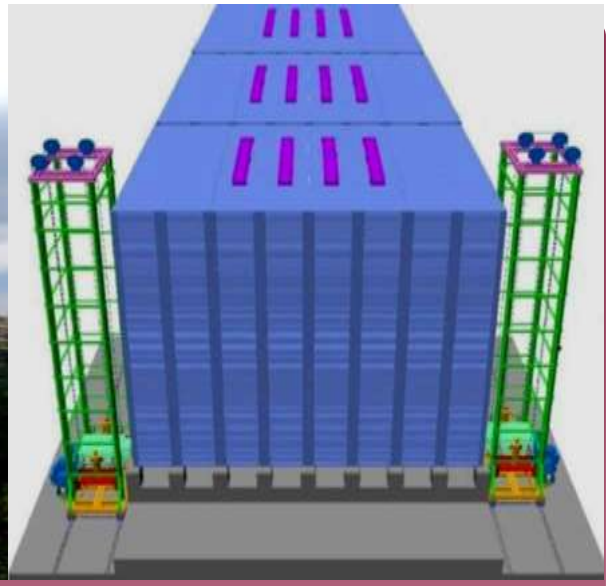


India-based Neutrino Observatory (INO)

Moon Moon Devi

TIFR, Mumbai

(For the INO collaboration)

http://www.ino.tifr.res.in/ino/

Aug 27, 2014

NUFACT 2014

University of Glasgow SUPA

INO

INO The Collaboration

Ahmedabad: Physical Research Laboratory
Aligarh: Aligarh Muslim University
Allahabad: HRI
Bhubaneswar: IoP, Utkal University
Calicut: University of Calicut
Chandigarh: Punjab 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


Collaboration Meeting, April 2014, VECC

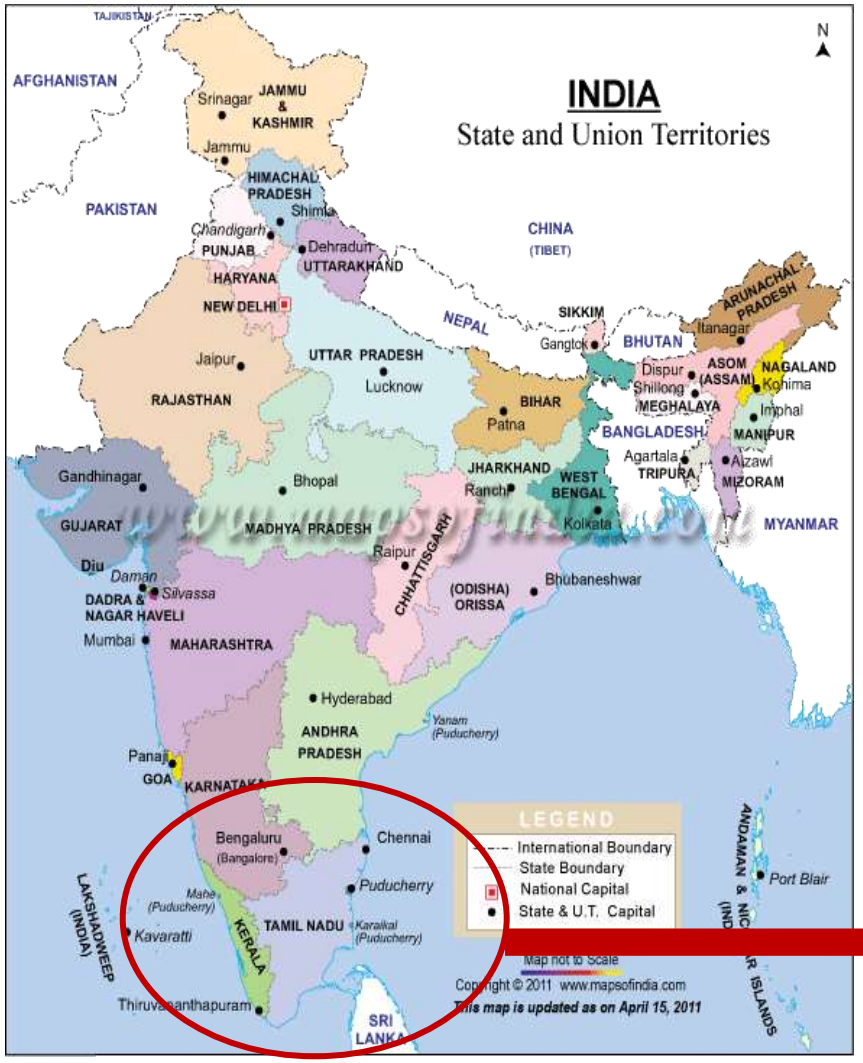
INO The Physics Motivation

- To study neutrino oscillations in the atmospheric sector → Wider range for E and L than accelerator/reactor neutrino sources
- Probing neutrino oscillations in the GeV range using matter effects in the earth's core
- Distinguishing between neutrinos and antineutrinos → efficient determination of neutrino mass ordering
- Magnetized **I**ron **CAL**orimeter (**ICAL**) → excellent reconstruction of muon momentum, and charge identification
- Hadron shower reconstruction → allows access to neutrino energy

The Physics Goals

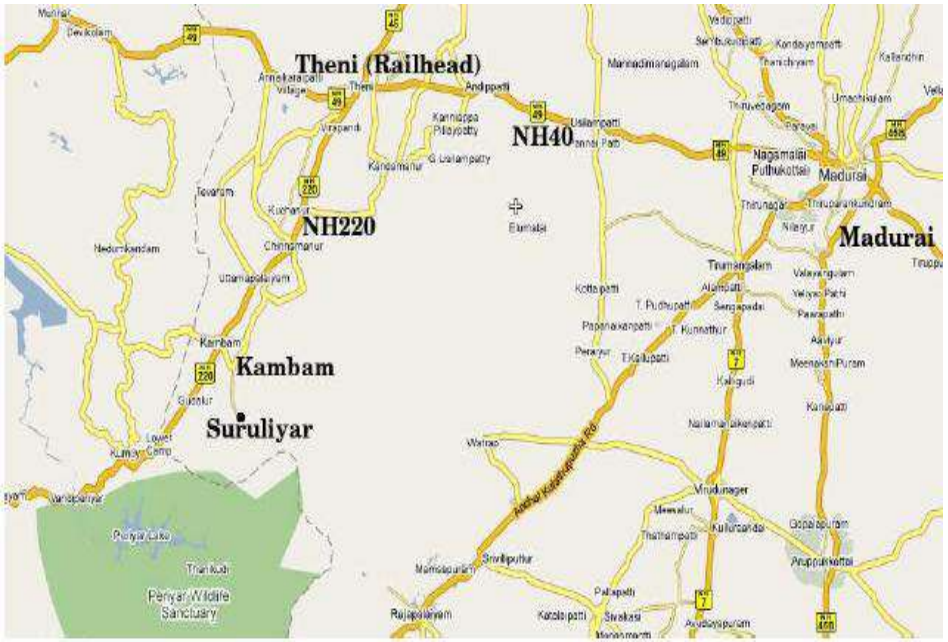
- Determination of neutrino mass hierarchy using matter effects and $\nu/\bar{\nu}$ discrimination
- More precise determination of the atmospheric oscillation parameters
- Non standard interactions, CPT violation, long range forces
- Ultra high energy muon fluxes, indirect searches of dark matter

INO The Location



- South India
- 120 km from the **Madurai city** of Tamil Nadu State
- Madurai has an international airport

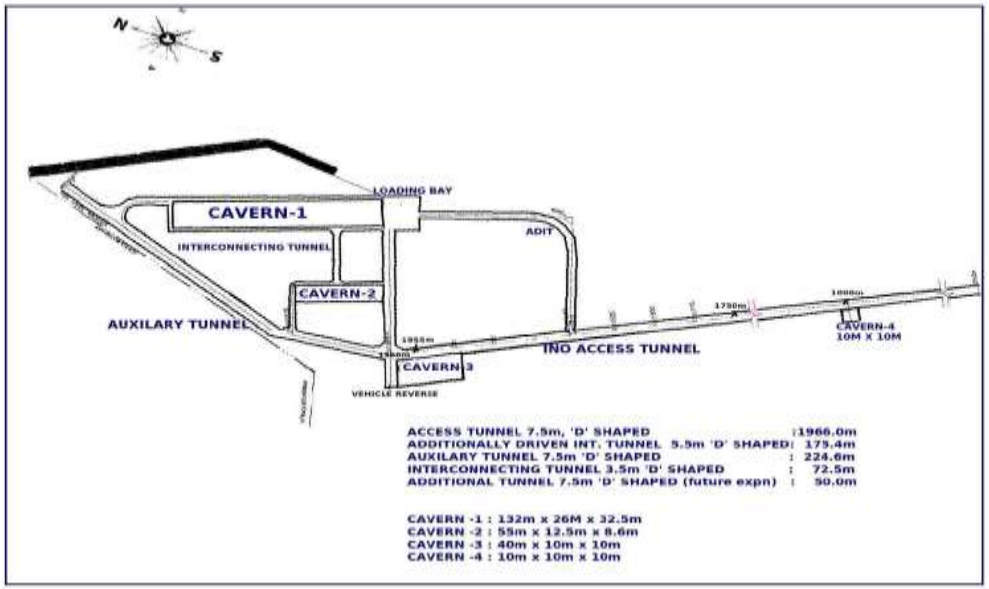
The Site

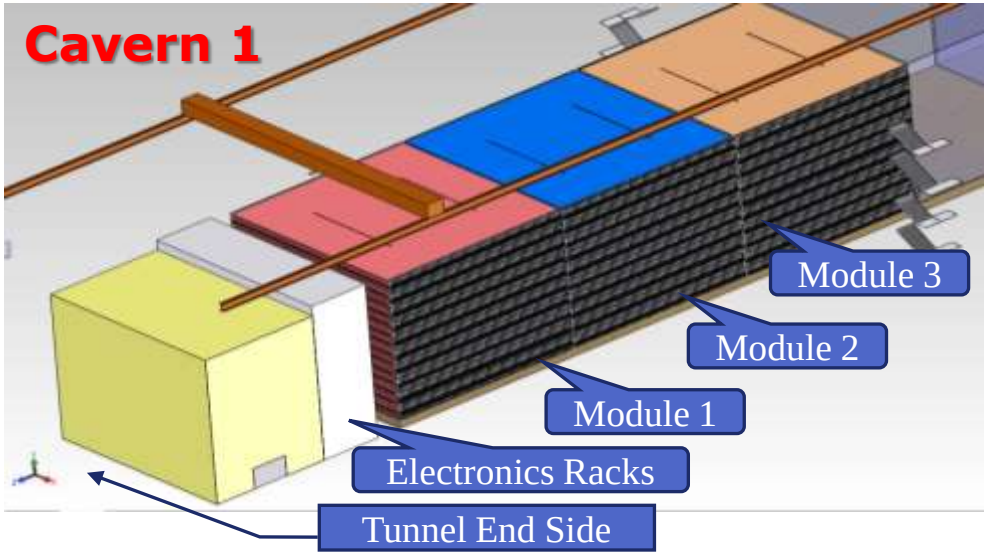


Bodi West Hills (9°58' N, 77°16' E)

- Pottipuram Village, Theni District, Tamil Nadu
- Charnockite rock under the 1589 m peak
- Vertical cover 1289 m, all-round cover ~ 1000 m

INO The caverns





- Cavern 1 will host 50kt ICAL (space for 100 kt)
- Accessible through a 2km tunnel
- Other caverns available for multiple experiments

(NDBD, dark matter, ...)

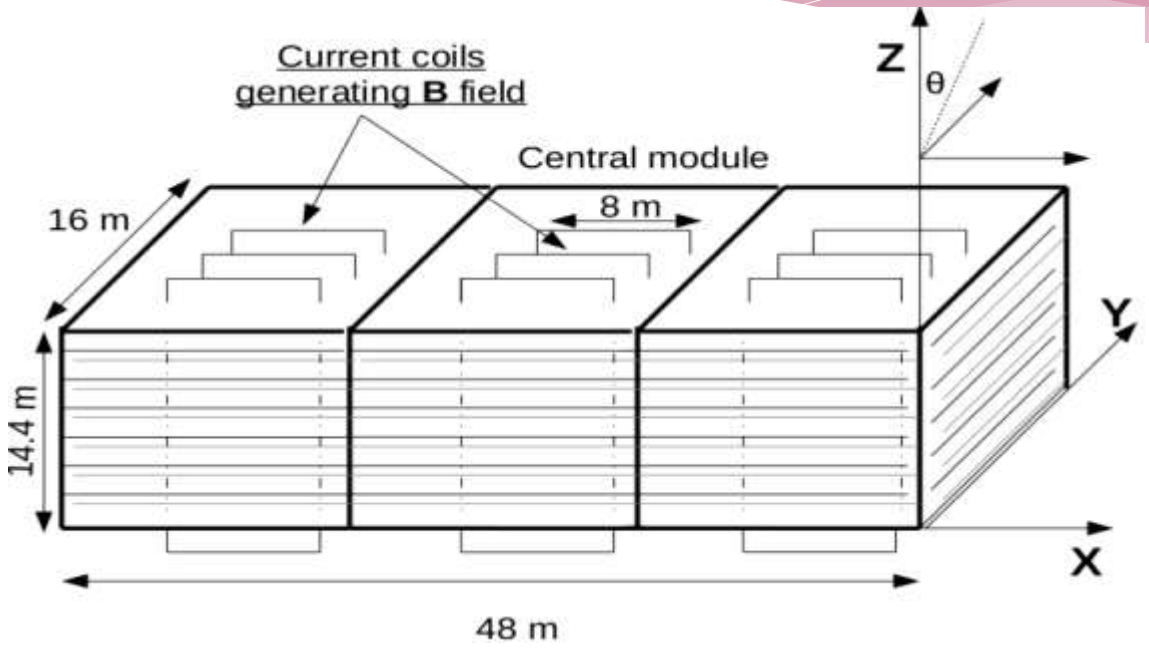
INO Highlights

- To 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) – Started from 2008
- Completely in-house Detector R&D with substantial INO-Industry interface

Time Frame for 1st module: 2019

ICAL The Detector

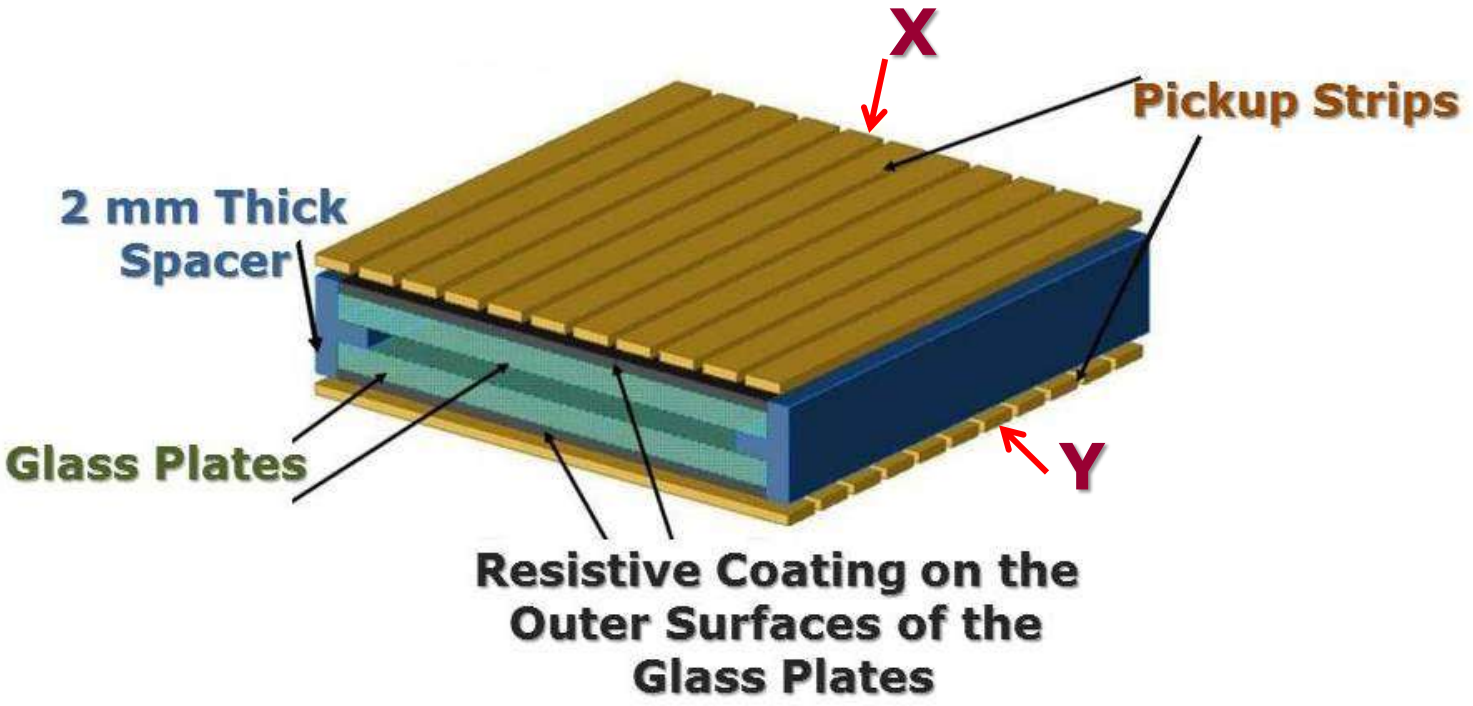
- **Magnetized Iron CALorimeter**



- Iron plates separated by resistive plate chambers (RPCs)
- 150 layers, 50 Kt
- Good energy measurement and charge identification through tracking of muons bending in the magnetic field
- Directionality through tracking and timing (~1ns resolution)

ICAL Active Detector Element

Resistive Plate Chamber (RPC)

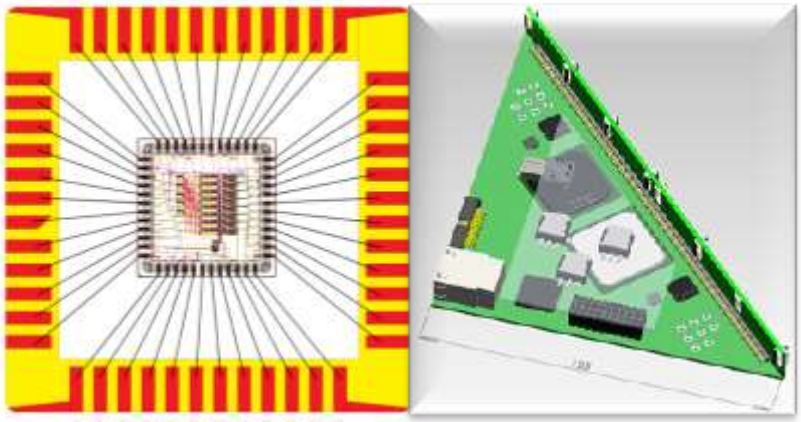


- The X and Y side pickup strips are orthogonal to each other, helps to locate the passage of a charged particle passing through the detector

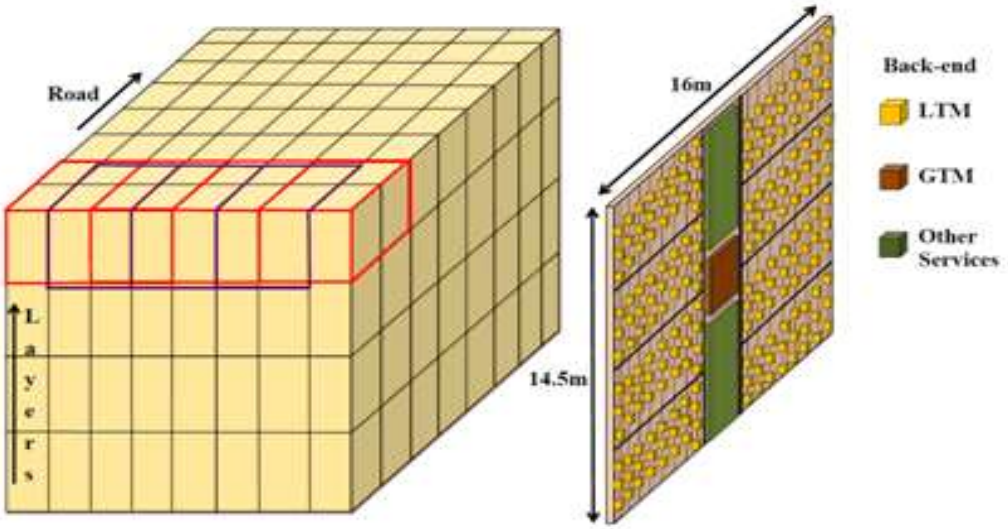
ICAL Factsheet

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

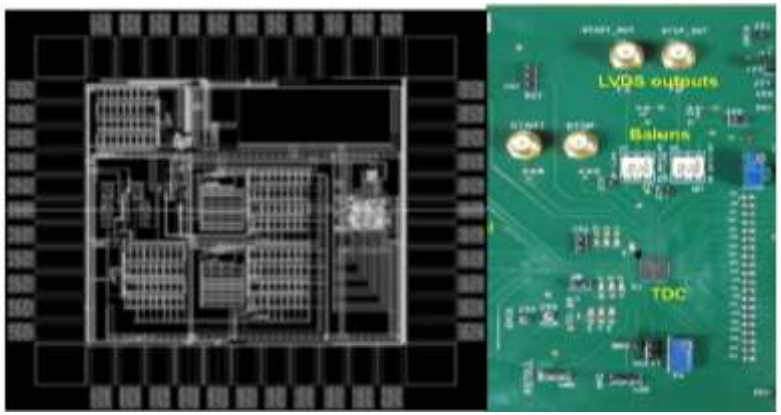
ICAL Electronics



Front-end ASIC



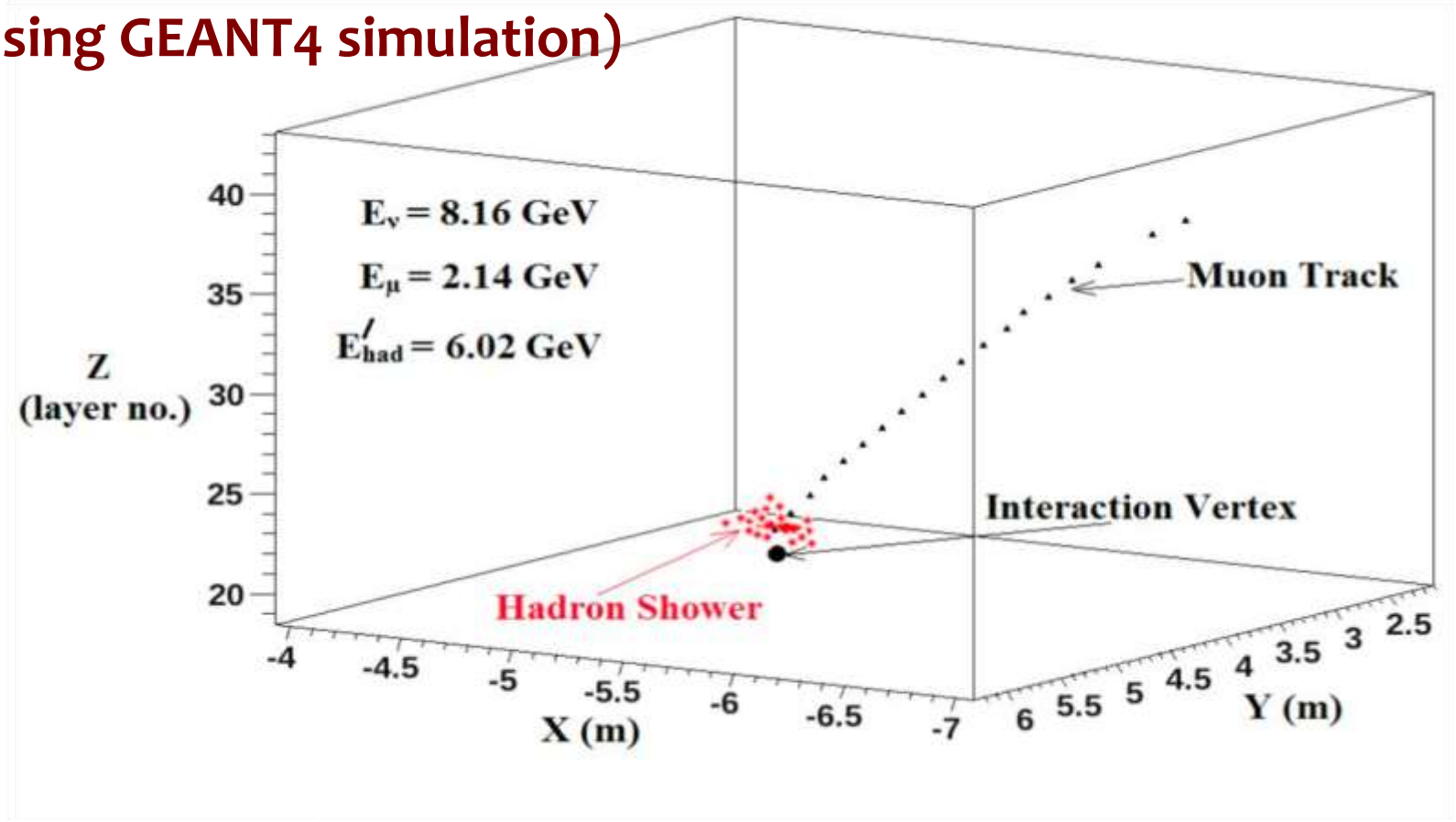
Trigger Scheme



TDC ASIC

Event Display in ICAL

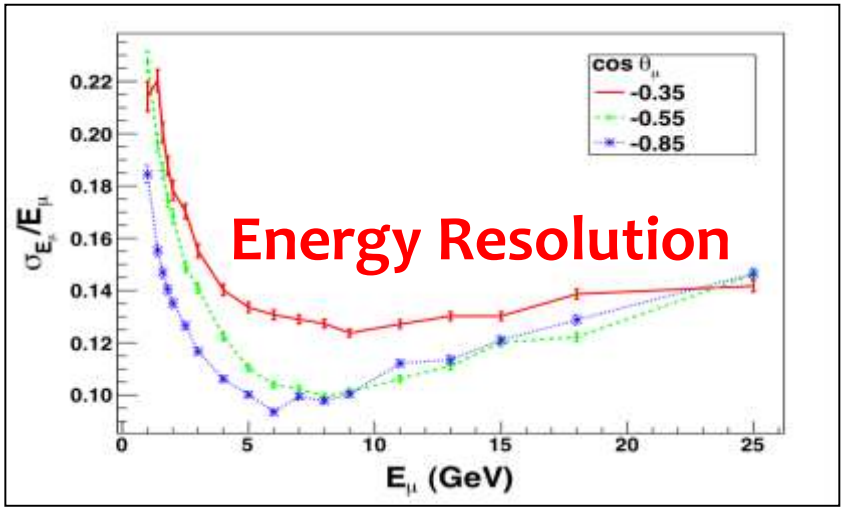
(Using GEANT4 simulation)

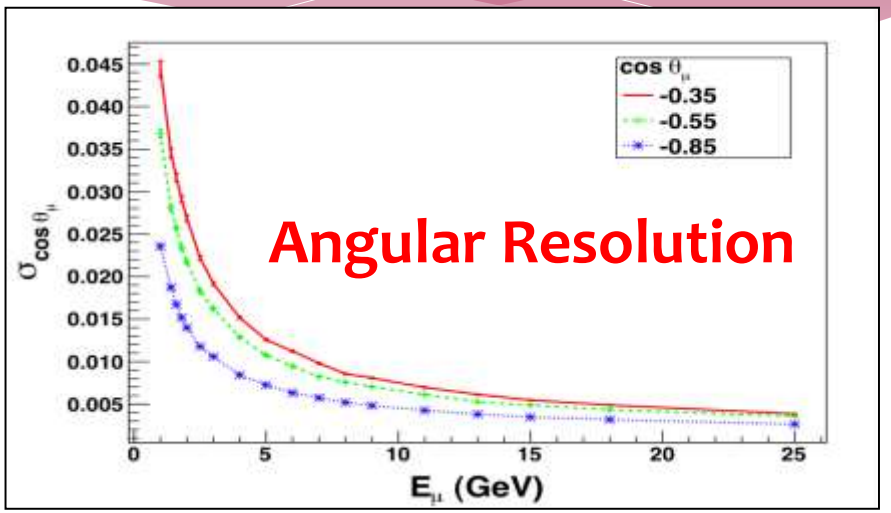


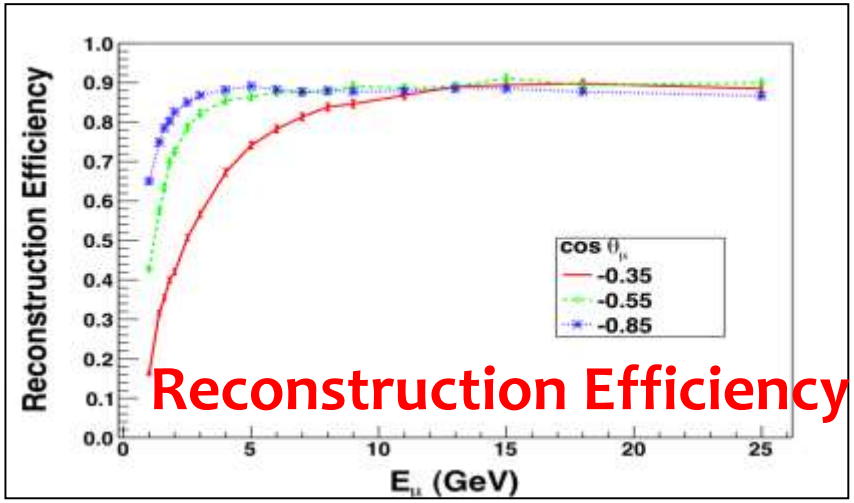
- The muon hits leave a **track like** feature
- The hadron hits form a **shower**

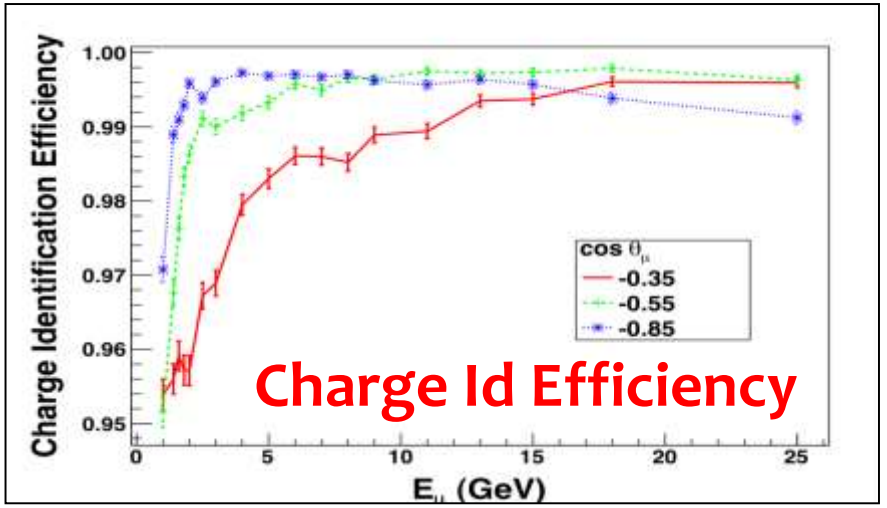
INO ICAL

Muon efficiencies and resolutions



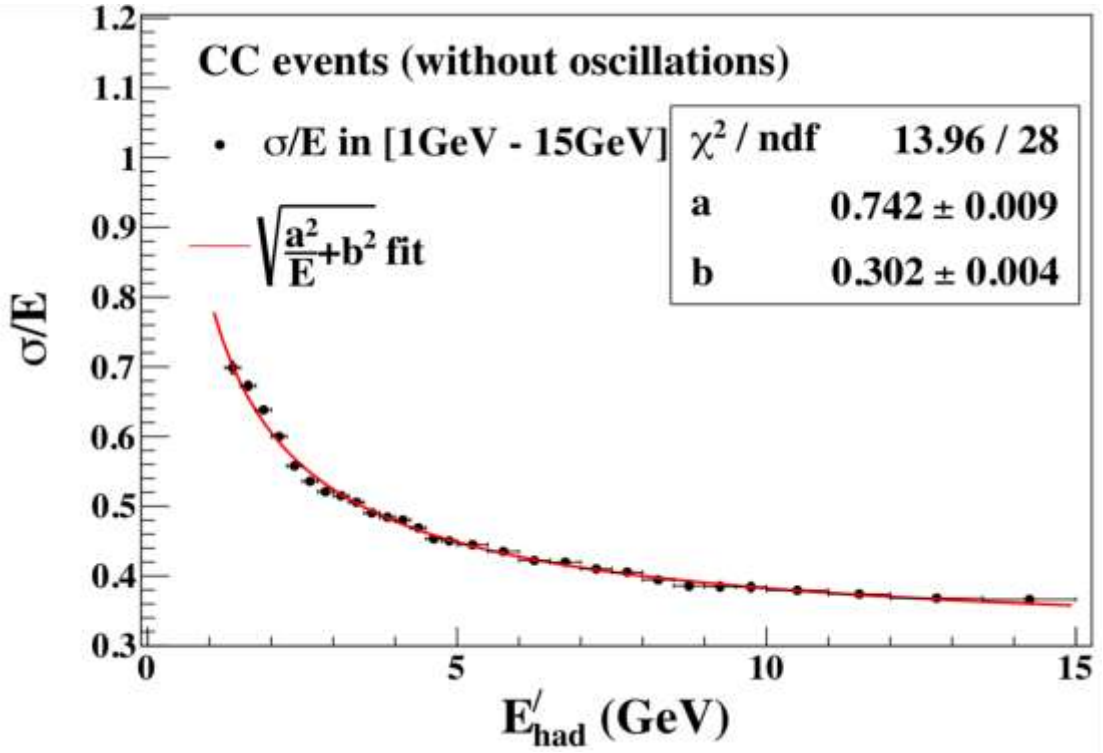






A. Chatterjee, Meghna K.K., K. Rawat, T. Thakore et al., JINST ***9*** *(2014) P07001*

INO ICAL Hadron Energy Resolution



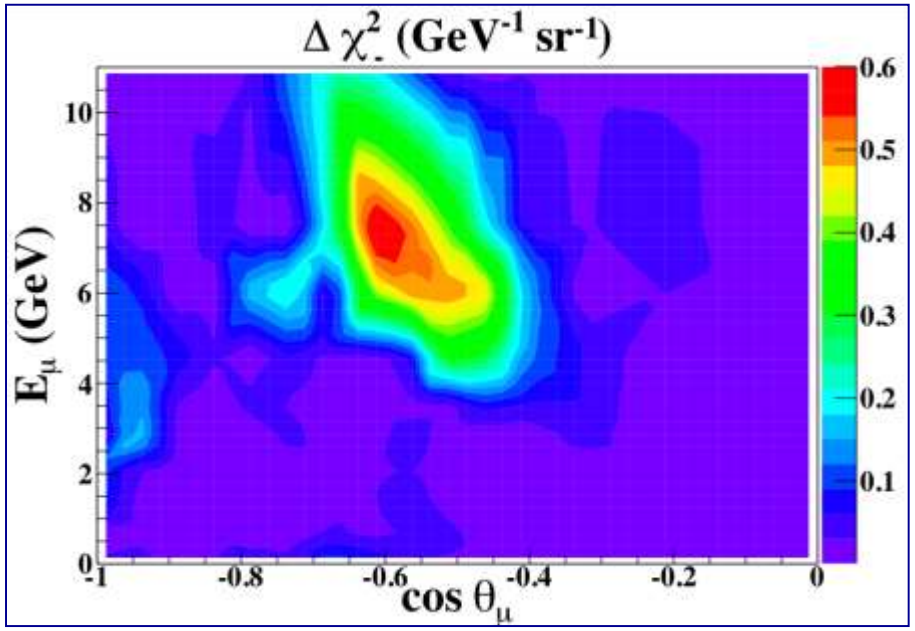
- $E'_{had} = E_\nu - E_\mu$
- E'_{had} is calibrated from the number of hadron hits
- Hadron energy resolution:

85% at 1 GeV and
36% at 15 GeV

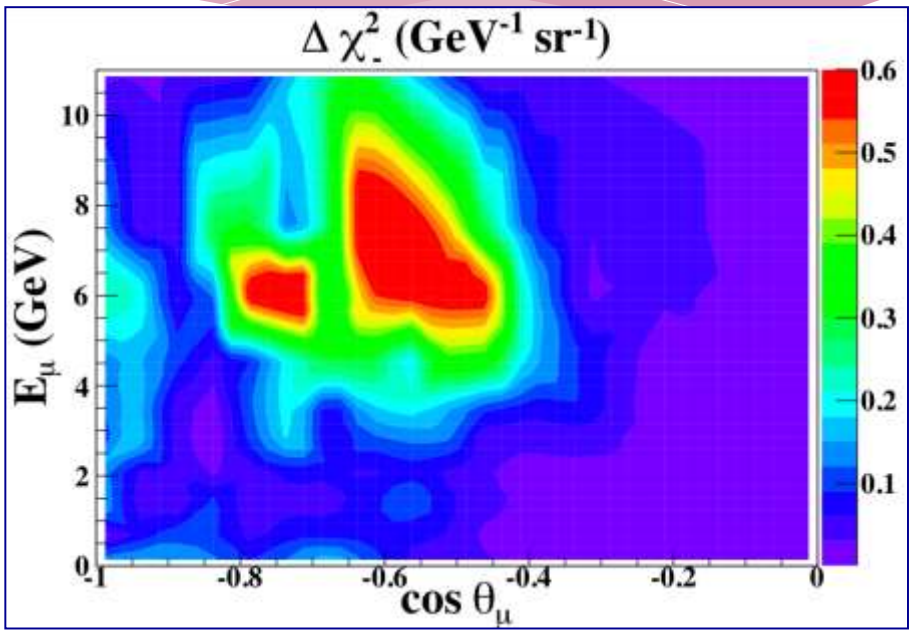
*M.M. Devi, A. Ghosh, D. Kaur, S.M. Lakshmi, JINST **8** (2013) P11003*

INO ICAL

Mass Hierarchy Discrimination



Without hadron energy information



With hadron energy information

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

- Hadron energy carries crucial information
- **Correlation** between hadron energy and muon momentum is very important

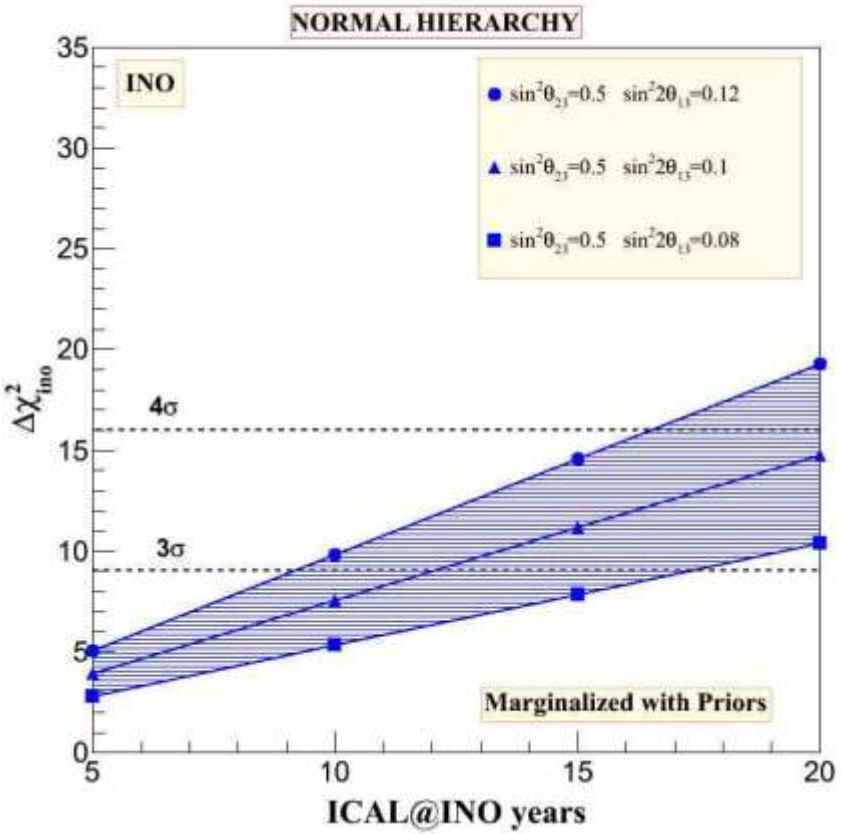
10 E_μ bins
21 $\cos\theta_\mu$ bins
4 E'_{had} bins

INO ICAL

Mass Hierarchy Sensitivity

- With muon information only via $(E_\mu, \cos\theta_\mu)$ binning

- The 50 kt ICAL can discard the wrong hierarchy With median $\Delta\chi^2 \approx 7.5$ in 10 years for
  $\sin^2\theta_{23}$ (true)=0.5,
  $\sin^2 2\theta_{13}$ (true)=0.1



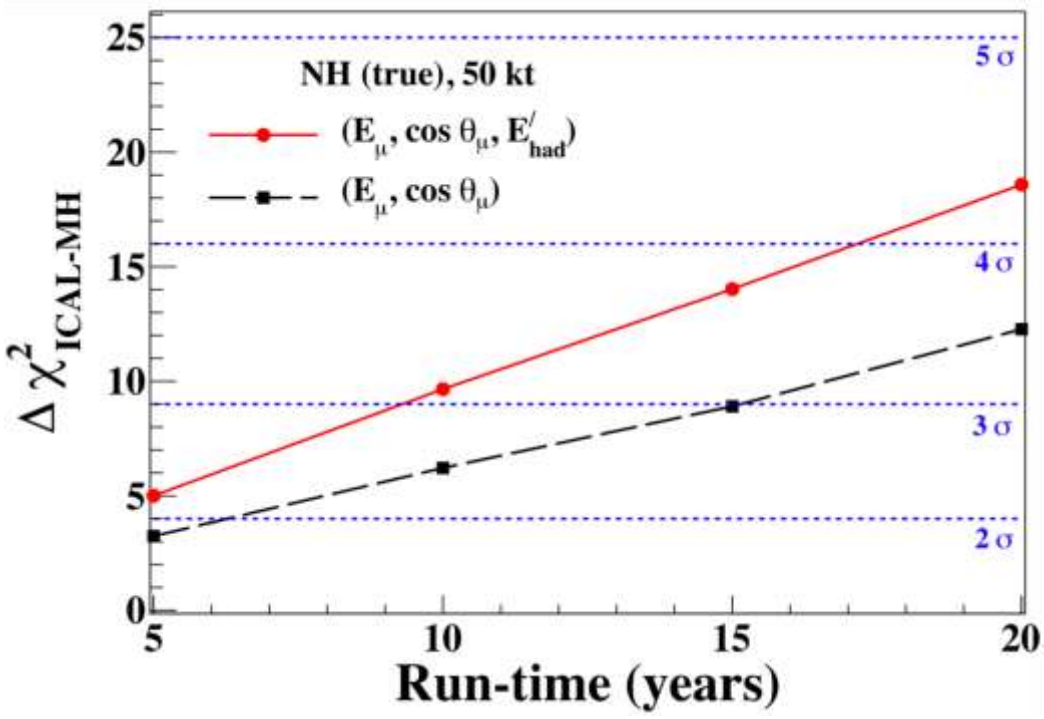
20 E_μ bins, 80 $\cos\theta_\mu$ bins

A. Ghosh, T. Thakore, S. Choubey, JHEP 1304 (2013) 009

INO ICAL

Mass Hierarchy Sensitivity

- Inclusion of hadron energy information via $(E_\mu, \cos\theta_\mu, E'_{had})$ binning



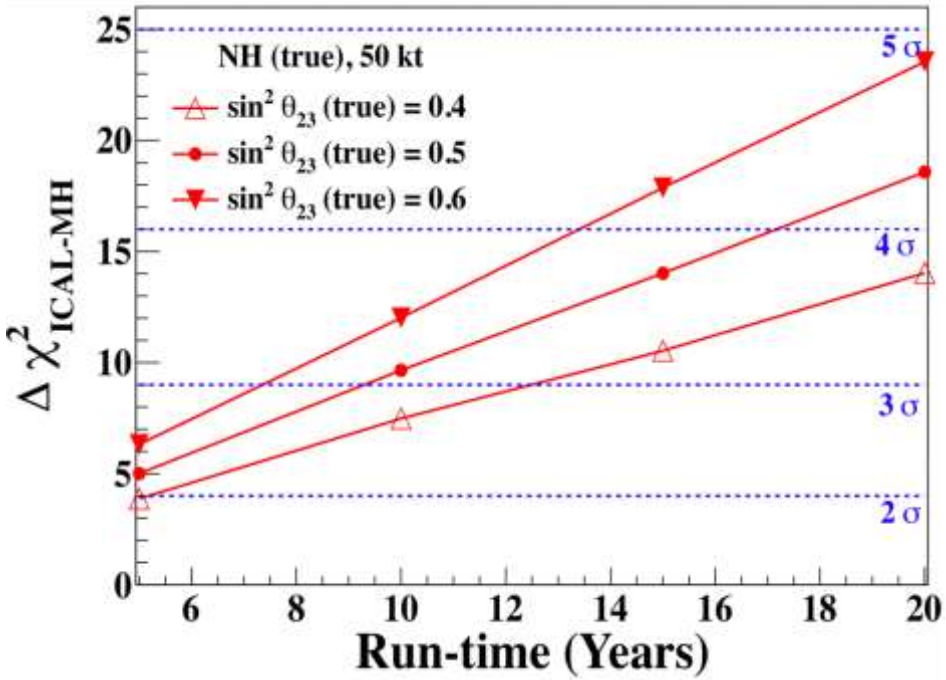
- The 50 kt ICAL can discard the wrong hierarchy with median $\Delta\chi^2 \approx 9.6$ in 10 years

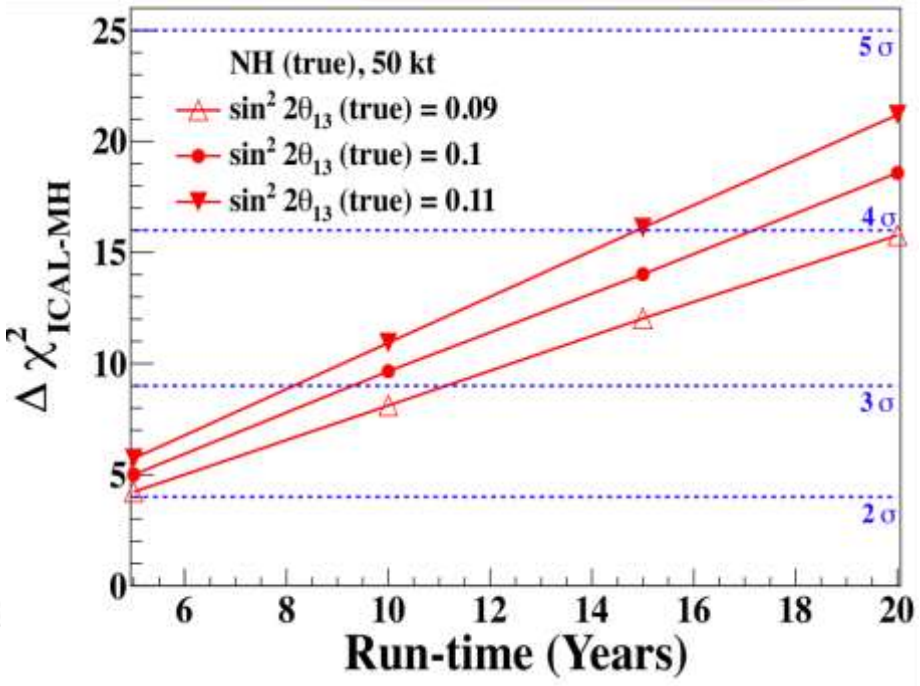
- About 40% improvement Over the muon-only analysis

10 E_μ bins, 21 $\cos\theta_\mu$ bins, 4 E'_{had} bins

M.M. Devi, T. Thakore, S.K. Agarwalla, A. Dighe, arXiv:1406.3689 [hep-ph]

INO ICAL Mass Hierarchy Study



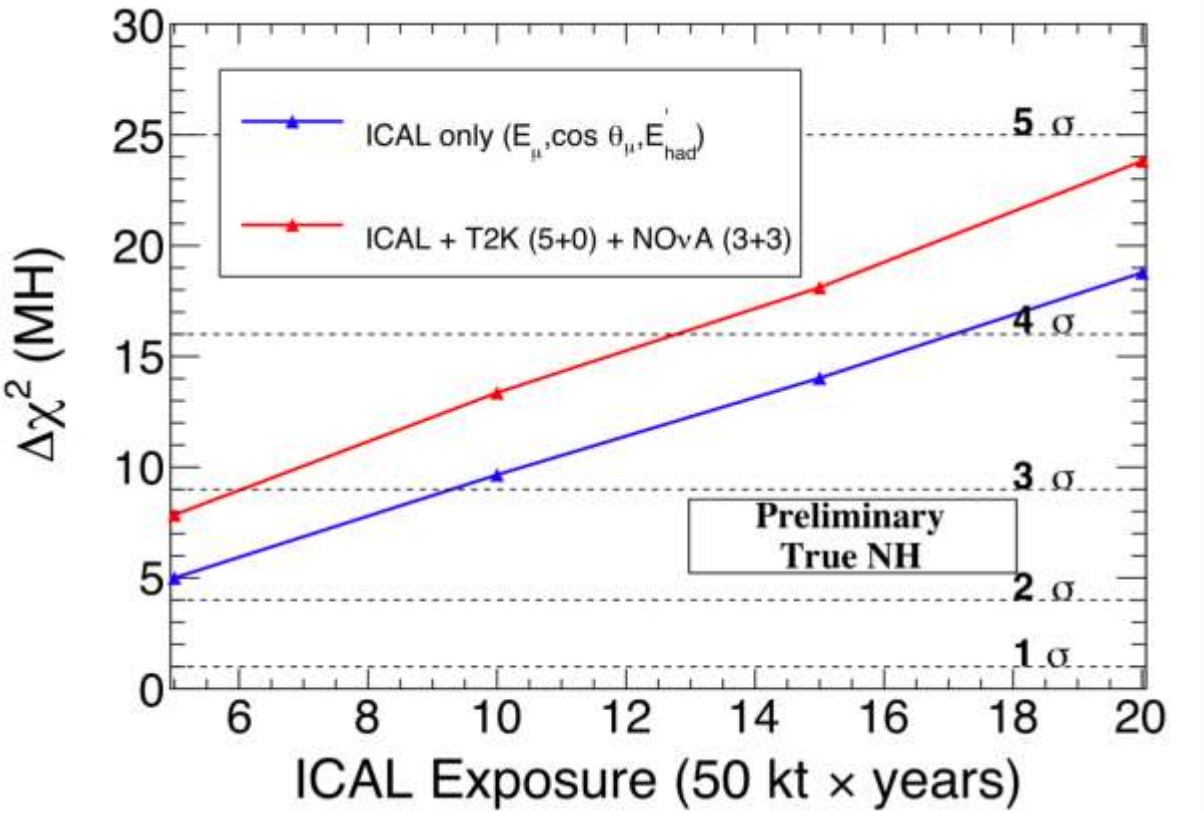


- 50 kt ICAL can rule out the wrong hierarchy with median $\Delta\chi^2 \approx 7$ to 12 depending on the true values of θ_{23} and θ_{13} in 10 years

M.M. Devi, T. Thakore, S.K. Agarwalla, A. Dighe, arXiv:1406.3689 [hep-ph]

INO ICAL Mass Hierarchy Study

ICAL+T2K+NOvA

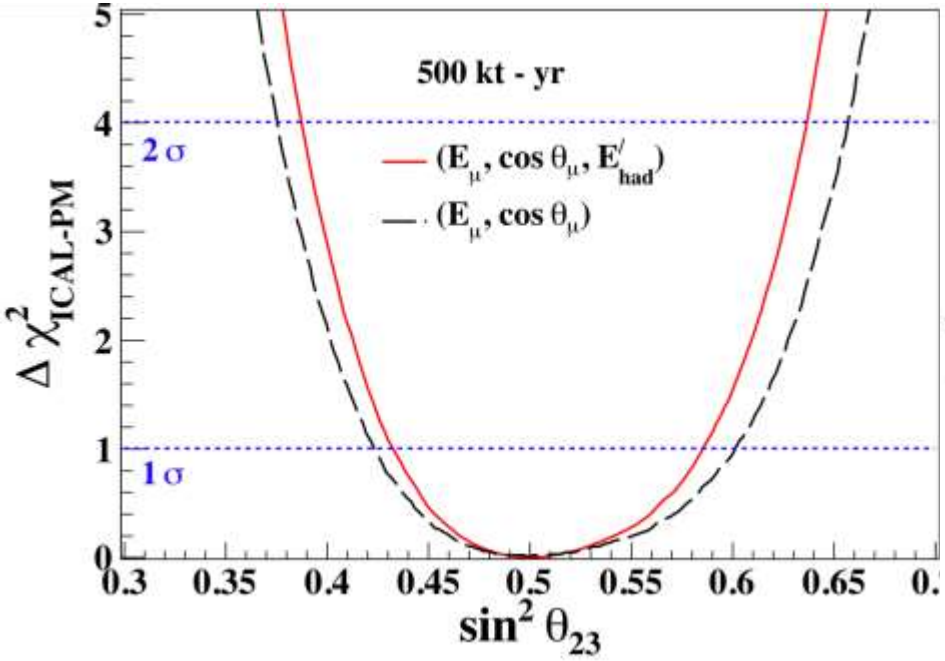


- 3σ median sensitivity can be achieved in 6 years

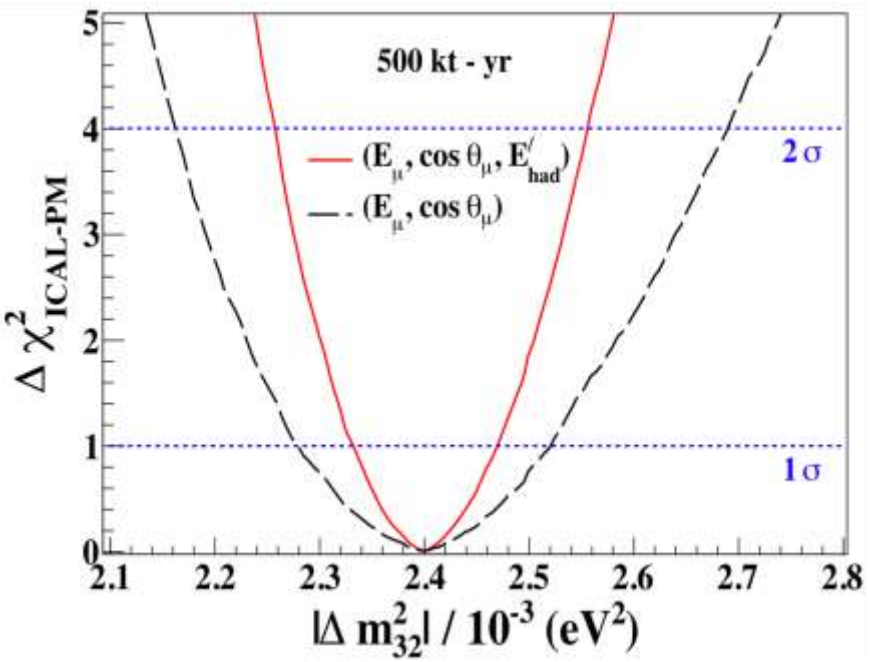
T. Thakore, S.K. Agarwalla, in preparation

INO ICAL

Precision of atmospheric parameters



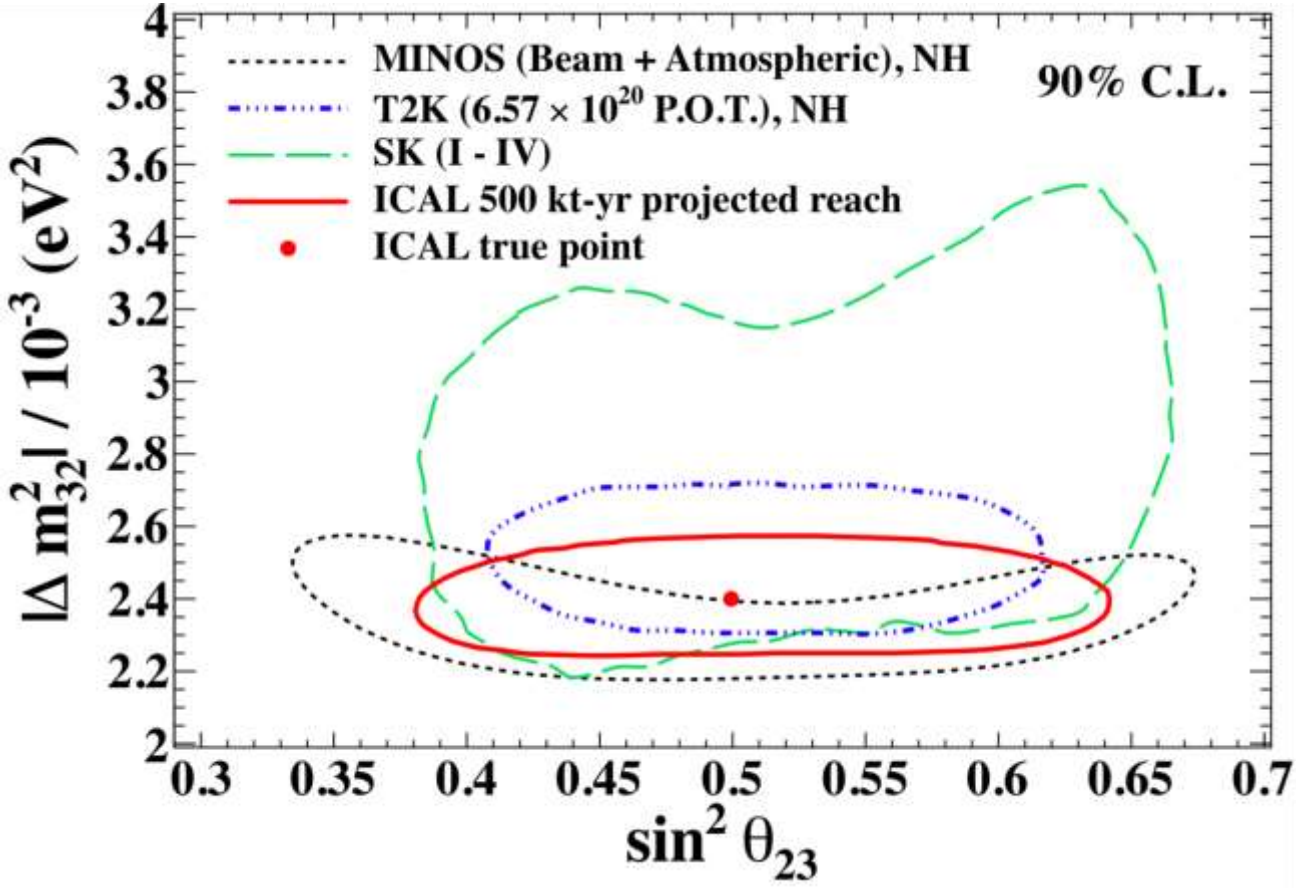
Relative 1σ precision: 12%



Relative 1σ precision: 2.9%

M.M. Devi, T. Thakore, S.K. Agarwalla, A. Dighe, arXiv:1406.3689 [hep-ph]

INO ICAL Precision of atmospheric parameters

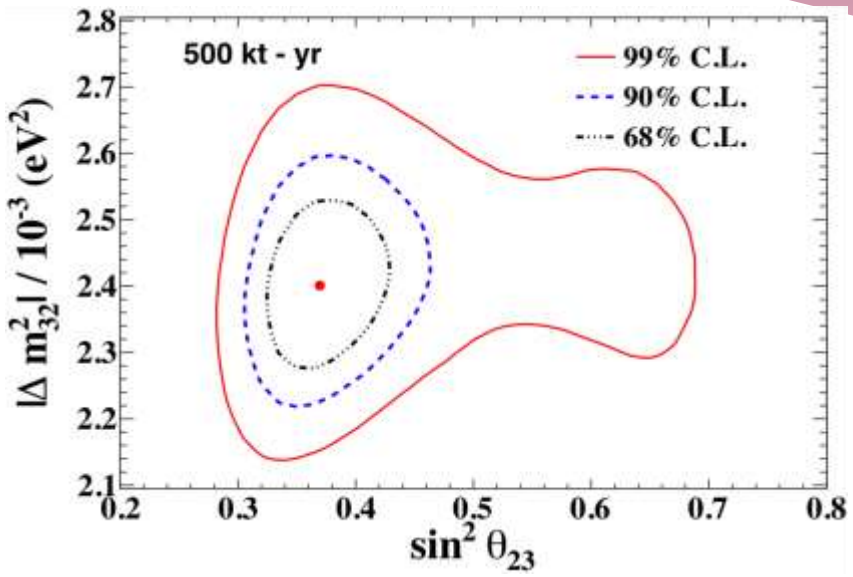


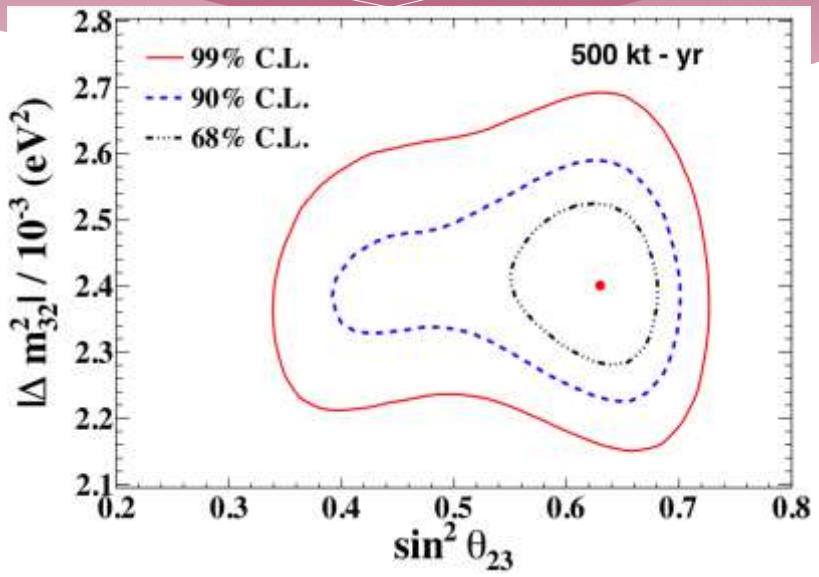
- ICAL 500 kt-yr projected reach is shown by the red Contour (90% C.L.)

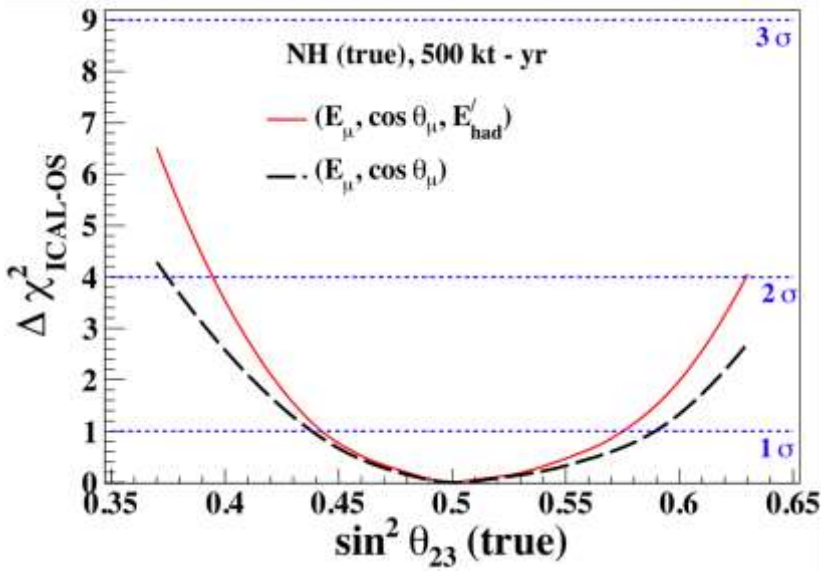
M.M. Devi, T. Thakore, S.K. Agarwalla, A. Dighe, arXiv:1406.3689 [hep-ph]

INO ICAL

Octant of θ_{23}



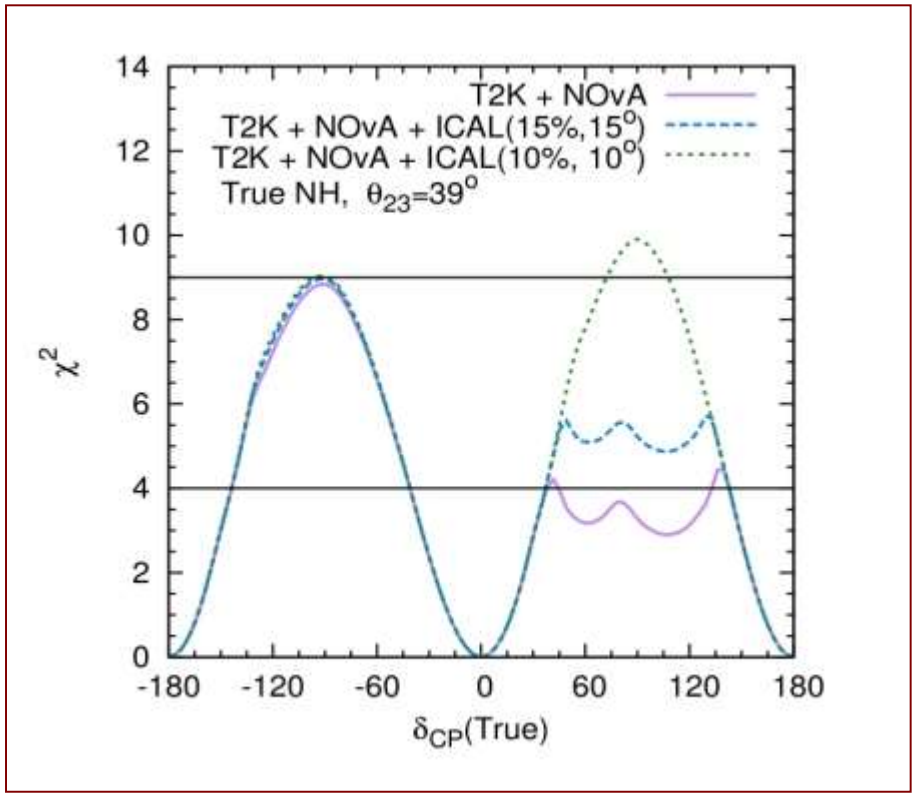




- Median 2σ discovery of $\boldsymbol{\theta_{23}}$ octant is possible if $\boldsymbol{\theta_{23}}$ is sufficiently away from maximal value

M.M. Devi, T. Thakore, S.K. Agarwalla, A. Dighe, arXiv:1406.3689 [hep-ph]

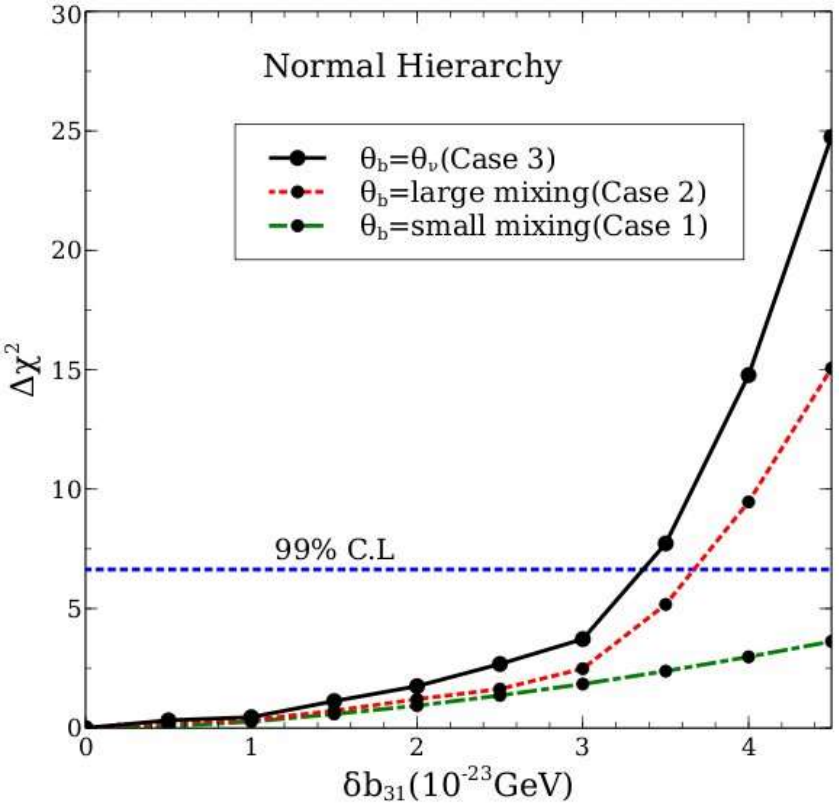
Synergy with T2K and NOvA



- Hierarchy information from ICAL-INO would contribute to the discovery of CP violation, though ICAL itself is not sensitive to CP violation

Monojit Ghosh, Pomita Ghoshal, Srubabati Goswami, Sushant Raut arXiv: 1306.2500 [hep-ph]

- LIV/CPTV is taken as a subleading term in the effective Hamiltonian
- Bounds on δb_{31} has been shown for 3 generic cases representing mixing in the CPT violating part in the Hamiltonian.
- ICAL should be sensitive to $\delta b_{31} \geq 4 \text{ X } 10^{23}$ GeV at 99% C.L. with 500kT-yr exposure, unless the mixing in the CPTV sector is small.



A. Chatterjee, R. Gandhi, J. Singh, arXiv:1402.6265

INO Current Status

- **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
- Industrial production of RPCs and associated front-end electronics to be started soon
- Full project approved by Indian Atomic Energy Commission. Waiting for approval from Prime Minister's cabinet committee

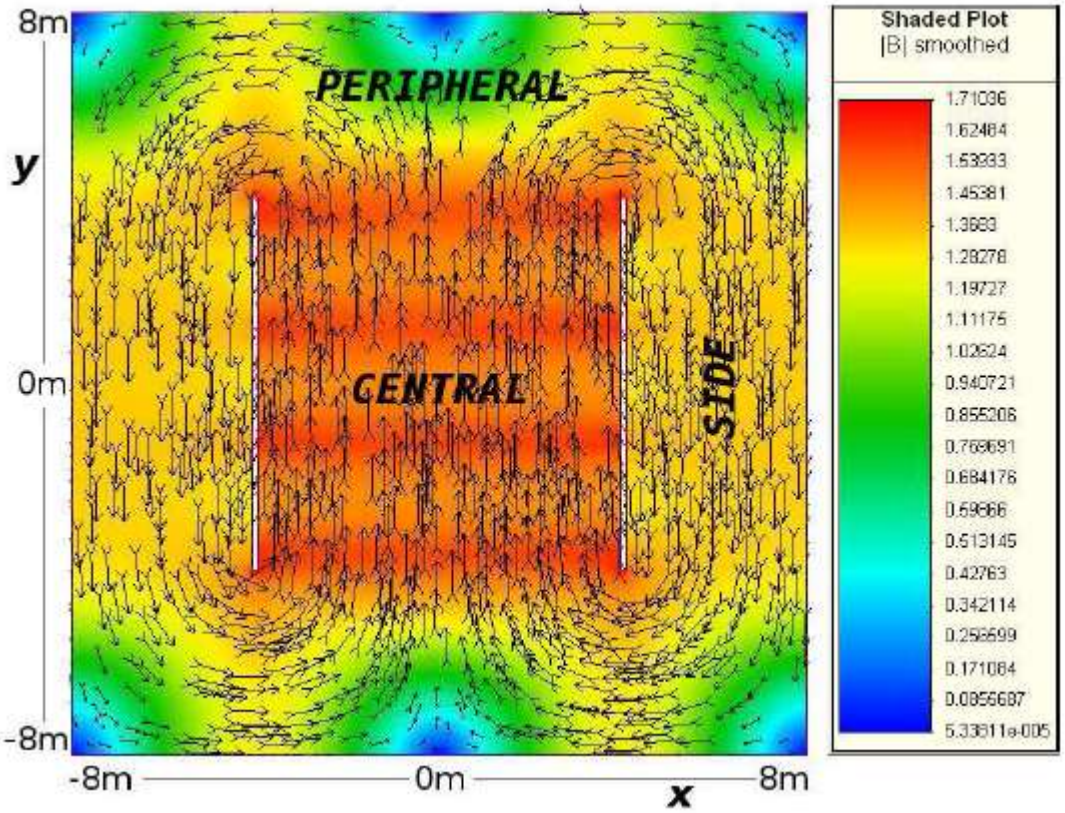
INO Concluding Remarks

- The ICAL detector at INO will study the oscillations in the atmospheric neutrinos in the multi GeV range through resonances in the earth's core. The R&D in all fronts are in progress.
- The capability of muon charge identification enables us to use matter effects in neutrinos and anti neutrinos separately to distinguish the mass hierarchy.
- The 50 kt ICAL, after 10 years of running, can discard the wrong hierarchy with median $\Delta\chi^2 \approx 9.6$. ICAL would contribute to the precision measurement of the atmospheric parameters. It would also be a test bed for NSI, CPT violation etc.

More updates on http://www.ino.tifr.res.in/ino
International collaboration most welcome!

Back-up slides

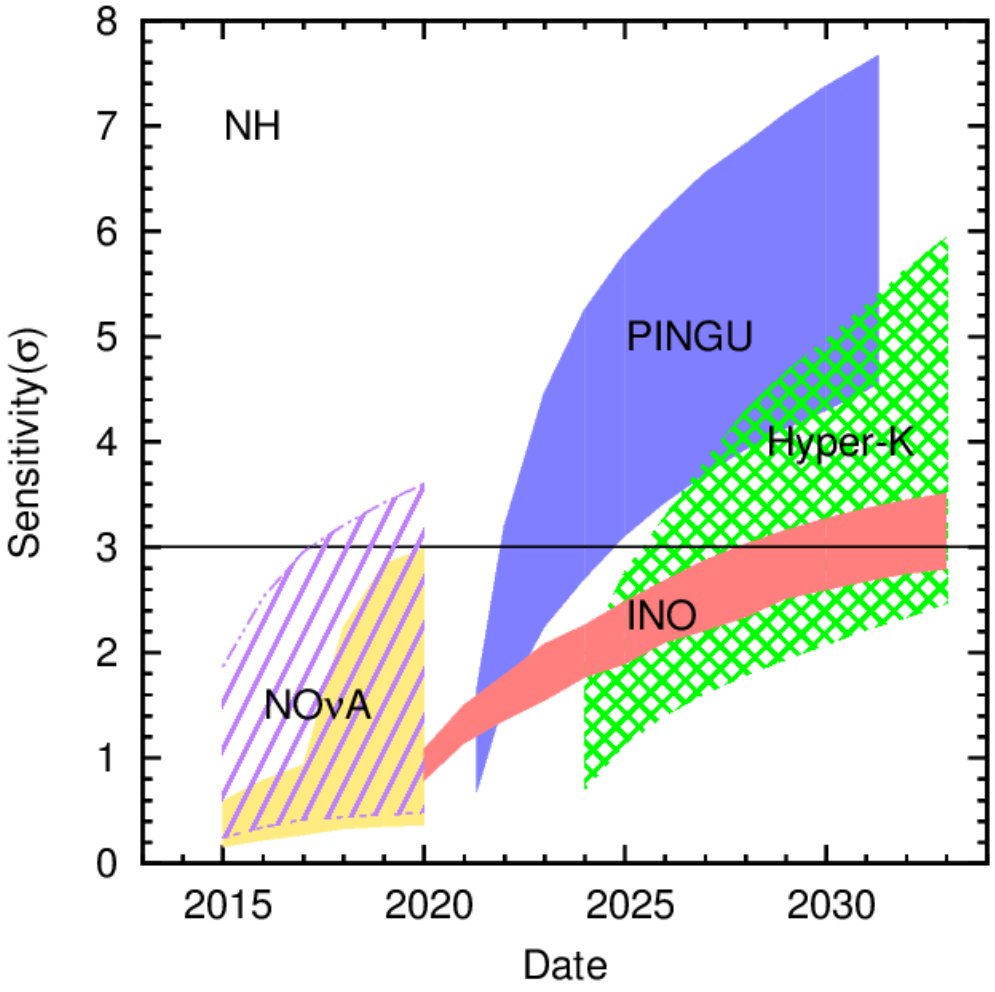
Magnetic Field Map



- The magnetic field map in the central plane of the central module, as generated by the MAGNET6 software

INO

MH Sensitivity



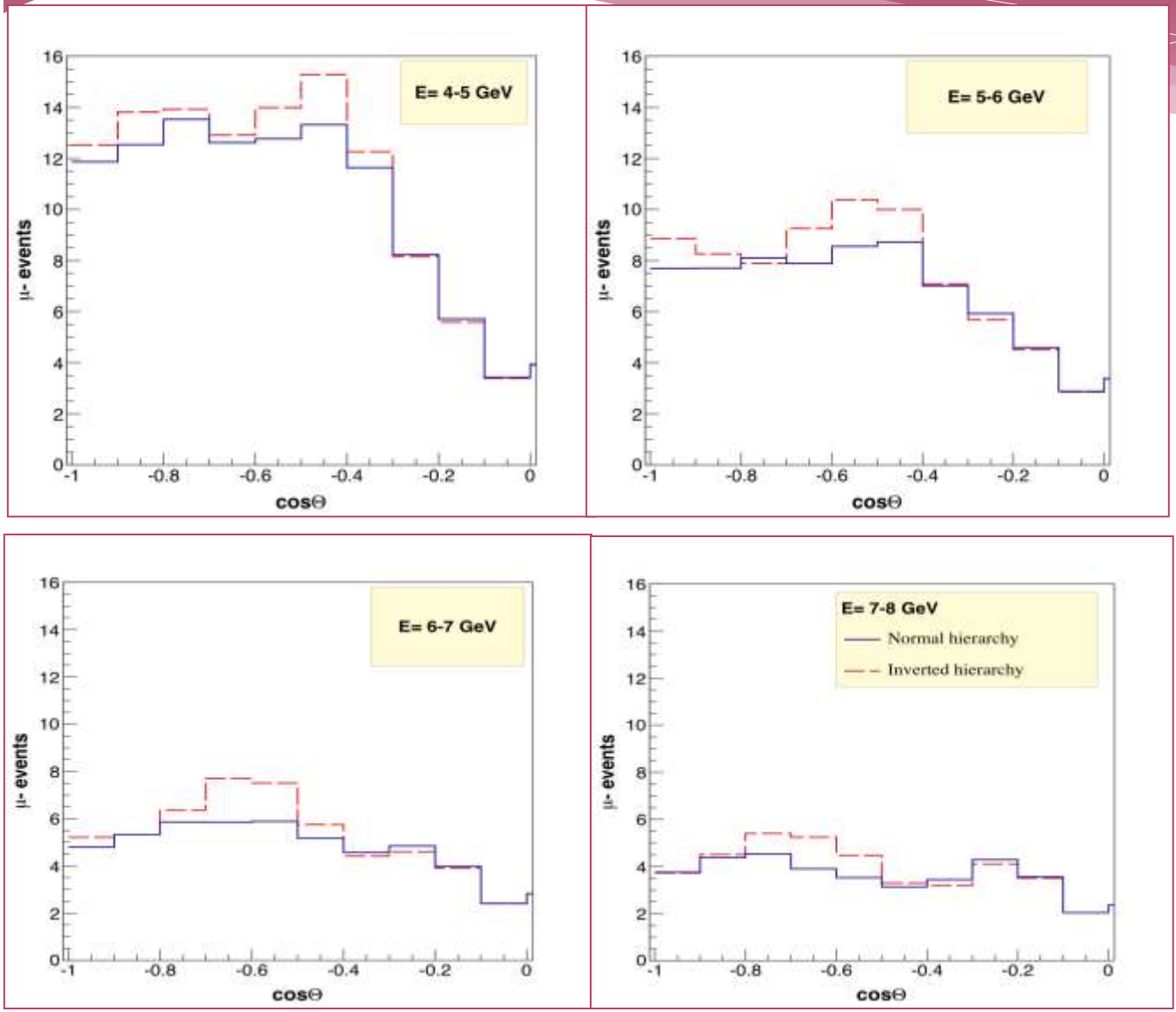
- Reaches of INO and PINGU are given by the collaborations during ICHEP2014

Re-designing Kalman Filter

- The Kalman filter used for the muon reconstruction was not optimized for larger θ. This has been fixed by implementing the 3rd order correction terms calculated using analytical track extrapolation formula. The issues like merging different track lengths were also fixed.
- Random covariance terms involving q/P were also calculated analytically.
- These corrections improved the accuracy and precision of muon reconstruction.

"*Error Propagation of the Track Model and Track Fitting Strategy for the Iron CALorimeter Detector in India-based Neutrino Observatory*" -- by Kolahal Bhattacharya et. al (submitted to Computer Physics Communications)

INO Event Spectrum in ICAL



- μ^- event spectrum for 10 years exposure

A. Ghosh, T. Thakore, S. Choubey, JHEP 1304 (2013) 009

INO Bakelite RPC R&D at VECC & SINP (Kolkata)

- *Bakelite RPCs being developed, operating in streamer mode, inner surface coated with PDMS (silicone) for smooth surface, efficiency plateau over 96% with reduced noise rate and long term stability*

- *ICAL@INO being modular in size, can use both glass as well as bakelite RPCs*

- ***13 layers of soft iron***

Each Iron Plate: 2.48m x 2.17m x 0.05m

- ***12 layers of 1m × 1m RPCs***

8 glass RPCs and 4 Bakelite RPCs

- ***Total of 4 coils, each having 5 turns***

perpendicular to the plane of the Fe (1.6 Tesla)

- ***512 channels of preamp for 8 glass RPCs***

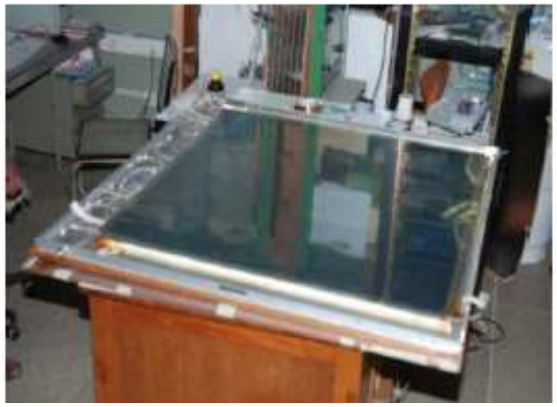
timing discriminators for avalanche RPCs

- ***Designed to study the behavior of RPCs***

together with the front end electronics in presence of magnetic field

ICAL@INO Prototype Detector
~ 50 tons, total Height 1.302 m

INO Glass RPC Fabrication






- *30 glass RPCs of 1m × 1m developed, tested for long in avalanche mode*
- *5 glass RPCs of 2m × 2m successfully assembled and tested*

INO GTP

- **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 at the final stage of writing their theses. A few of them have received good post-doctoral offers from various experiments**
- **7th batch of 6 students have started their course work in 2014**