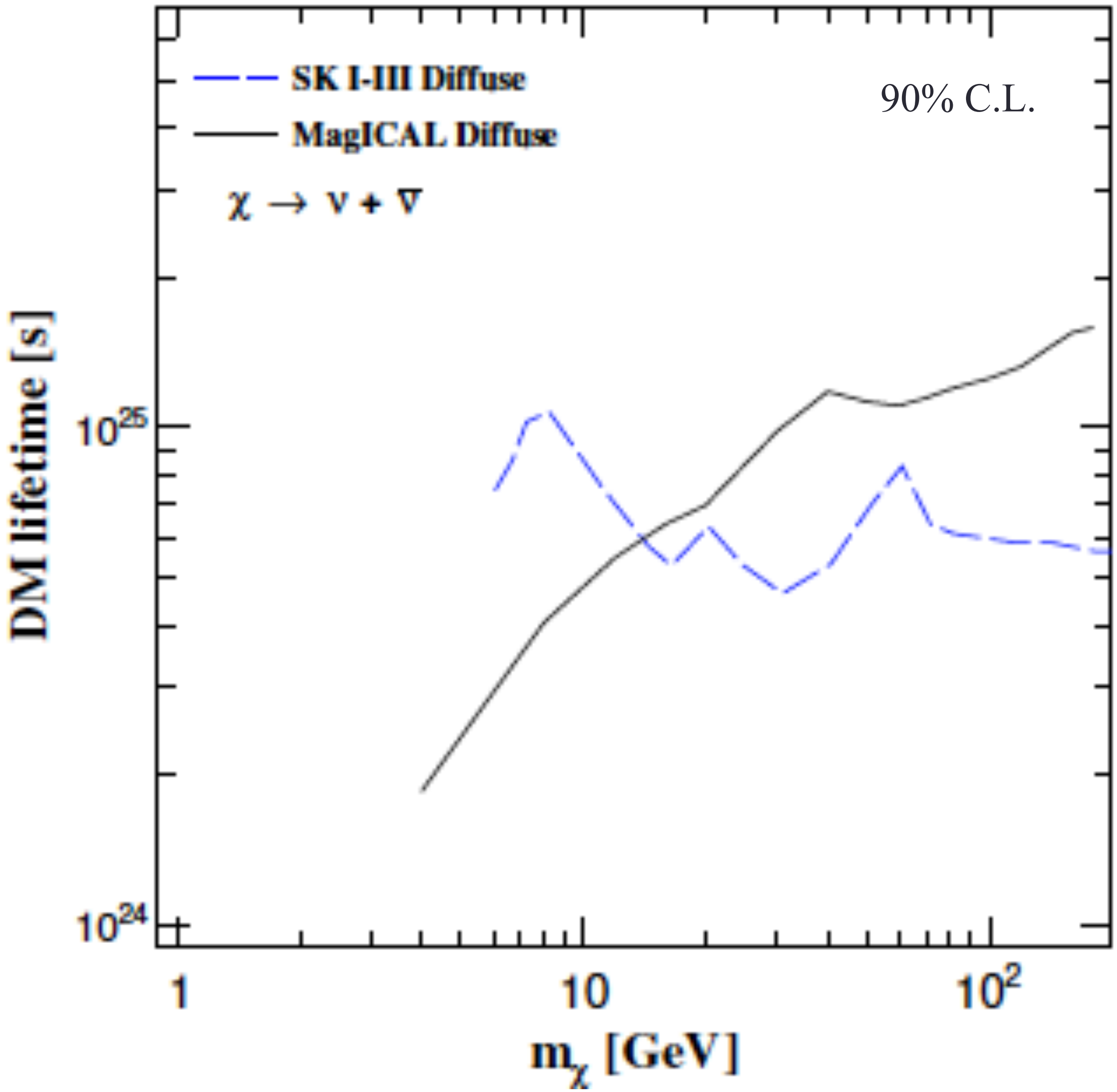
Indirect Searches of Galactic Diffuse Dark matter



$<\sigma v>$ = velocity averaged self-annihilation cross-section

Khatun, Laha, Agarwalla, arXiv:1703.10221 [hep-ph]

Indirect Searches of Galactic Diffuse Dark matter



Khatun, Laha, Agarwalla, arXiv:1703.10221 [hep-ph]

Magnetized ICAL@INO offers an unique opportunity to study the properties of neutrinos and antineutrinos separately using atmospheric neutrinos over a wide range of energies & baselines

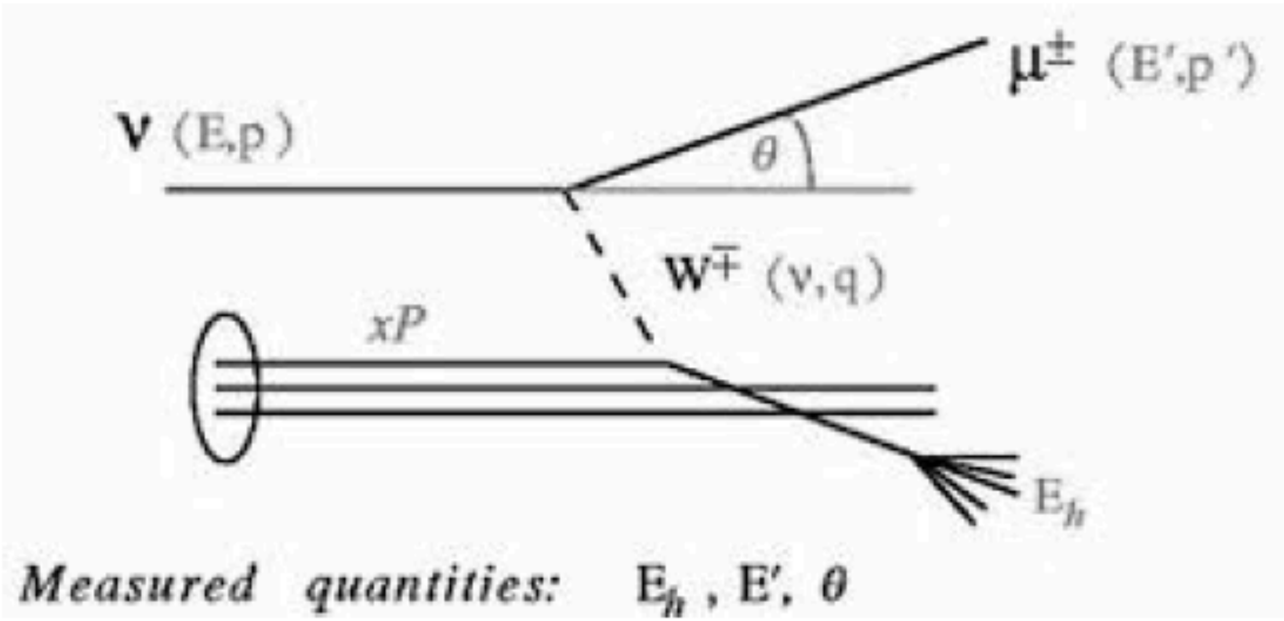
It will provide crucial information to test the three-flavor neutrino oscillation paradigm in presence of Earth Matter Effect

We hope to receive all the clearances soon to start the construction

You are most welcome to join us in this effort of unraveling the mysteries of neutrinos

Thank You

Inelasticity in Neutrino Interactions

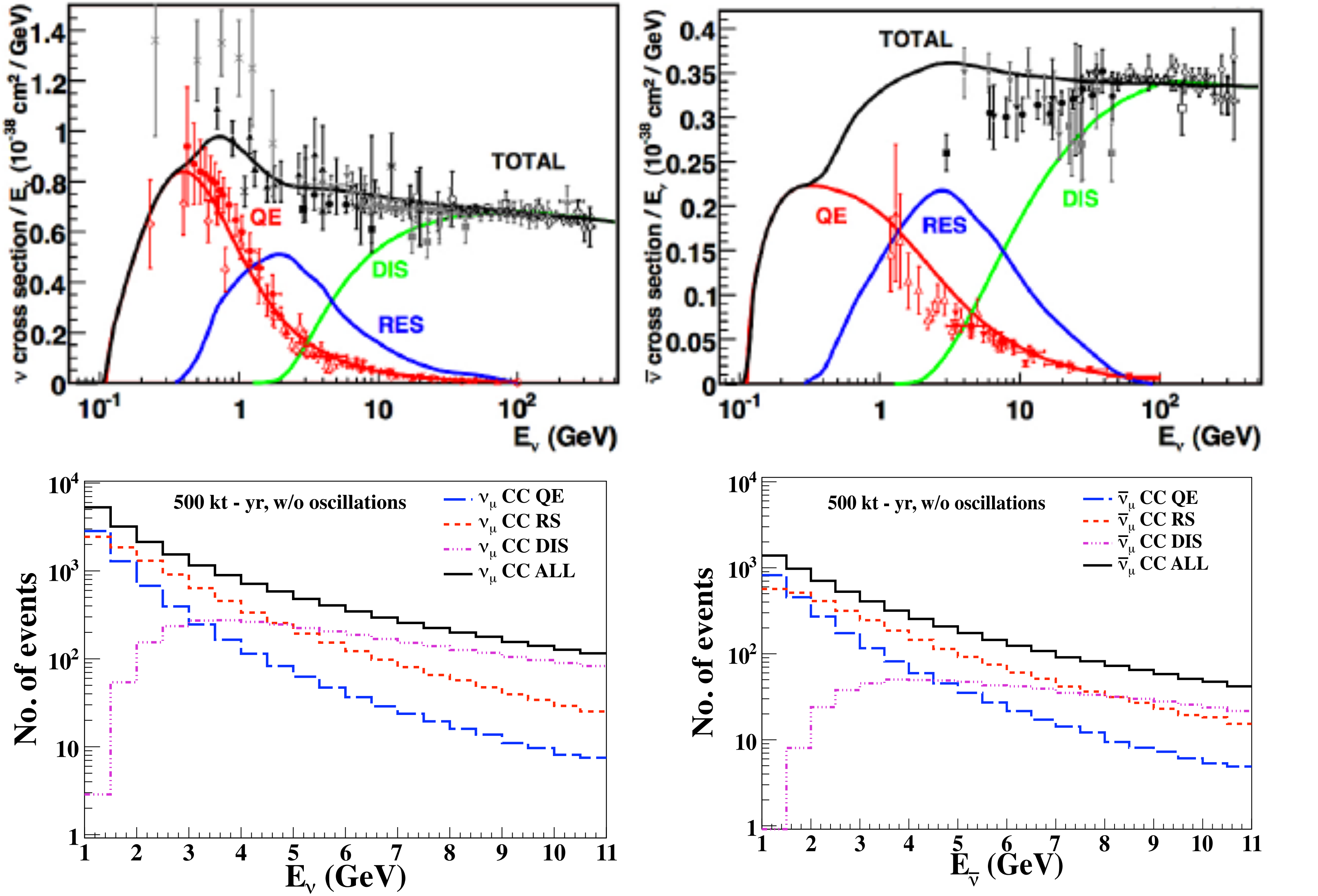


$$y \equiv \frac{E_\nu - E_\mu}{E_\nu} = \frac{E_h - m_N}{E_\nu} = \frac{E'_h}{E_\nu}$$

Issues with unknown inelasticity

- E_ν cannot be determined given only E_μ
- All "clean" probability expressions involve E_ν
- Statistical determination $\Rightarrow$ dilutes results

QE, RES, and DIS Processes (CC Interactions)



without oscillation and detector properties

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

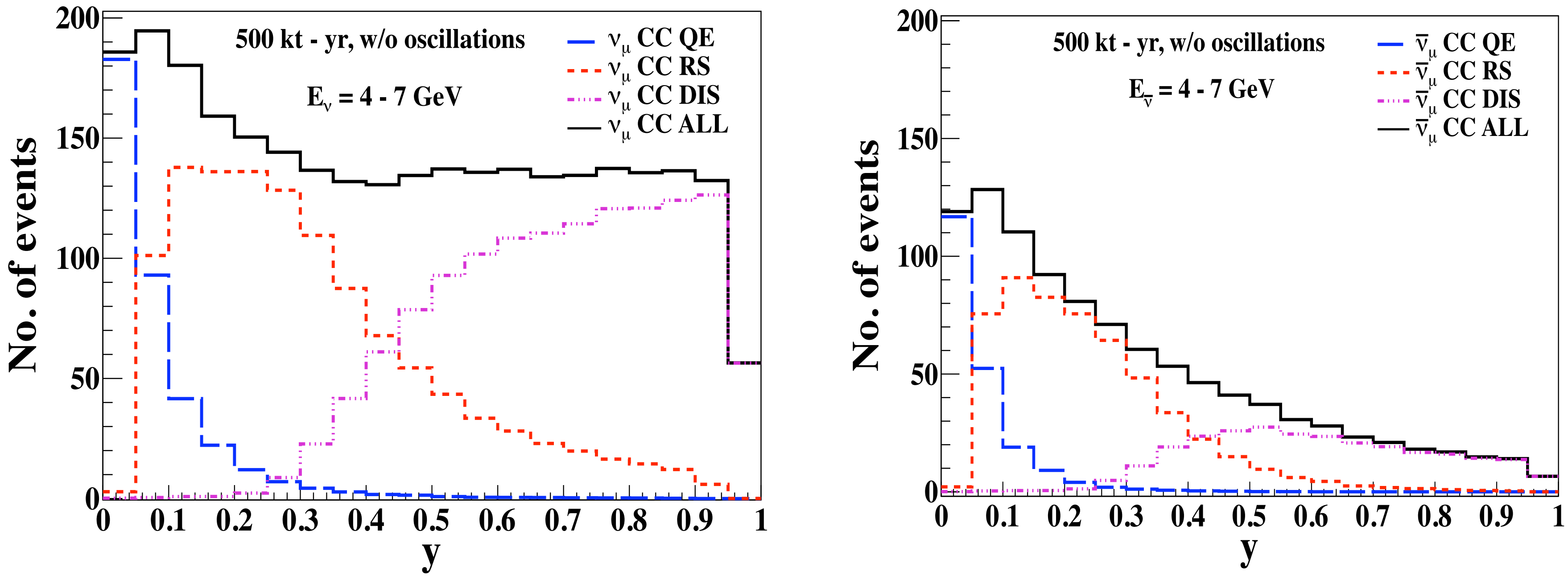
Distribution of Inelasticities in Events

$$\frac{d\sigma^{CC}}{dy} = -[a + b(1-y)^2] \times 10^{-38}\ \mathrm{cm}^2\ \frac{E_\nu}{1\ \mathrm{GeV}}$$

Neutrinos: $a \gtrsim b$, Antineutrinos: $a \lesssim b$

Normalized Inelasticity Distribution

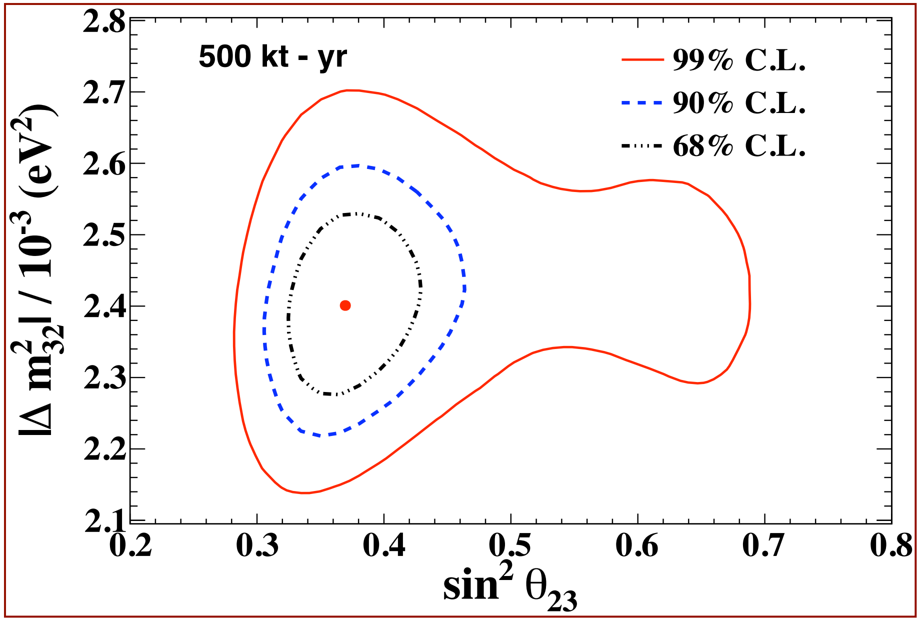
$$p \equiv -\frac{1}{\sigma}\frac{d\sigma}{dy} = \frac{a + b(y-1)^2}{a + b/3}$$

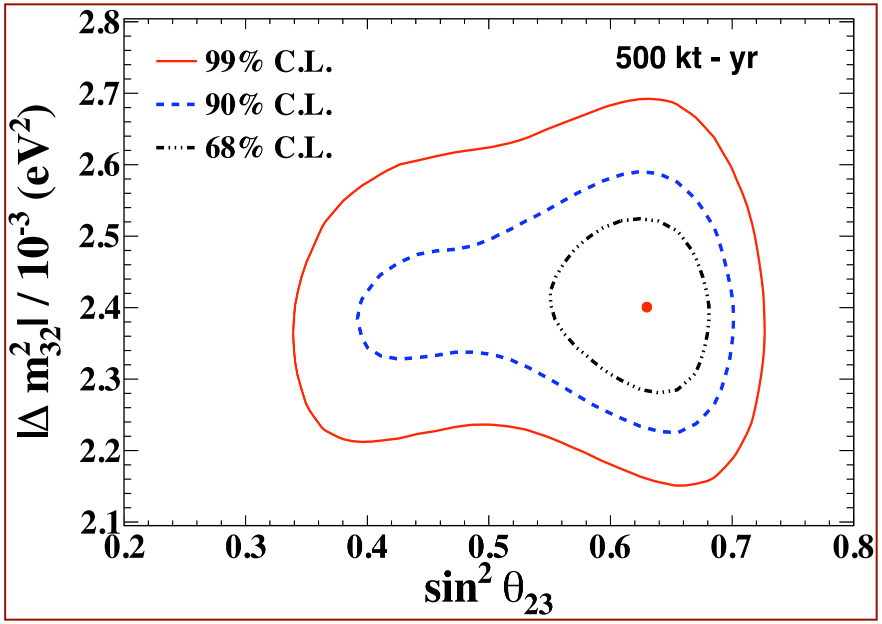


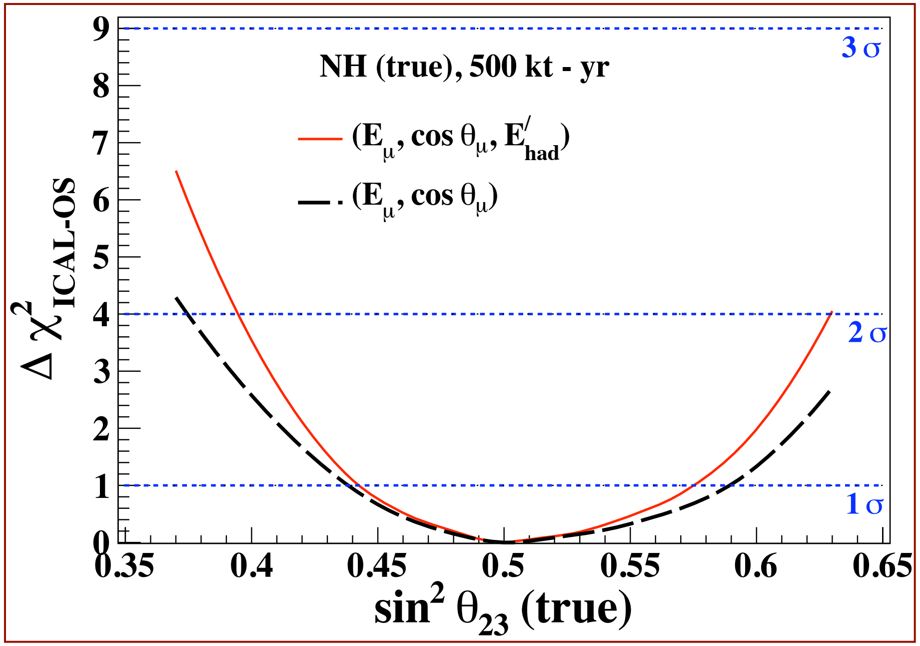
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Inelasticities in individual events have a wide distribution, crucial to measure it in individual events

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)

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

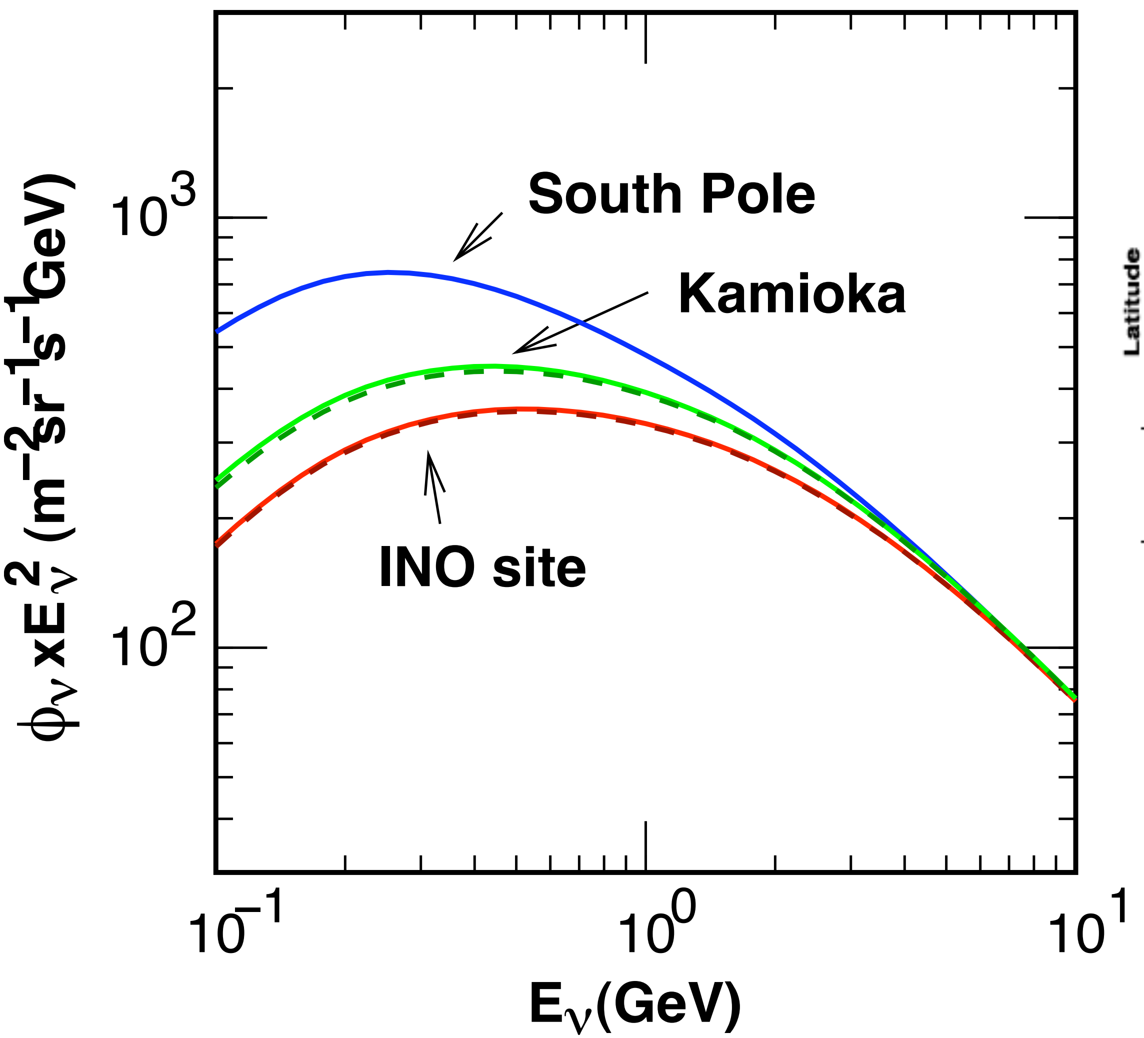
Press Release

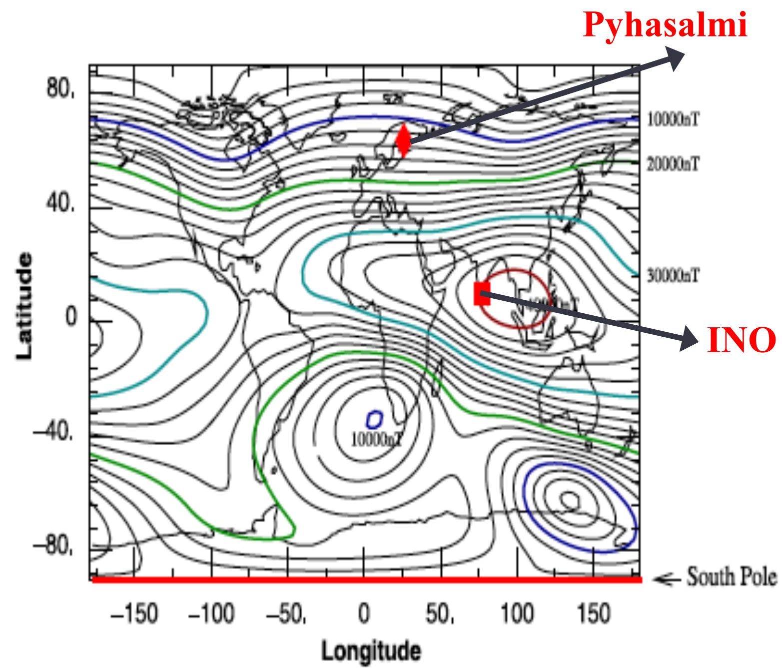
The Union Cabinet of the Govt. of India chaired by the Prime Minister, Shri Narendra Modi, has given its approval for the establishment of India-based Neutrino Observatory (INO) at an estimated cost of Rs. 1500 crores.

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 was over! But, we have miles to go…

Atmospheric Neutrino Flux





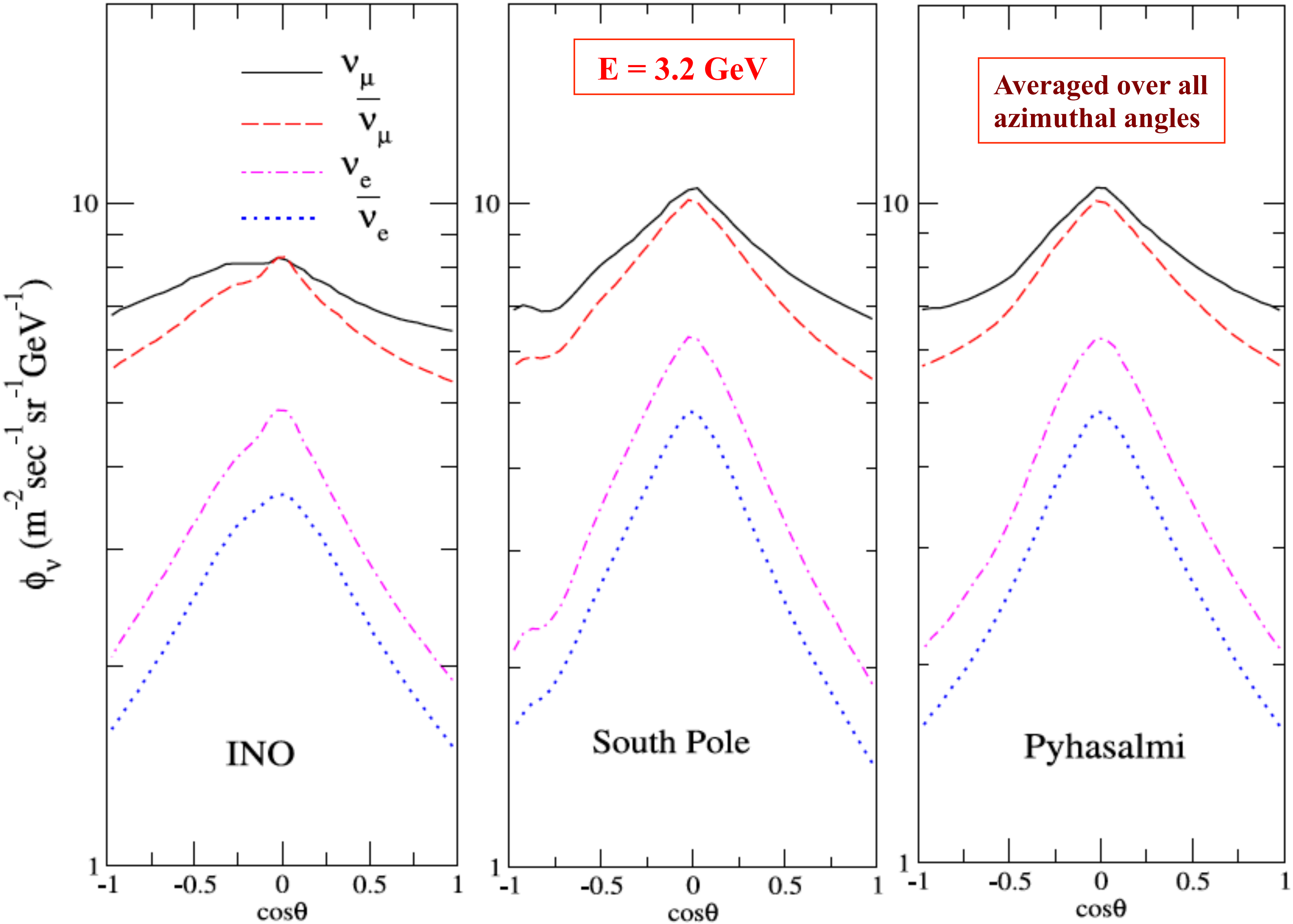
Horizontal component of the geomagnetic field

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]

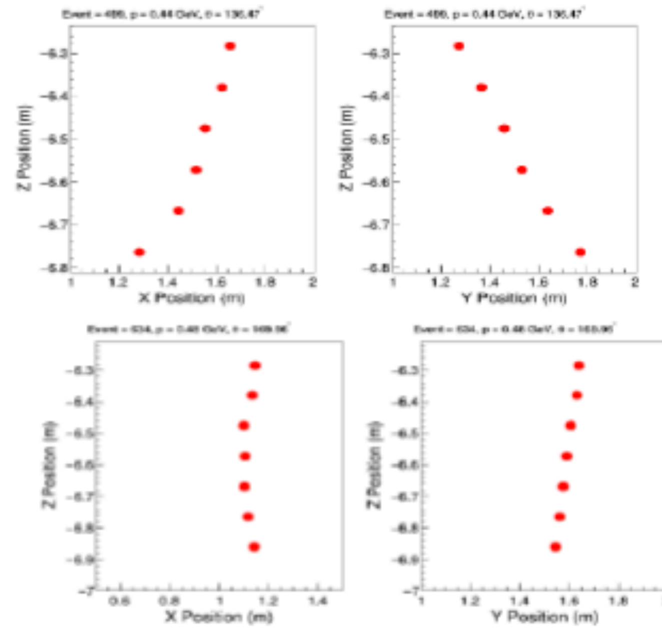
Atmospheric Neutrino Flux



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

Mini-ICAL at IICHEP, Madurai

85 ton mini-ICAL detector measuring natural cosmic muons using 10nos. 2m×2m Resistive Plate Chambers with glass gaps made is St. Gobain, Sriperumbudur.



Muon tracks in mini-ICAL detector.

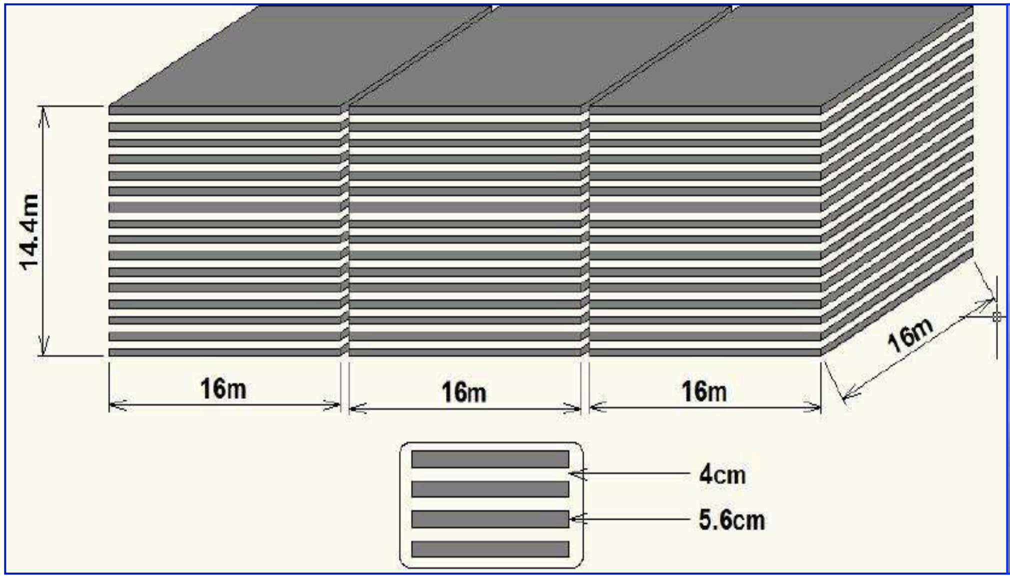
Opposite curvatures in bending (X-) plane due to opposite electric charges of down-going muons.

Detector Characteristics

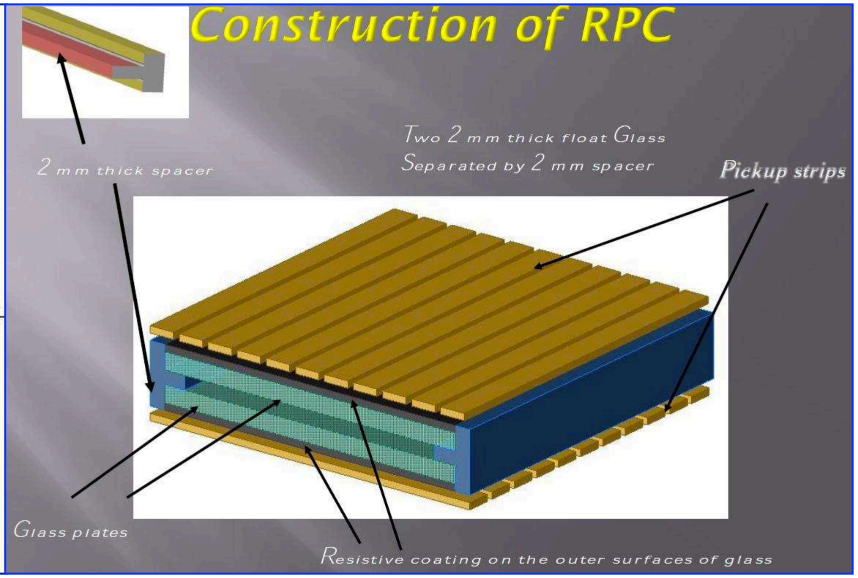
- *Should have large target mass (50 – 100 kt)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*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

Our choice

Magnetized iron (target mass): ICAL



RPC (active detector element)

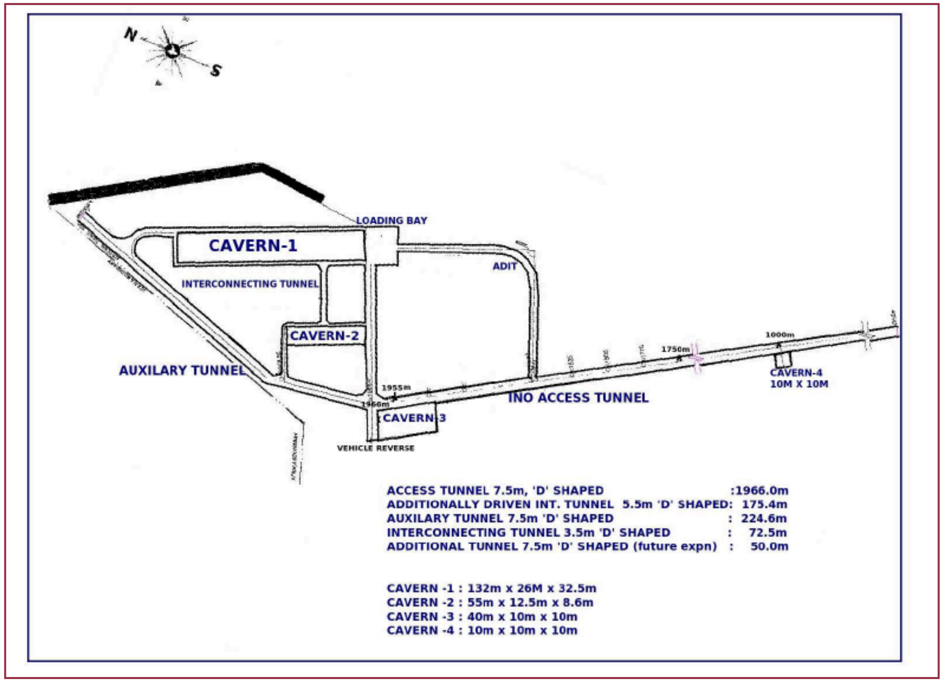


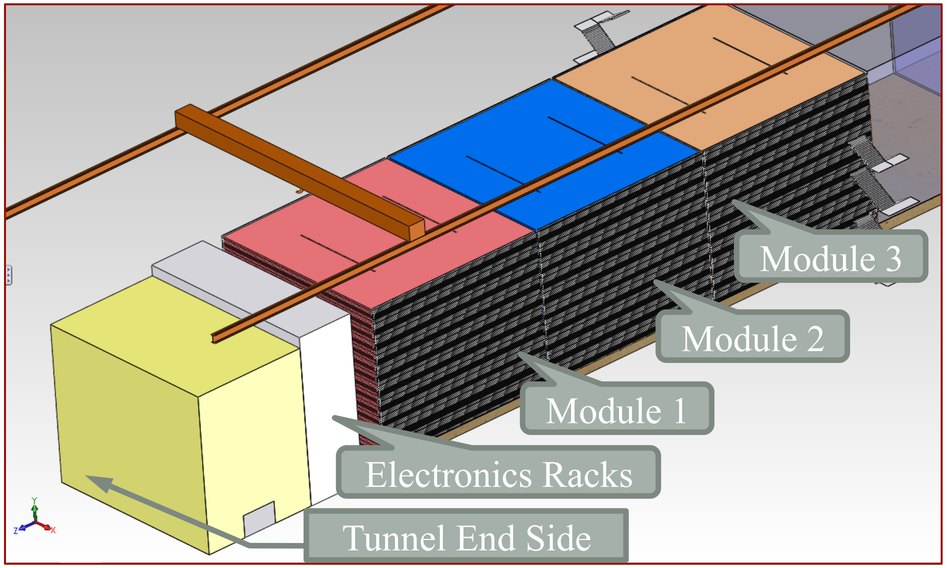
Specifications of the ICAL Detector

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

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*





Physics Issues with ICAL-INO

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

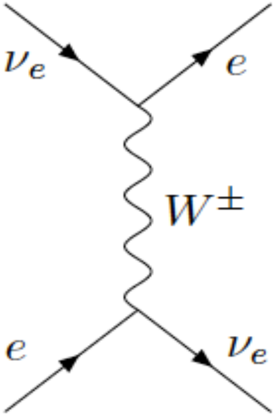
Recent discovery of large θ_{13} : A good news for ICAL-INO

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***

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

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

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***

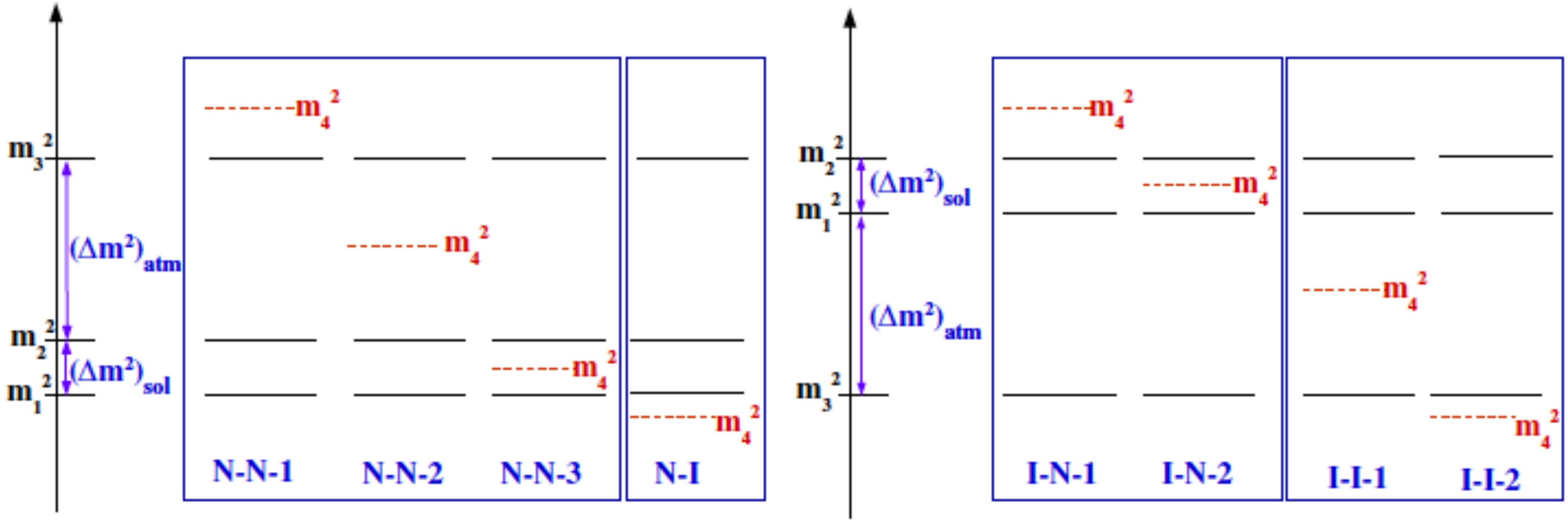
Matter term modifies oscillation probability differently depending on the sign of Δm^2

$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\ \mathrm{GeV}$ → ***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)***

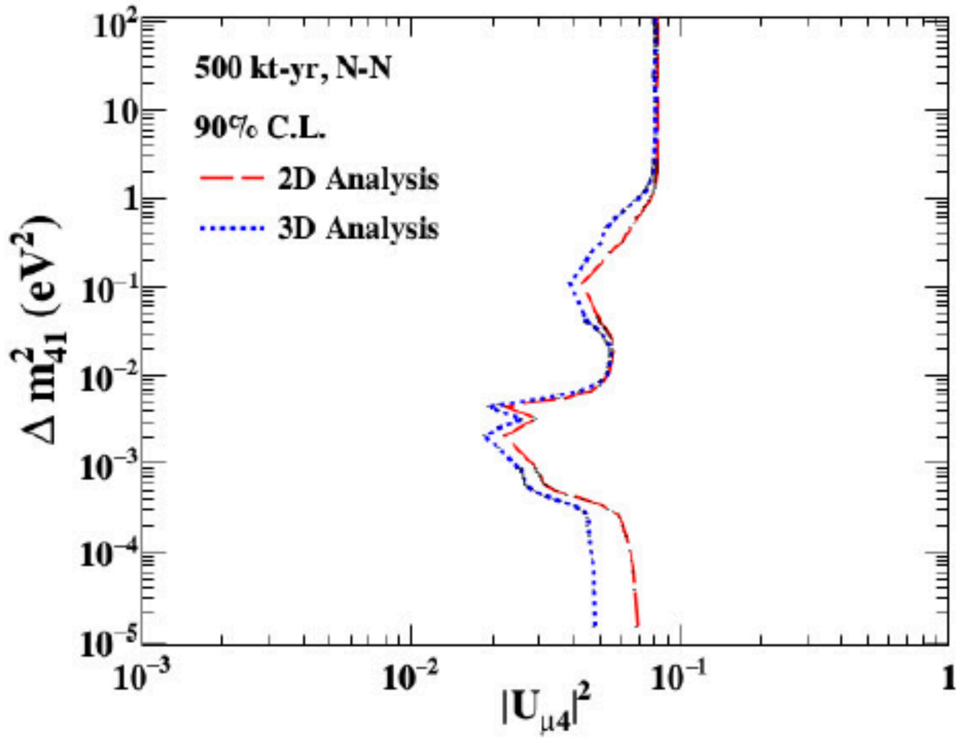
Mass Ordering in 4ν Scheme



Ordering scheme	N-N			N-I	I-N		I-I	
Sign of Δm^2_{31}	+			+	-		-	
Sign of Δm^2_{41}	+			-	+		-	
Sign of Δm^2_{42}	+	+	-	-	+	-	-	-
Sign of Δm^2_{43}	+	-	-	-	+	+	+	-
Configuration	N-N-1	N-N-2	N-N-3	N-I	I-N-1	I-N-2	I-I-1	I-I-2

Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph] (INO Collaboration)

Sterile Neutrino Sensitivity with ICAL at INO



- For higher Δm^2, information is mainly in the number of events, so information about E'_h not so useful
- For lower Δm^2, oscillation information in the energy and angular spectra, so E'_h crucial

$$V_{es} = \sqrt{2} G_F (N_e - N_n/2) \quad \text{between } \nu_e \text{ and } \nu_s ,$$
$$V_{\mu s} = V_{\tau s} = -\sqrt{2} G_F N_n/2 \quad \text{between } \nu_{\mu/\tau} \text{ and } \nu_s ,$$

Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph] (INO Collaboration)

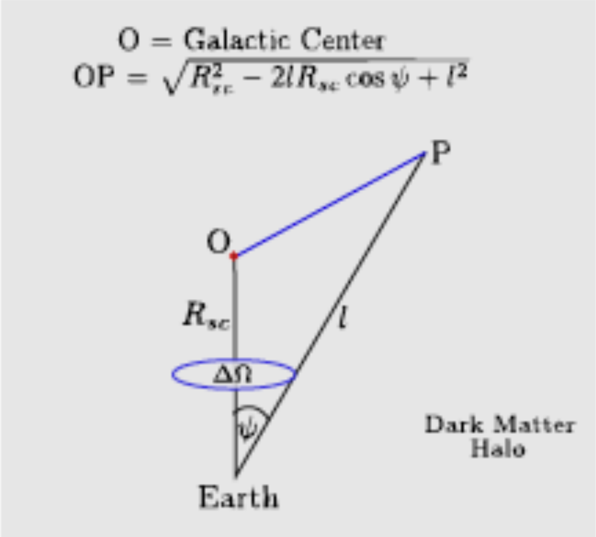
DM Annihilation

$$\chi\chi \to \nu\bar{\nu}$$

- Neutrino can be ν_e, ν_μ type and ν_τ type.

Flux of neutrinos from dark matter Phys. Rev. D76 (2007)

$$\frac{d^2\Phi^{ann}}{dE\,d\Omega} = \frac{\langle\sigma v\rangle}{2}\mathcal{J}^{ann}_{\Delta\Omega}\frac{R_{sc}\rho^2_{sc}}{4\pi\,m^2_\chi}\frac{1}{3}\frac{dN^{ann}}{dE}\,.$$



$$\mathcal{J}^{ann}(\psi) = \frac{1}{R_{sc}\rho^2_{sc}}\int_0^{l_{max}} dl\;\rho^2\left(\sqrt{R^2_{sc} - 2l\,R_{sc}\cos\psi + l^2}\right),$$

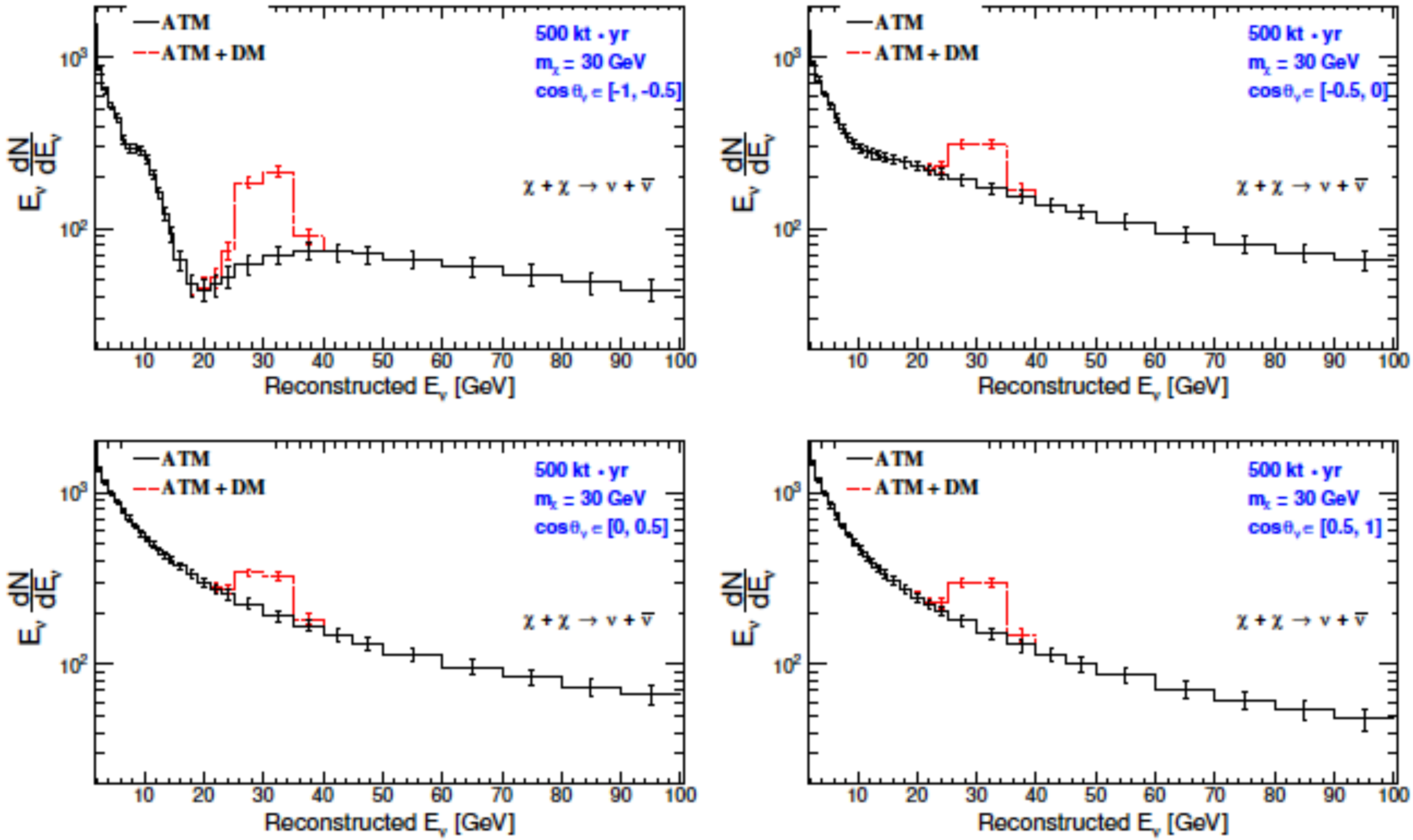
$$l_{max} = \sqrt{(R^2_{MW} - R^2_{sc}\sin^2\psi)} + R_{sc}\cos\psi\,,$$

$$\mathcal{J}^{ann}_{\Delta\Omega}(\psi) = \frac{1}{2\pi(1-\cos\psi)}\int_{\cos\psi}^{1} 2\pi\,\mathrm{d}(\cos\psi')\,\mathcal{J}(\psi')\,,$$

$$\frac{dN^{ann}}{dE} = \delta(E_{\nu\bar{\nu}} - m_\chi)\,.$$

Event Spectrum

$$< \sigma v >= 3.5 \times 10^{-23}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$$



Data: Predicted atmospheric neutrino event in MagICAL (ATM), Theory: ATM + DM

Decay of Dark Matter

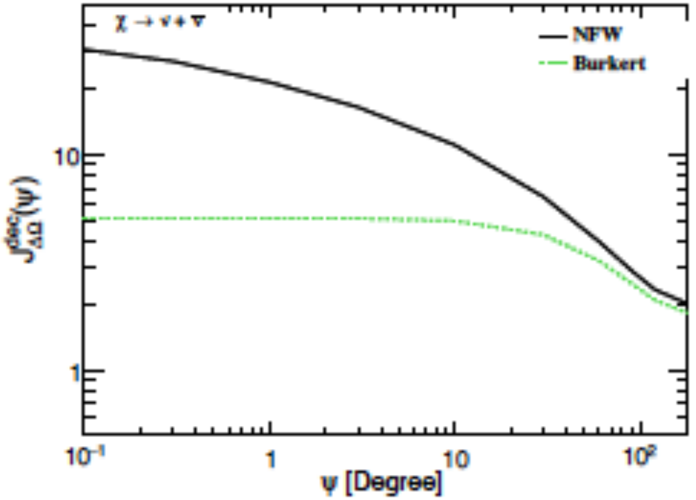
$$\chi \to \nu\bar{\nu}$$

$$\mathcal{J}^{dec} = \frac{1}{R_{sc}\rho_{sc}} \int_0^{l_{max}} dl \; \rho(\sqrt{R_{sc}^2 - 2lR_{sc}\cos\psi + l^2}) \, ,$$

$$\mathcal{J}^{dec}_{\Delta\Omega}(\psi) = \frac{1}{2\pi(1-\cos\psi)} \int_{\cos\psi}^{1} 2\pi \, d(\cos\psi') \, \mathcal{J}^{dec}(\psi$$

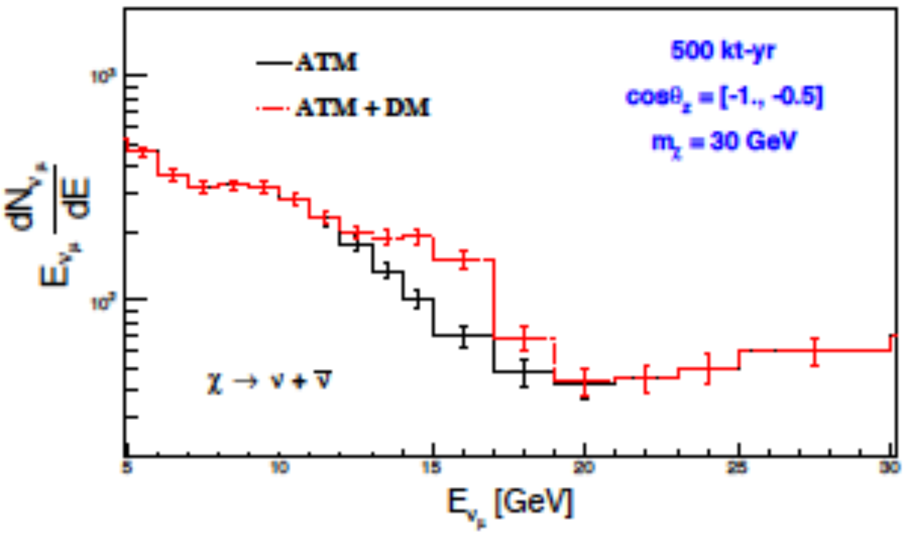
$$\frac{d^2\Phi^{dec}_{\nu,\bar{\nu}}}{dE\,d\Omega} = \mathcal{J}^{dec}_{\Delta\Omega} \frac{R_{sc}\rho_{sc}}{4\pi\, m_\chi\, \tau_\chi} \frac{1}{3} \frac{dN^{dec}}{dE} \, ,$$

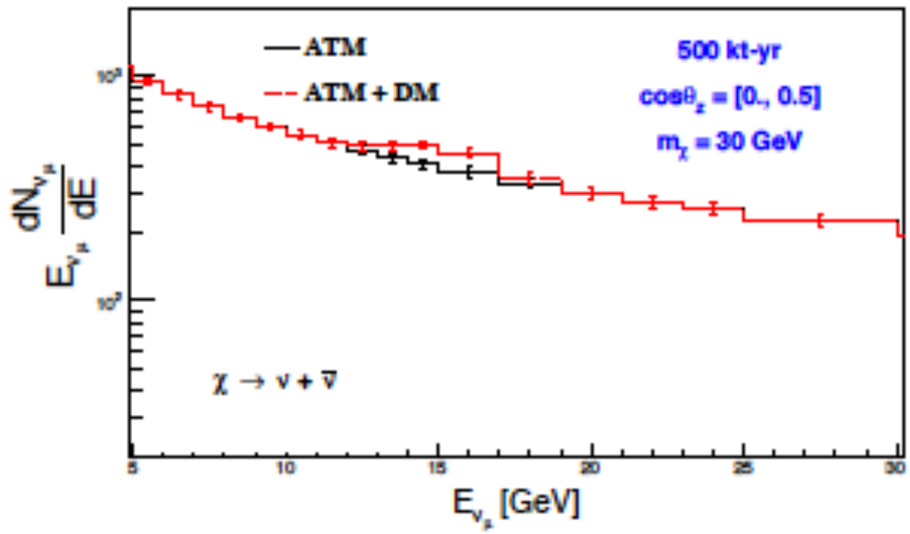
$$\frac{dN^{ann}}{dE} = \delta(E_{\nu\bar{\nu}} - \frac{m_\chi}{2}) \, .$$



Event Spectrum

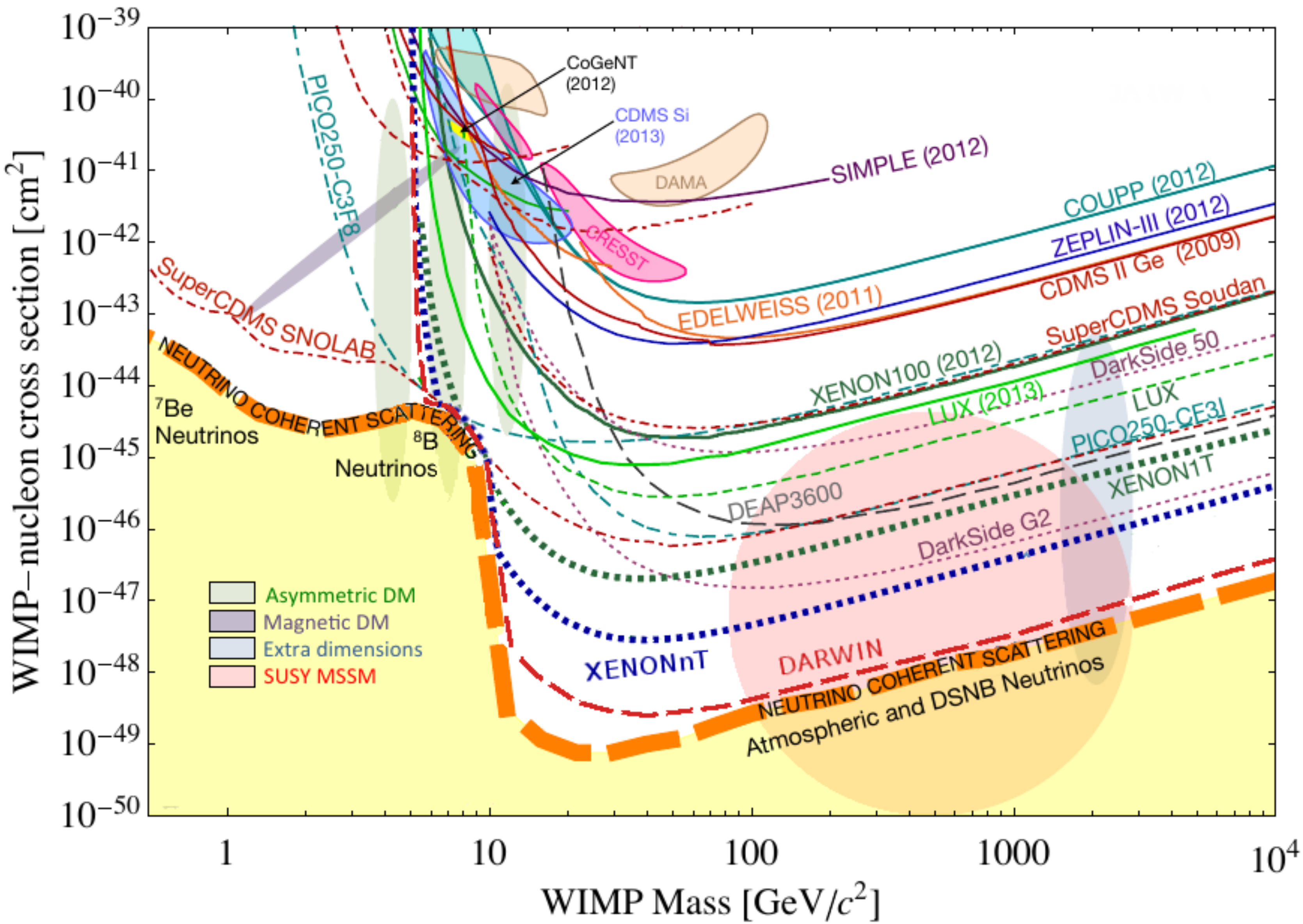
$$(4.7 \times 10^{24}\ \text{s})$$





- 30 GeV dark matter decay to neutrino having energy 15 GeV.

A Snapshot of Results from Direct Detection Experiments



Sensitivities are improving rapidly

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

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

0.03   0.3

$$\begin{aligned} P_{\mu e} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\ & - \alpha \sin 2\theta_{13} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & + \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}; \end{aligned}$$

$\sin^2 2\theta_{13}$: 0.09 — first term: θ_{13} Driven

$\sin^2\theta_{23}$: Resolves octant

$\alpha \sin 2\theta_{13}$: 0.009 — second term: CP odd

Third term: CP even

α^2: 0.0009 — fourth term: 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?

Matter effect in Atmospheric Experiments