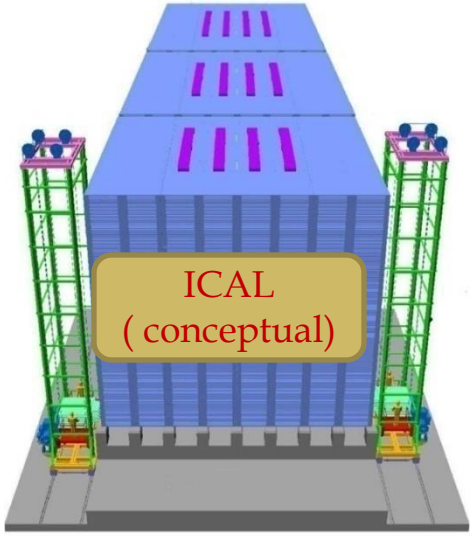
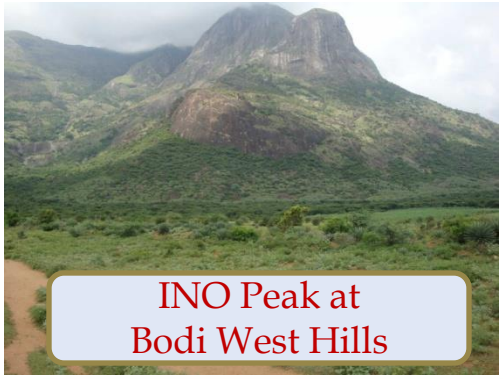
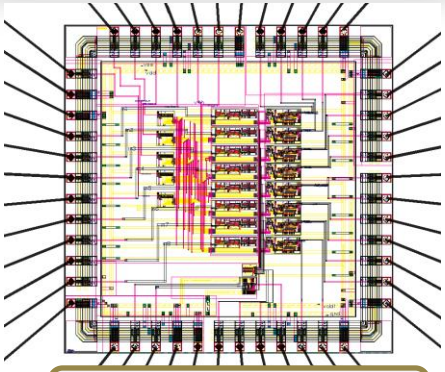


India-Based Neutrino Observatory (INO)

Naba K Mondal,
TIFR, Mumbai





INO-ICAL Collaboration

Ahmedabad: Physical Research Laboratory
Aligarh: Aligarh Muslim University
Allahabad: HRI
Bhubaneswar : IOP, Utkal University
Calicut : University of Calicut
Chandigarh: Panjab University
Chennai : IITM, IMSc
Delhi : Delhi University
Kolkata : SINP, CU, VECC
Lucknow : Lucknow University
Madurai : American College
Mumbai : BARC, IITB, TIFR
Mysore : University of Mysore
Srinagar : University of Kashmir
Varanasi : Banaras Hindu University

We are certainly looking forward to international participation

INO : Salient Features

- *Create an experimental facility to carry out front ranking experiments in the field of particle & astroparticle physics.*

- *Underground laboratory with ~1 km all-round rock cover accessed through a 1.9 km long tunnel. A large and several smaller caverns to facilitate many experimental programs.*

- *Frontline neutrino issues e.g., mass parameters and other properties, will be explored in a manner complementary to ongoing efforts worldwide.*

- *The ICAL detector, with its charge identification ability, will be able to address questions about the neutrino mixing parameter space – specially the issue of neutrino mass hierarchy.*

- *Will support several other experiments when operational. Neutrino-less Double Beta Decay and Dark Matter Search experiments foreseen in the immediate future.*

INO Project components

- *Construction of an underground laboratory and surface facilities near Pottipuram village in Theni district of Tamil Nadu.*
- *Construction of a 50 kton magnetised Iron calorimeter (ICAL) detector to study properties of neutrinos.*
- *Construction of the INO centre- The Inter-Institutional Centre for High Energy Physics (IICHEP) at Madurai.*
- *Human Resource Development (INO Graduate Training Program)*
- *Detector & Instrumentation R & D for future projects.*

Inter-Institutional Centre for High Energy Physics (IICHEP)

Status of IICHEP site related activities

ICAL@INO: the physics

ICAL: The physics goals

- *Accurate determination of the atmospheric parameters (θ_{23} octant, deviation of θ_{23} from maximality)*
- *Determination of neutrino mass hierarchy (large θ_{13} is good news !)*
- *Nonstandard interactions, CPT violation, long range forces, ultrahigh energy muon fluxes, ...*

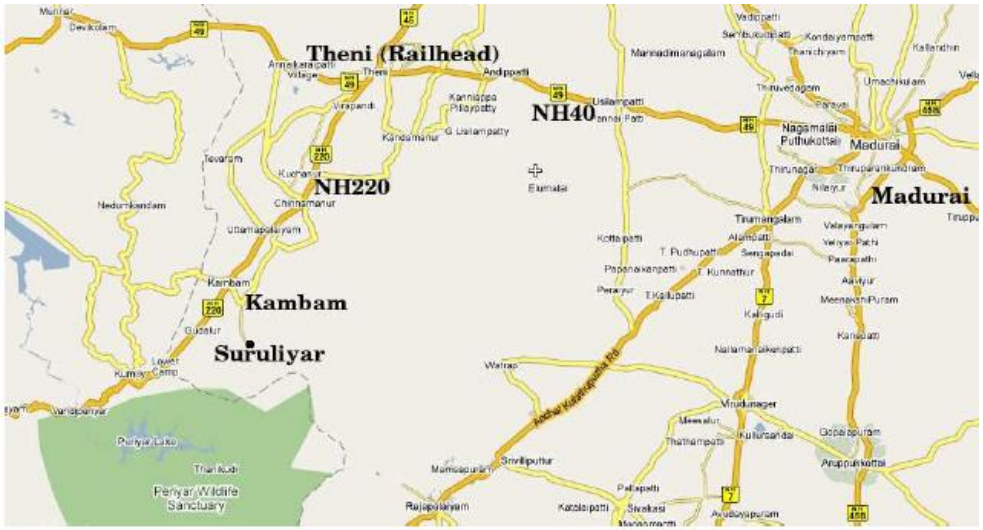
INO: the location

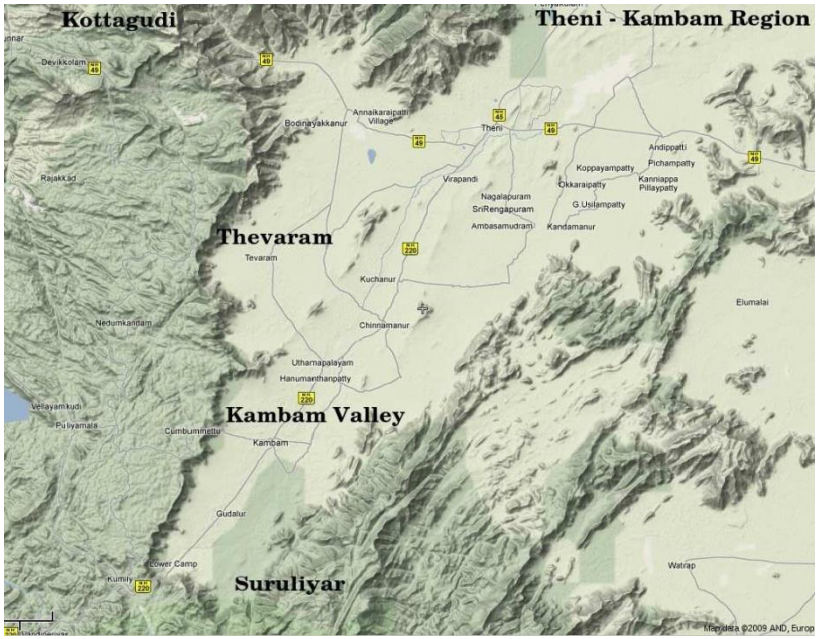
Madurai –the nearest major city

- ***INO site is located 115 km west of the temple city Madurai in the Theni district of Tamil Nadu.***

- ***Madurai has an international airport.***

INO site : Bodi West Hills

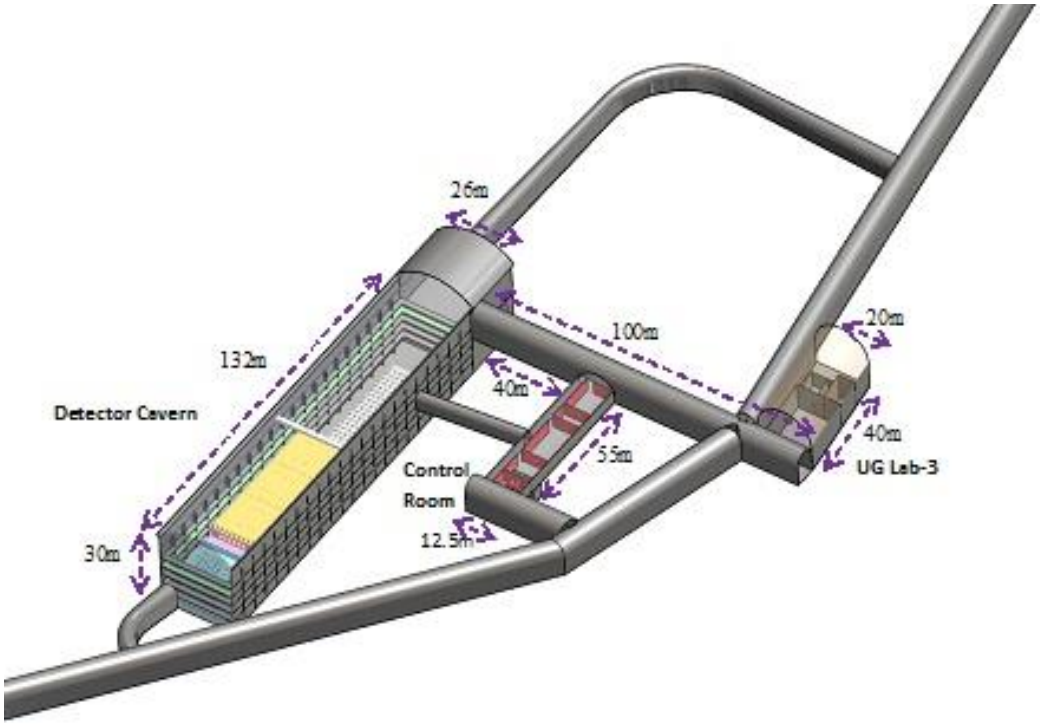




Contact us:

- ***9^0 58' N, 77^0 16' E***
- ***Pottipuram Village***
- ***Theni District***
- ***Tamil Nadu State***

Underground Laboratory Layout

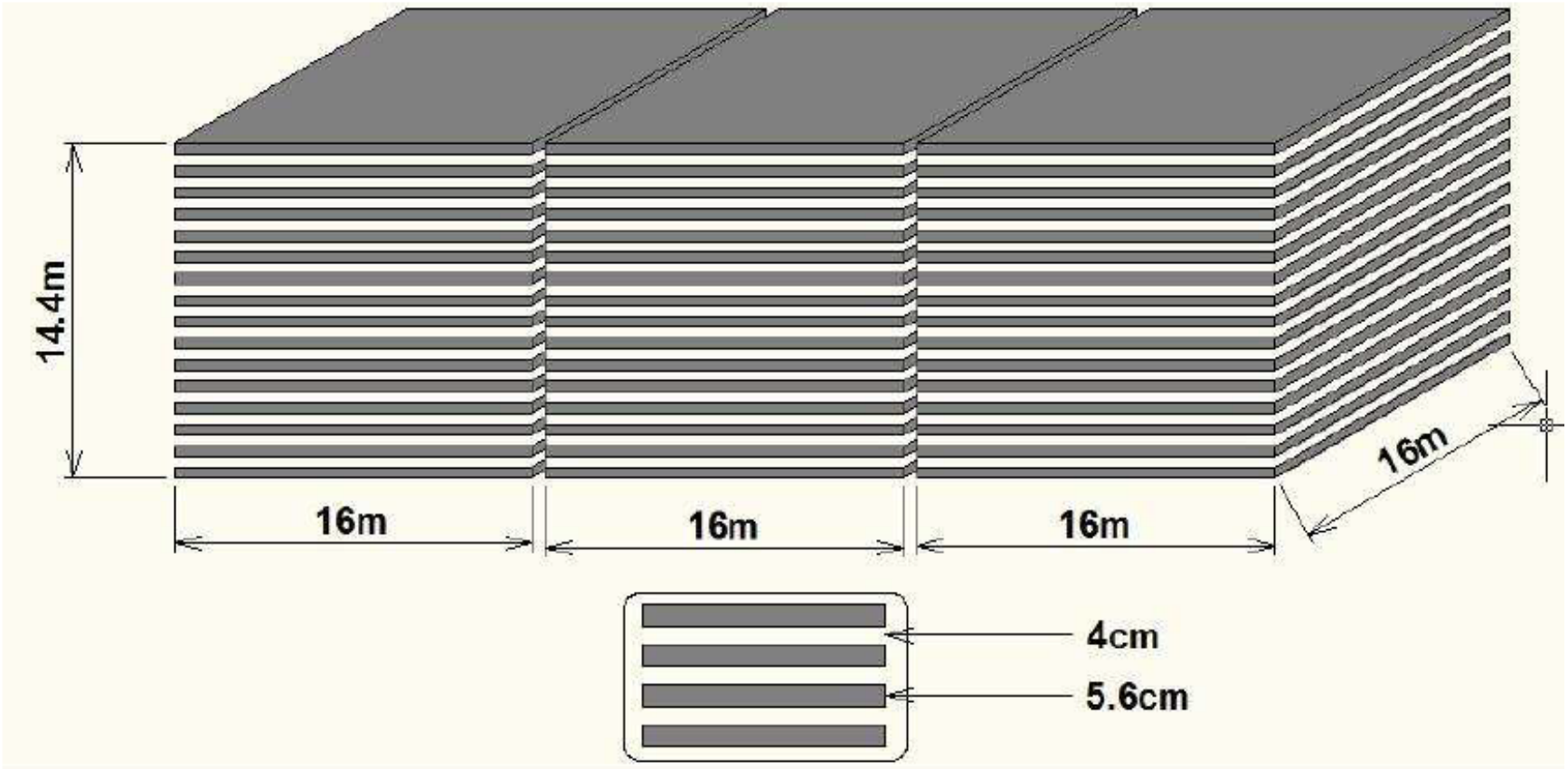


- *The cavern-I is set under 1589 m peak with vertical rock cover of 1289 m.*
- *Accessible through a 1.9 km long tunnel*
- *Cavern -1 will host 50 kt ICAL detector. Space available for additional 50 kt.*
- *Cavern-2 & 3 available for other experiments (NDBD, Dark Matter ….).*

Construction work at INO site at Pottipuram

ICAL@INO : The detector

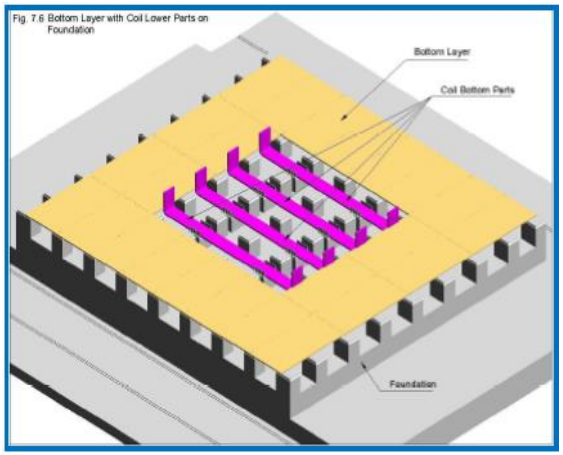
INO-ICAL Detector

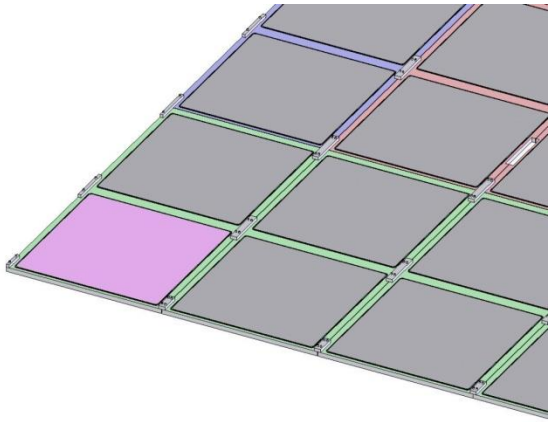


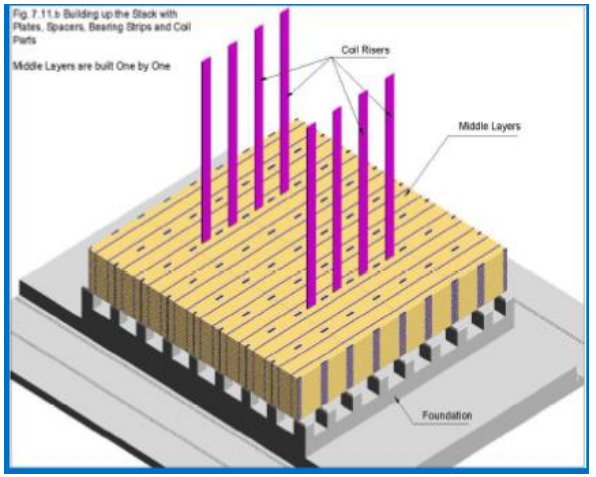
ICAL factsheet

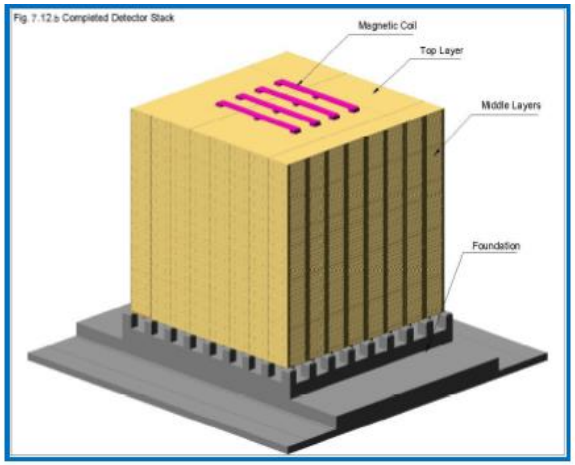
No of modules	*3*
Module dimension	*16 m X 16 m X 14.4m*
Detector dimension	*48.4 m X 16 m X 14.4m*
No of layers	*150*
Iron plate thickness	*5.6cm*
Gap for RPC trays	*4 cm*
Magnetic field	*1.4 Tesla*
RPC unit dimension	*195 cm x 184 cm x 2.4 cm*
Readout strip width	*3 cm*
No. of RPCs/Road/Layer	*8*
No.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

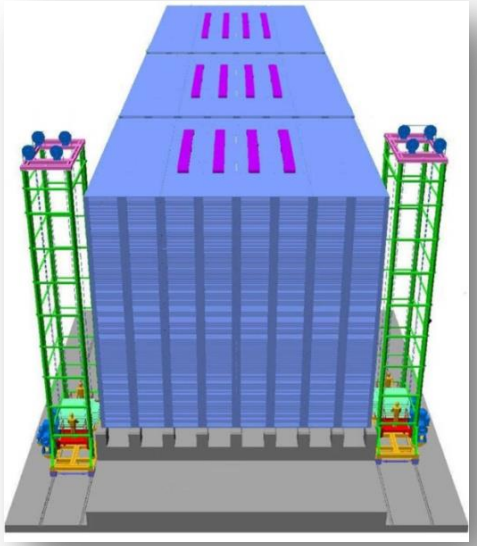
Construction of the ICAL detector

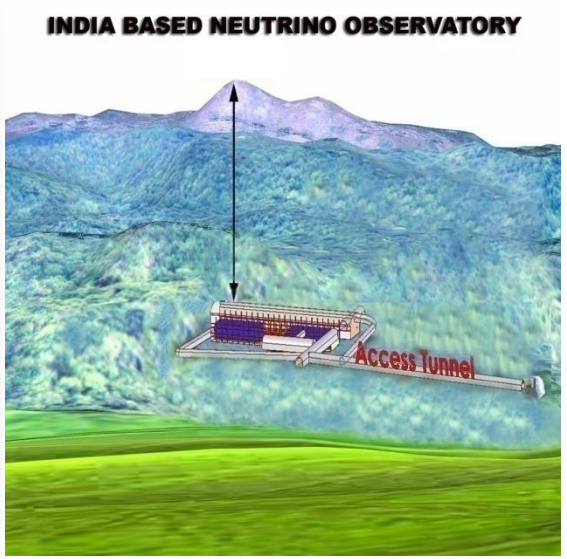


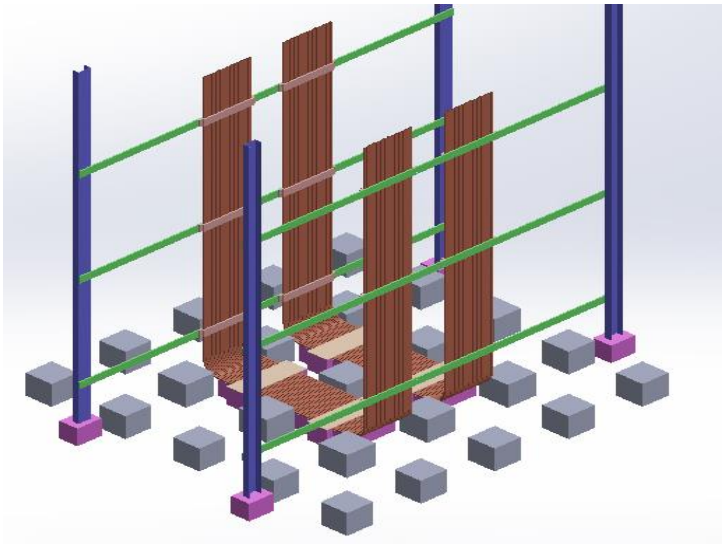


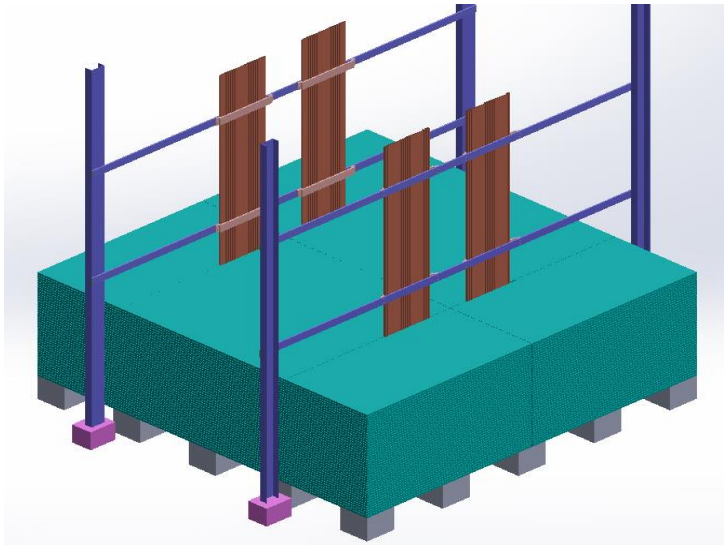


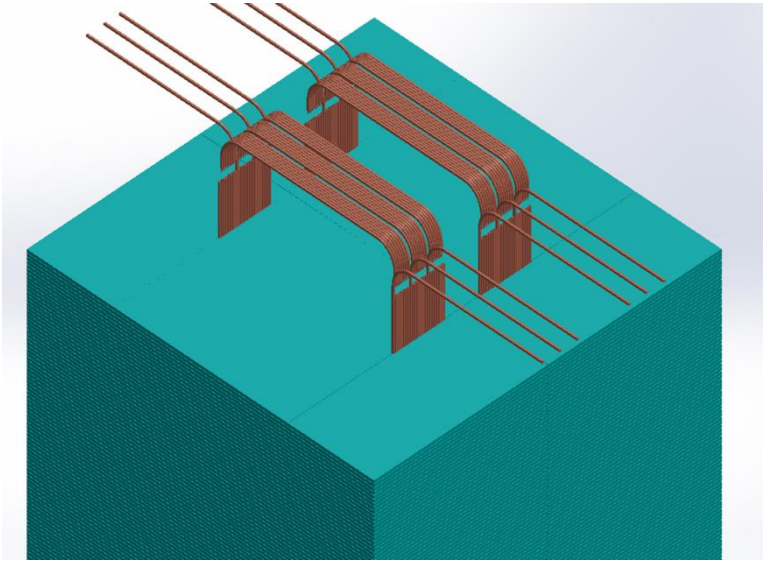


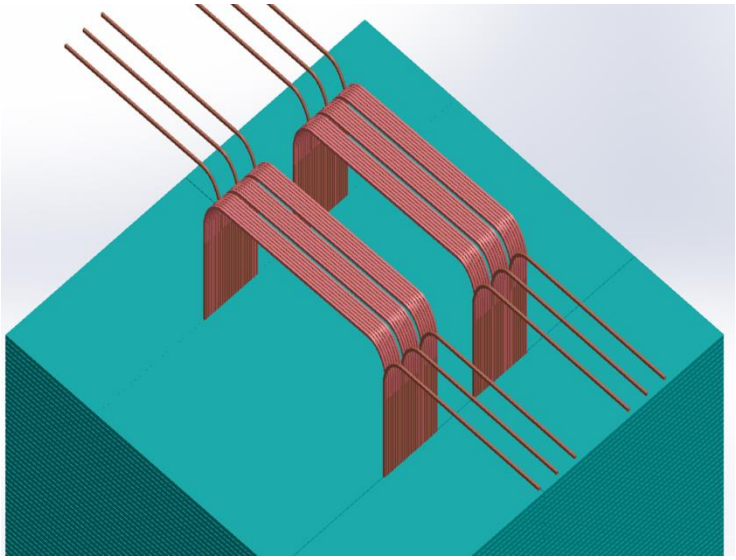




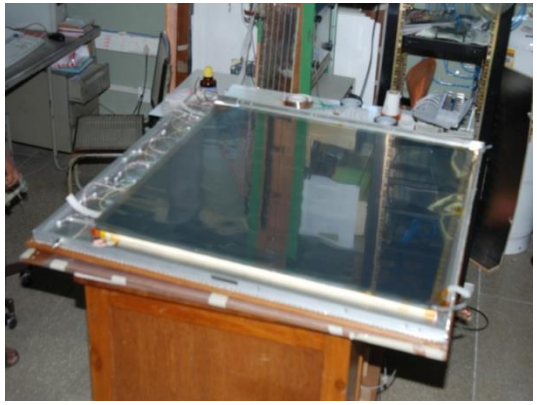


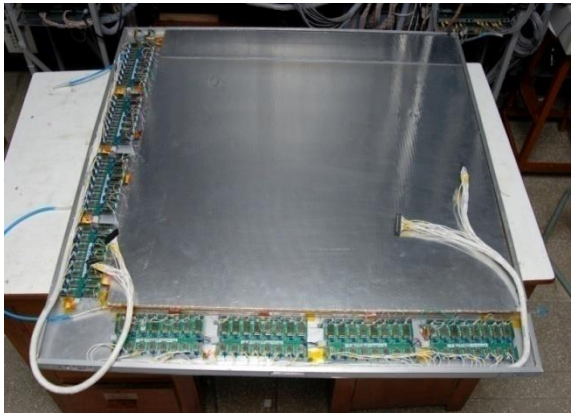




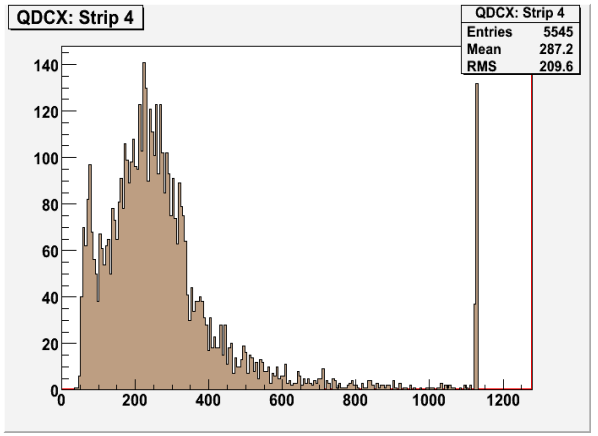


Fabrication of 1m x 1m RPCs

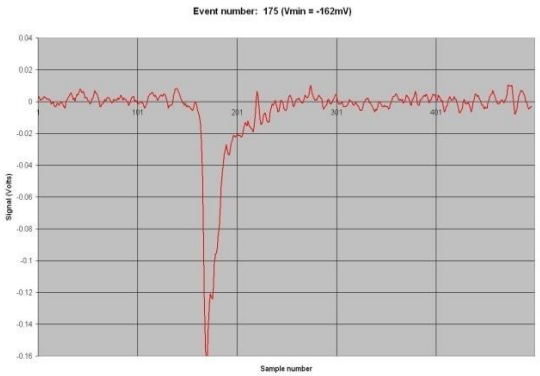




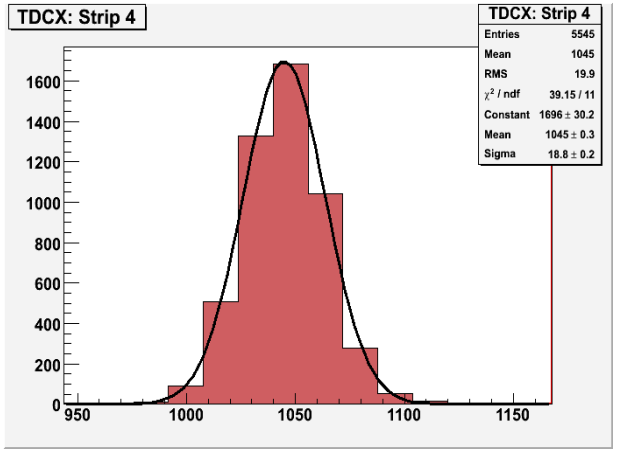
Prototype RPC Stack at TIFR tracking Muons



Charge spectrum

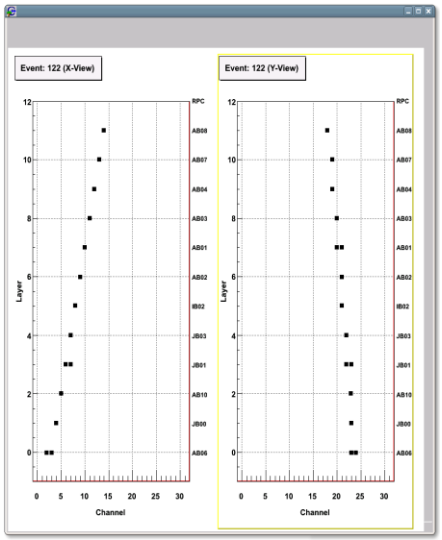


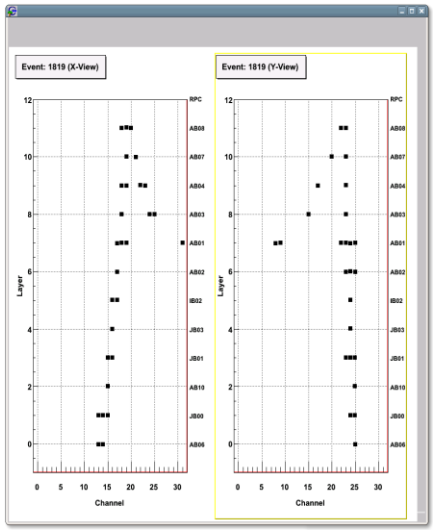
Analog signal due to muon

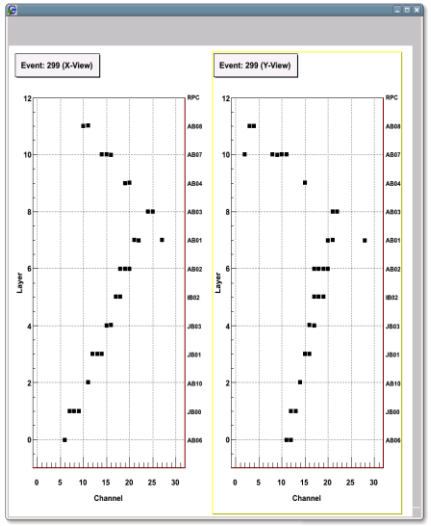


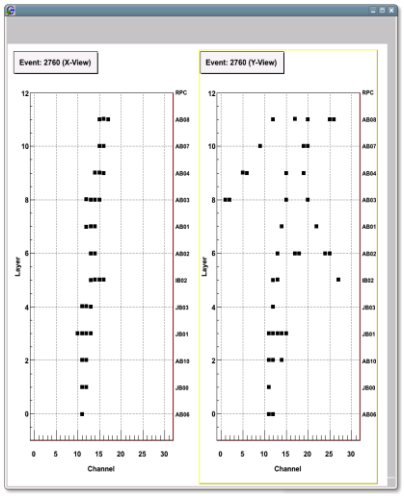
Time resolution

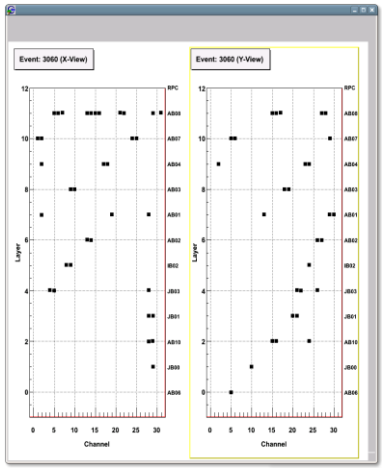
cosmic ray tracks in the RPC stand





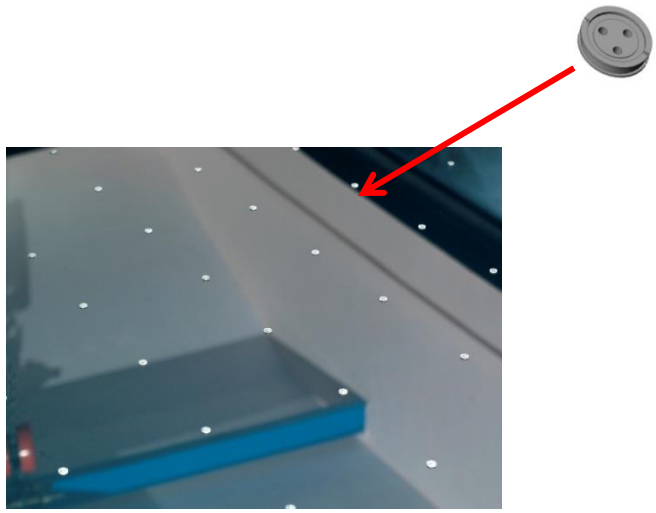


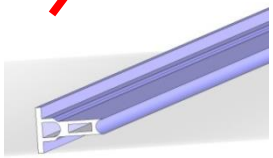




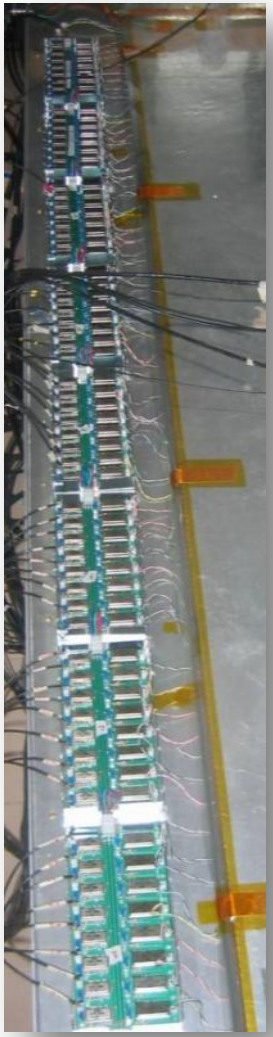
Demonstrate the Tracking Capability of the RPC system

Making of 2m x 2m RPCs



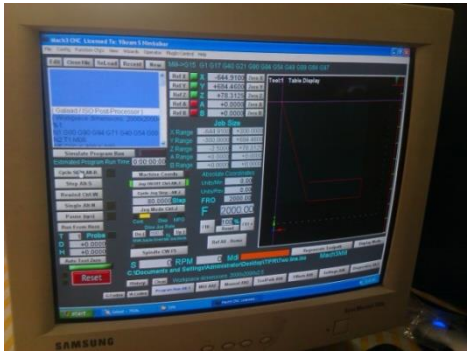


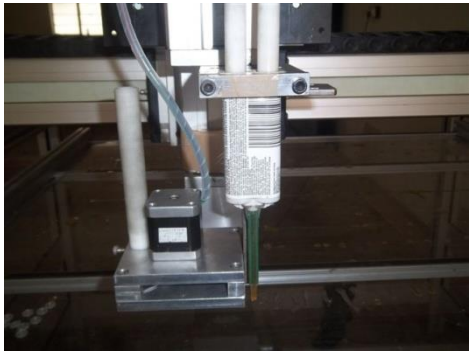
2m x 2m glass RPC test stand



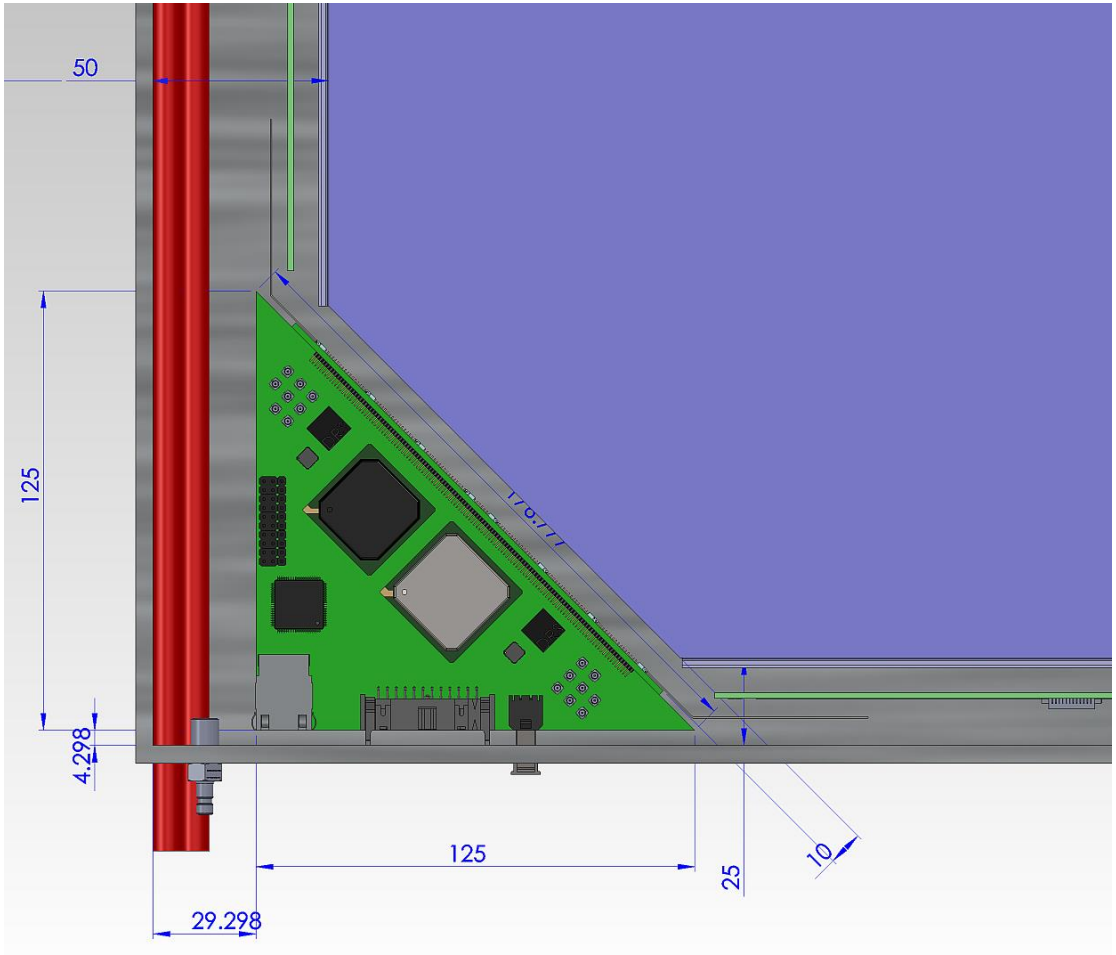
Painting/curing of glass plates

Automatic RPC gap making

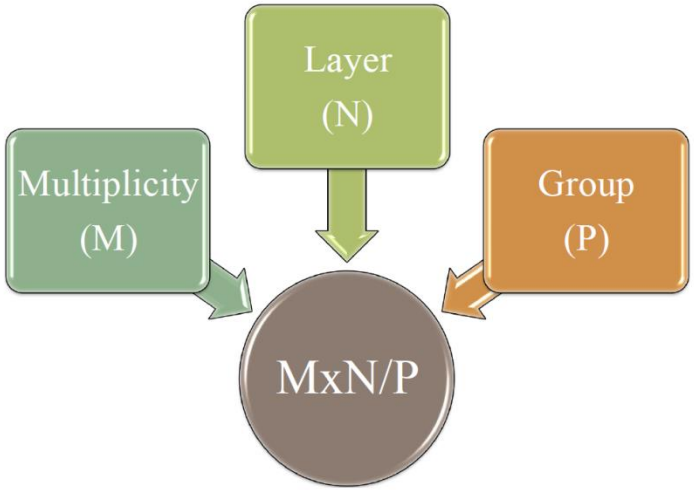


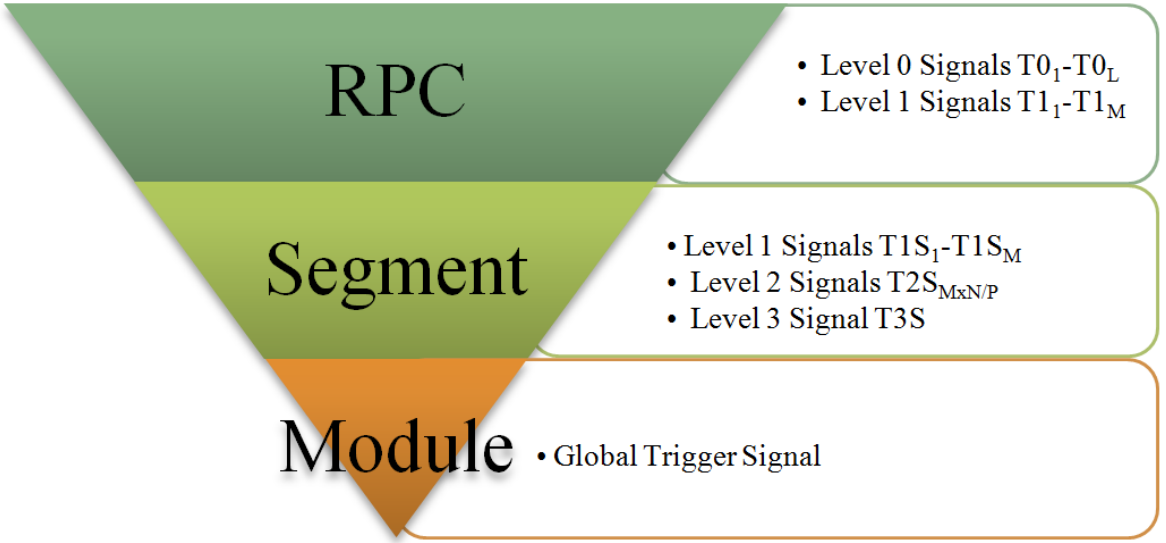


RPC-DAQ in the RPC

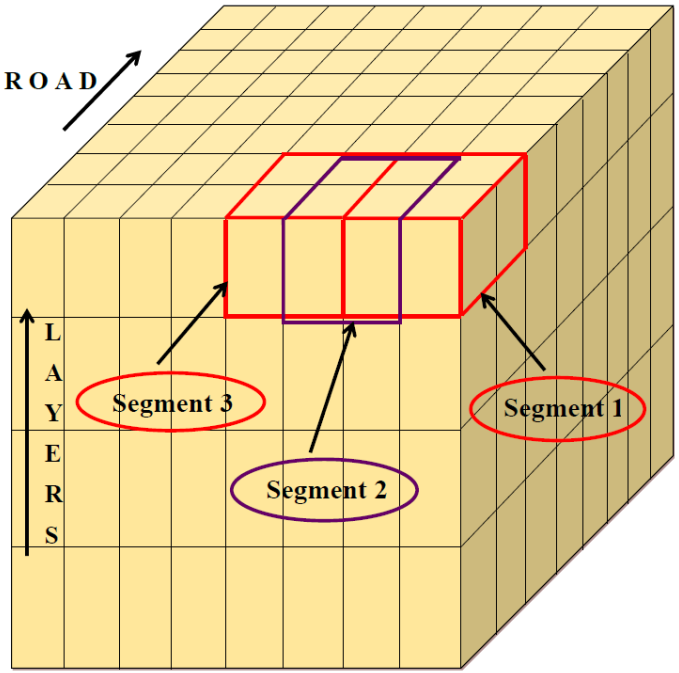


ICAL Trigger Scheme





- ***Trigger criteria based on event topology alone.***
- ***Distributed and hierarchical architecture.***
- ***Detector module segmented to generate local trigger.***
- ***Combination of local triggers produces global trigger.***
- ***Global trigger latches event data.***



Sudeshna Dasgupta et al, NIM, 678, 105 (2012) & NIM, 694, 126 (2012)

ICAL@INO: Simulations

Simulation Framework

NUANCE

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 4

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)

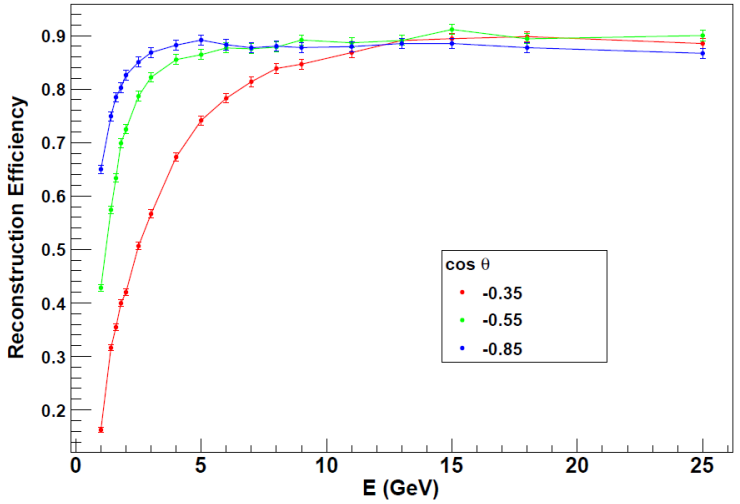
Event Reconstruction

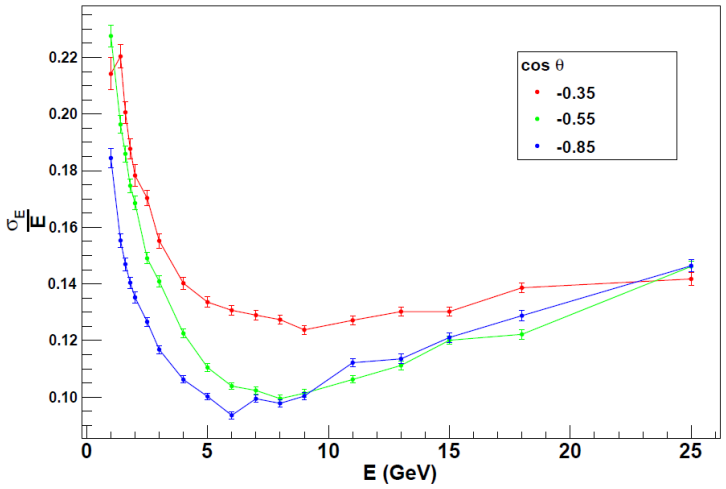
(E,p) of v + X = (E,p) of A + B + ...

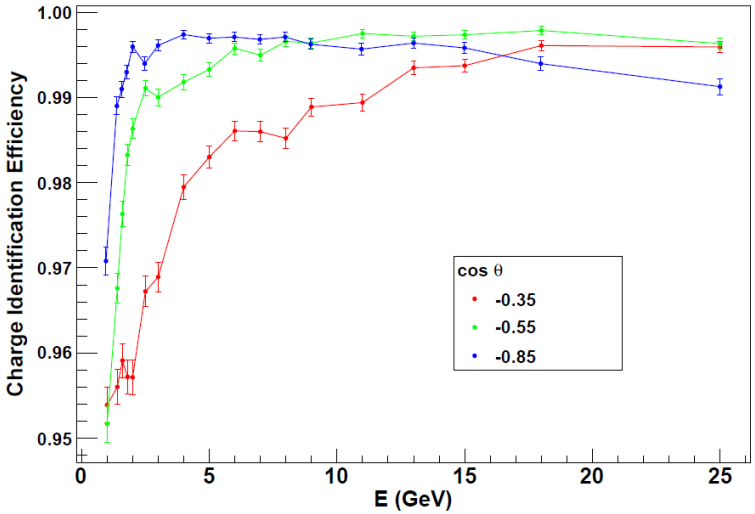
Fit the tracks of A + B + ... to get their energy and momentum.

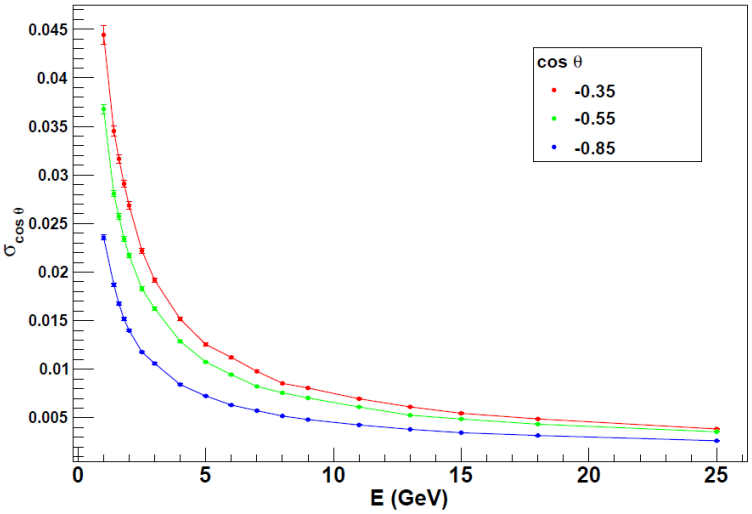
Output:
i) Energy & Momentum of the initial neutrino

Detector Performances: Muons







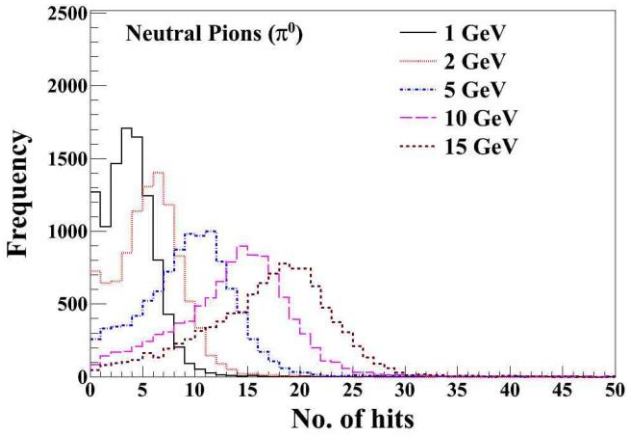


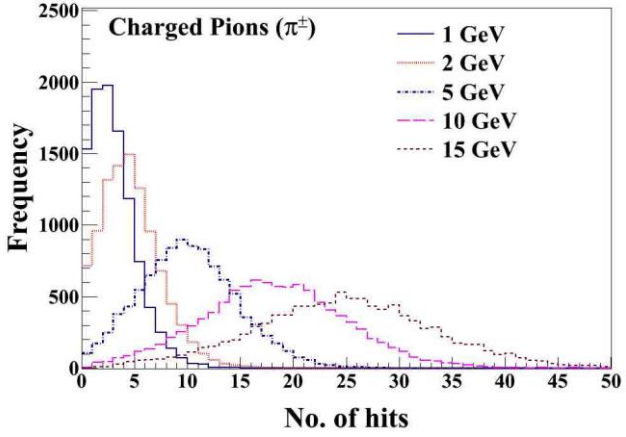
Reconstruction & Charge efficiencies

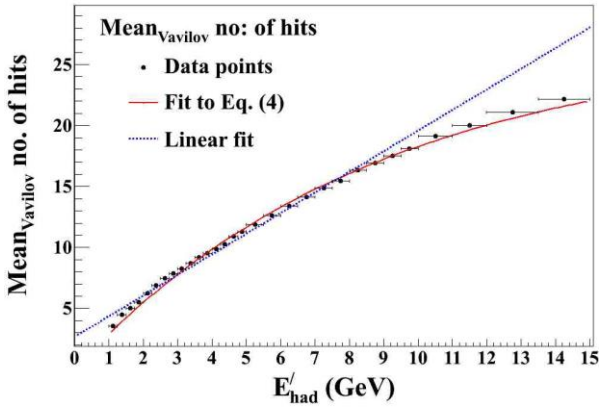
Energy & angular resolutions

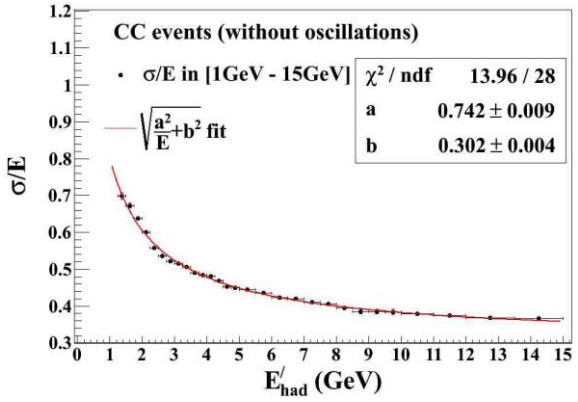
Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore et al, accepted for publication in JINST

Detector performances- hadrons









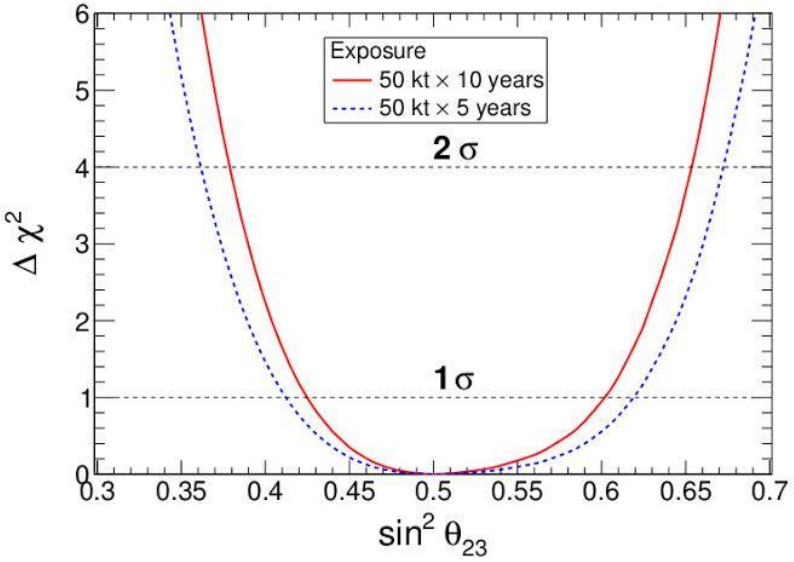
Moon Moon Devi, Anushree Ghosh, Daljeet Kaur, Lakshmi Mohan et al, JINST 2013

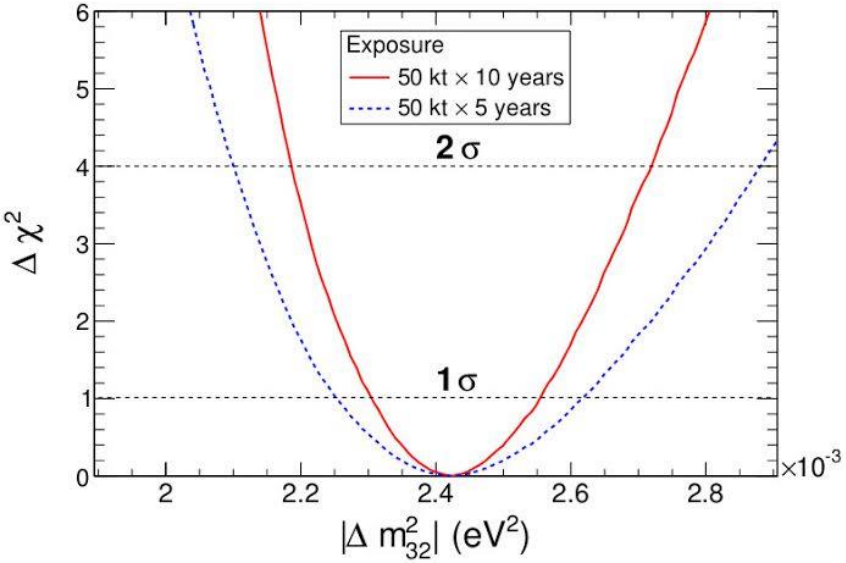
Calibration against $E'_{had} \equiv E_\nu - E_\mu$

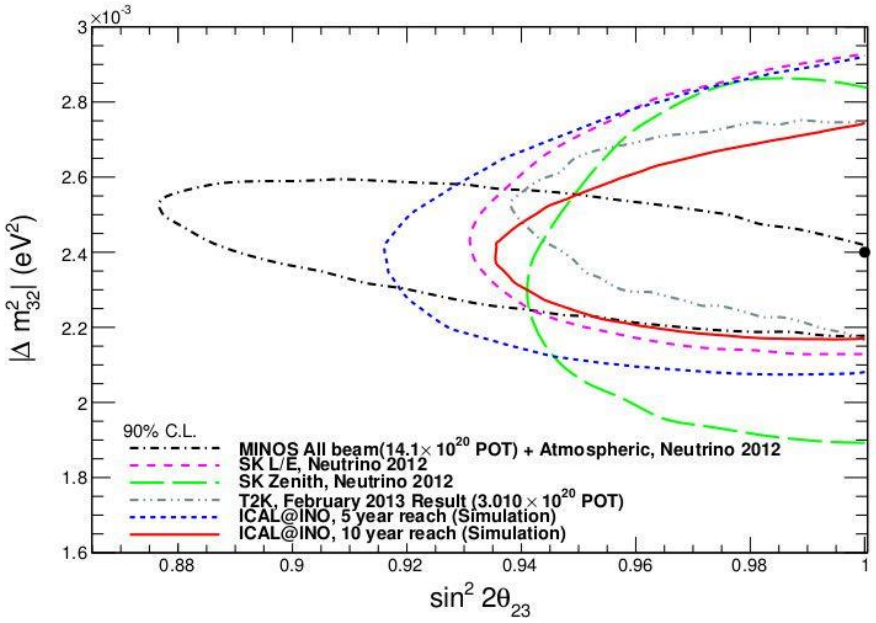
Vavilov distribution found to give a give good fit to the hit distribution

Hadron Energy resolution : $\frac{\sigma}{E} \approx \sqrt{\frac{(0.75)^2}{E} + (0.3)^2}$ ***85% at 1 Gev***

Atmospheric Parameters with INO ICAL (Muon only)



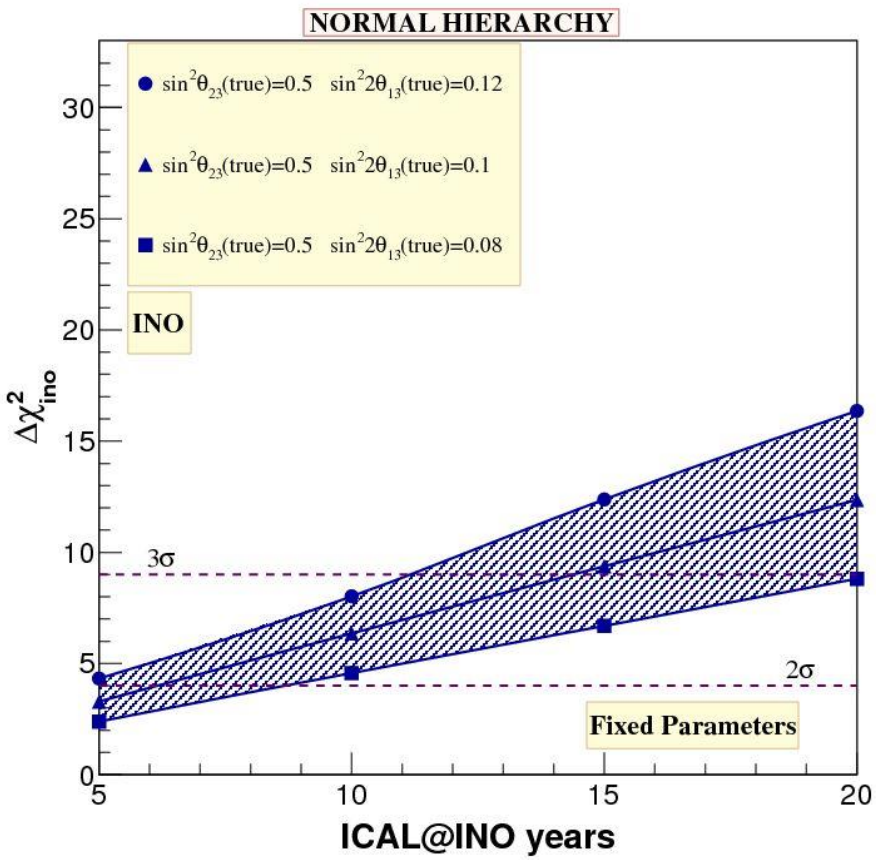


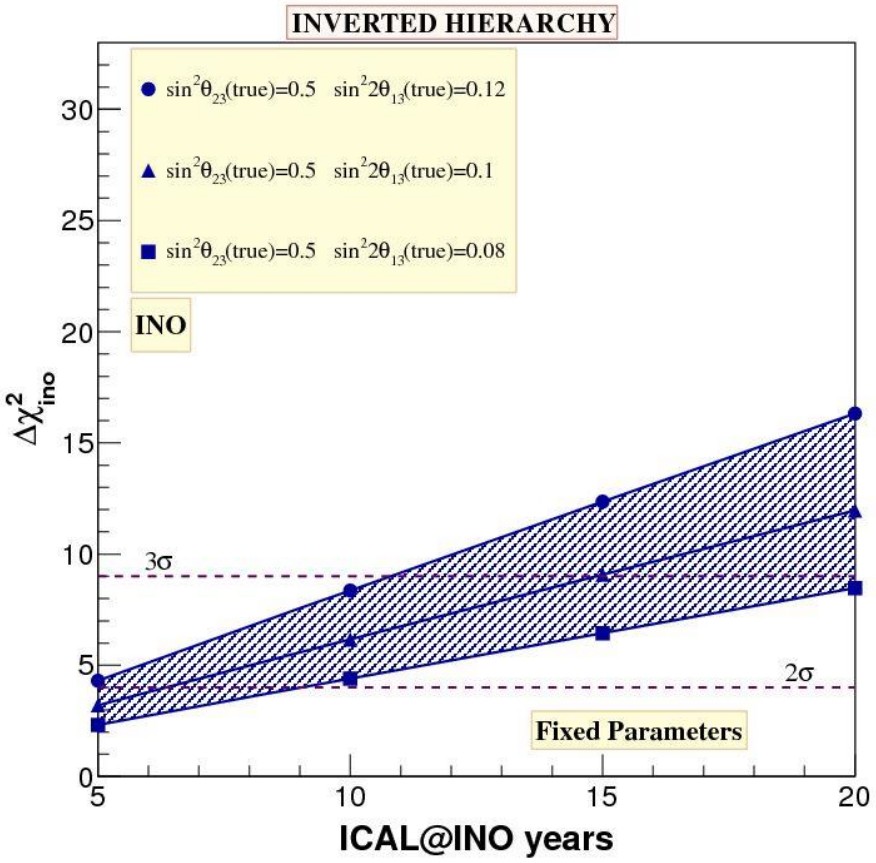


Sensitivity compared to SK
With a similar exposure

Tarak Thakore, Anushree Ghosh, et al, JHEP 1305 (2013) 058

Mass hierarchy with muon information only

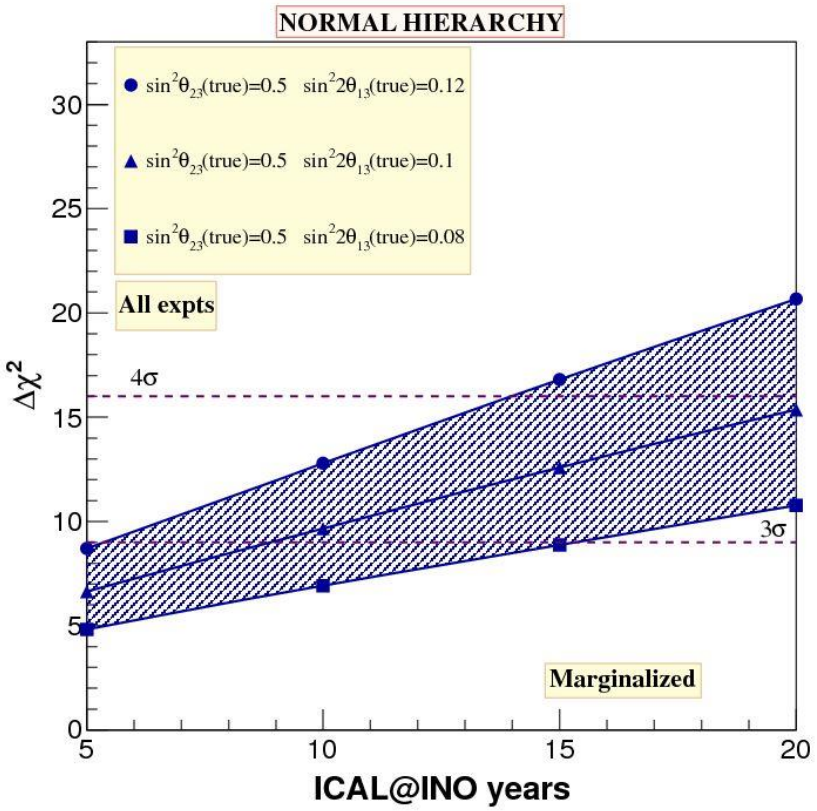


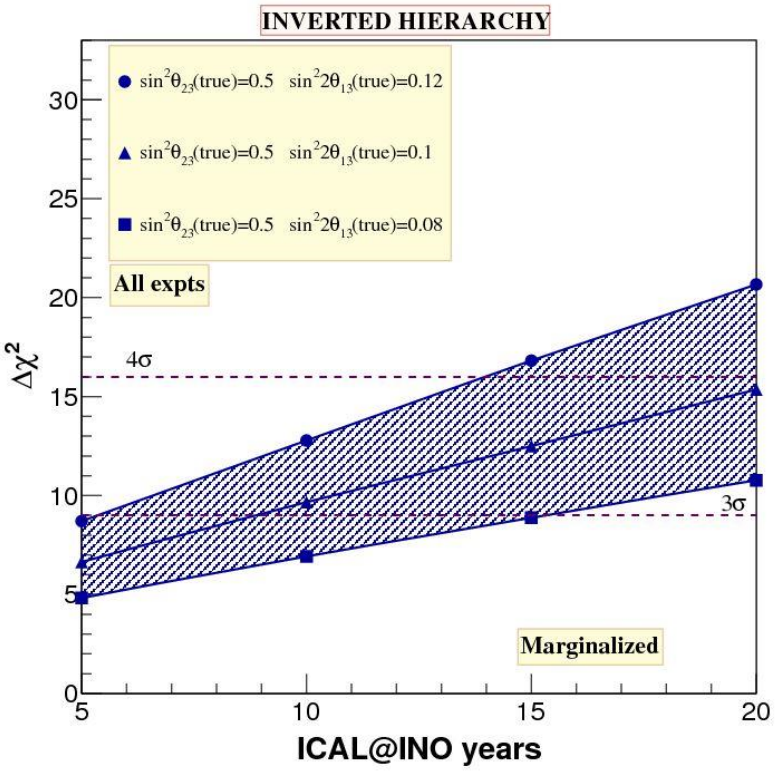


Mass hierarchy sensitivity with INO-ICAL data only using fixed Parameters - Sin² $2\theta_{13} = 0.12, 0.1, 0.08$ and $\sin^2\theta_{23} = 0.5$.

Anushree Ghosh, Tarak Thakore et. al. INO collaboration, JHEP, April 2013, 2013:9

Mass hierarchy with INO-ICAL combined with accelerator & reactor experiments

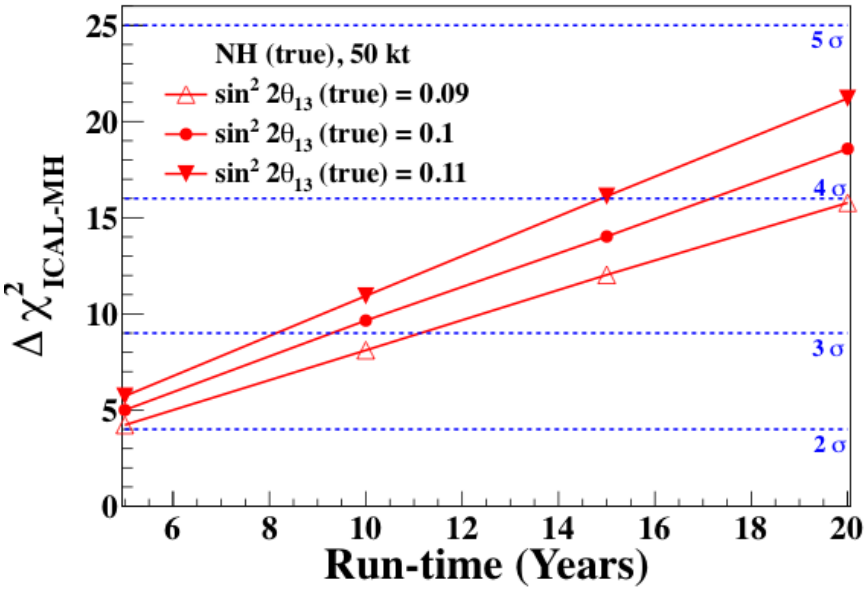


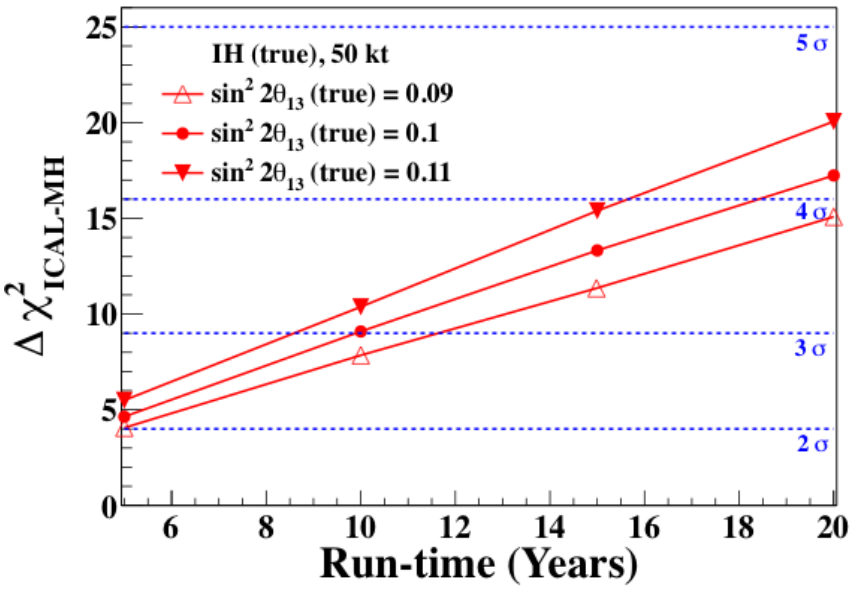


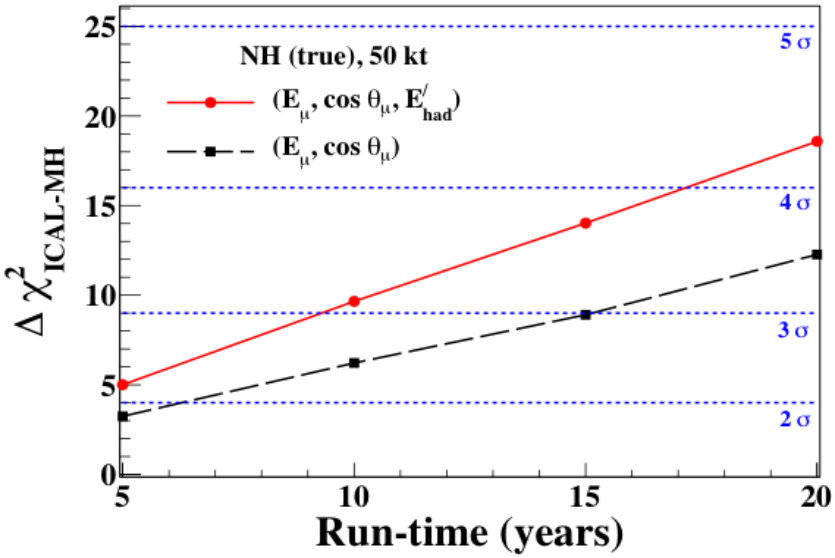
A combined analysis of all experiments including ICAL@INO as well NOvA, T2K, Double Chooz, RENO and Daya Bay experiments

Anushree Ghosh, Tarak Thakore et. al. INO collaboration, JHEP, April 2013, 2013:9

Mass hierarchy including hadron information



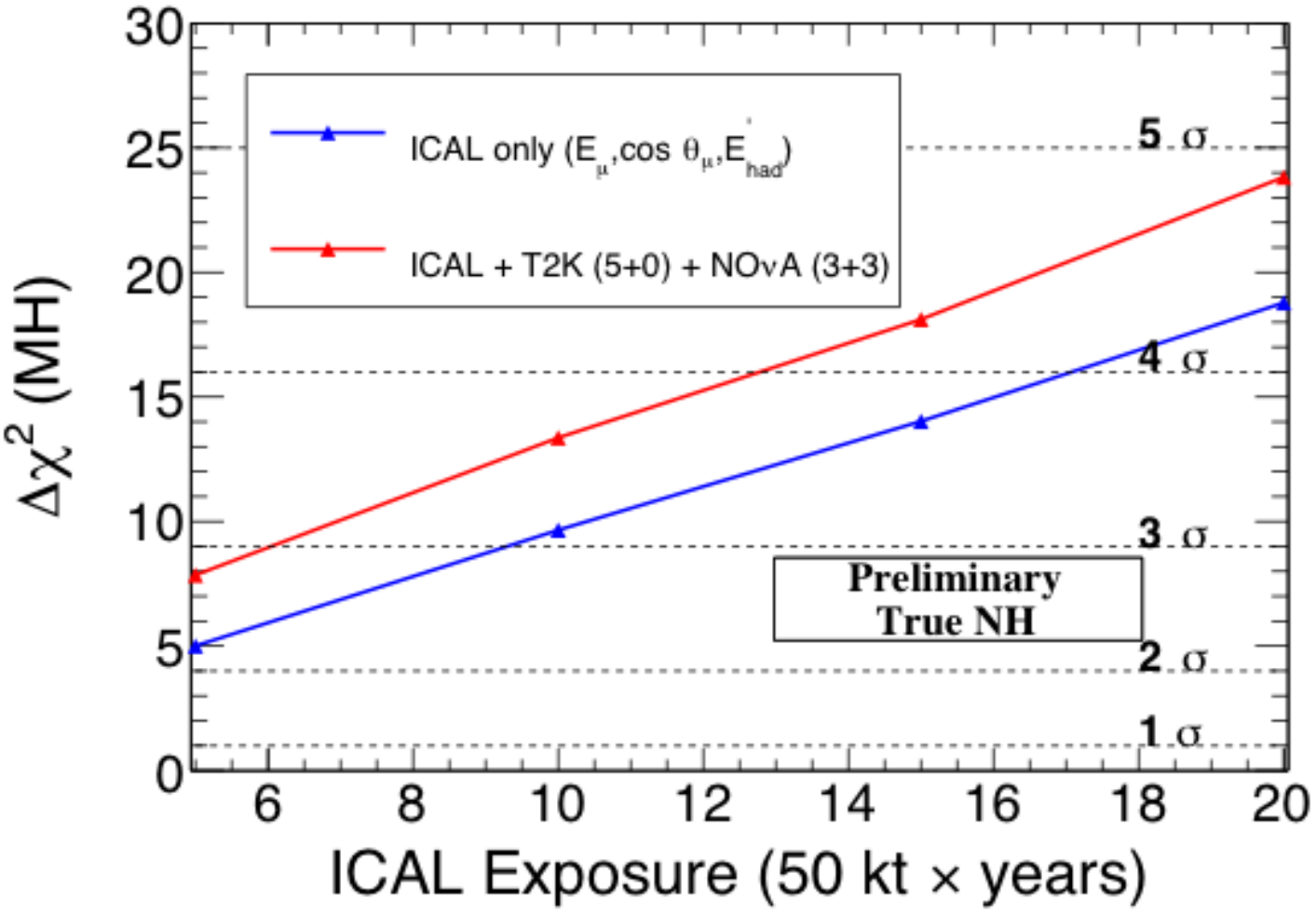




- ***Event-by-event data on E_μ, $\cos\theta_\mu$, E'_{had} used.***
- ***Hierarchy sensitivity improves significantly. χ^2 sensitivity improves by 40%***

Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689

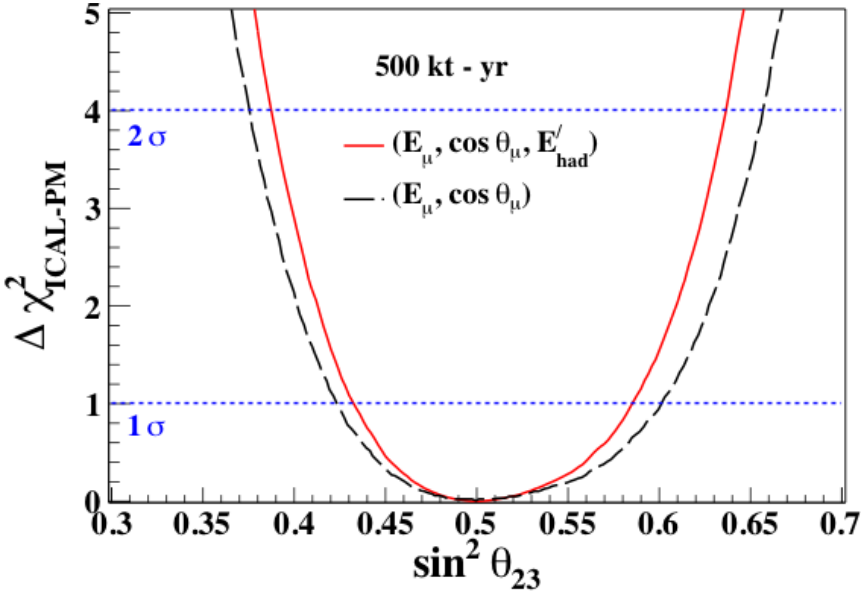
MH sensitivity with ICAL+T2K+NOvA

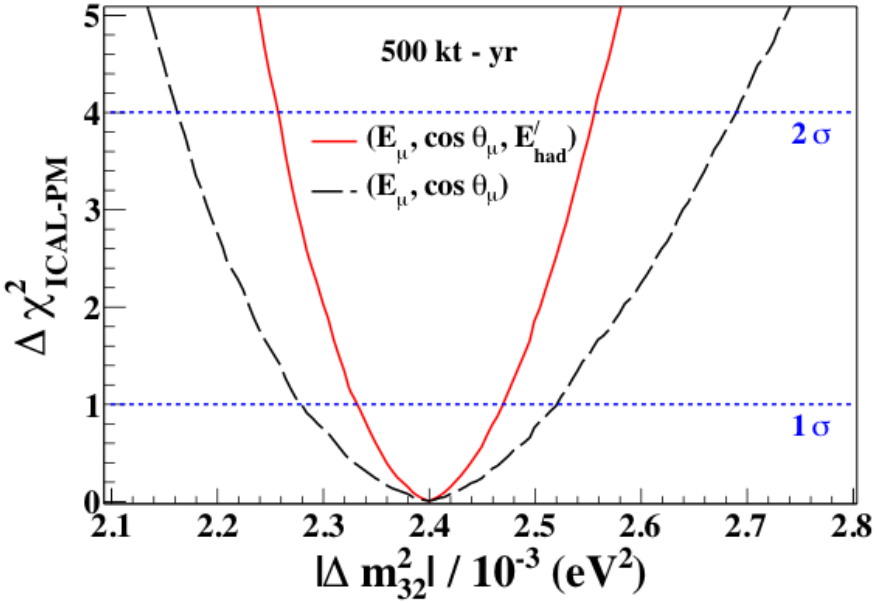


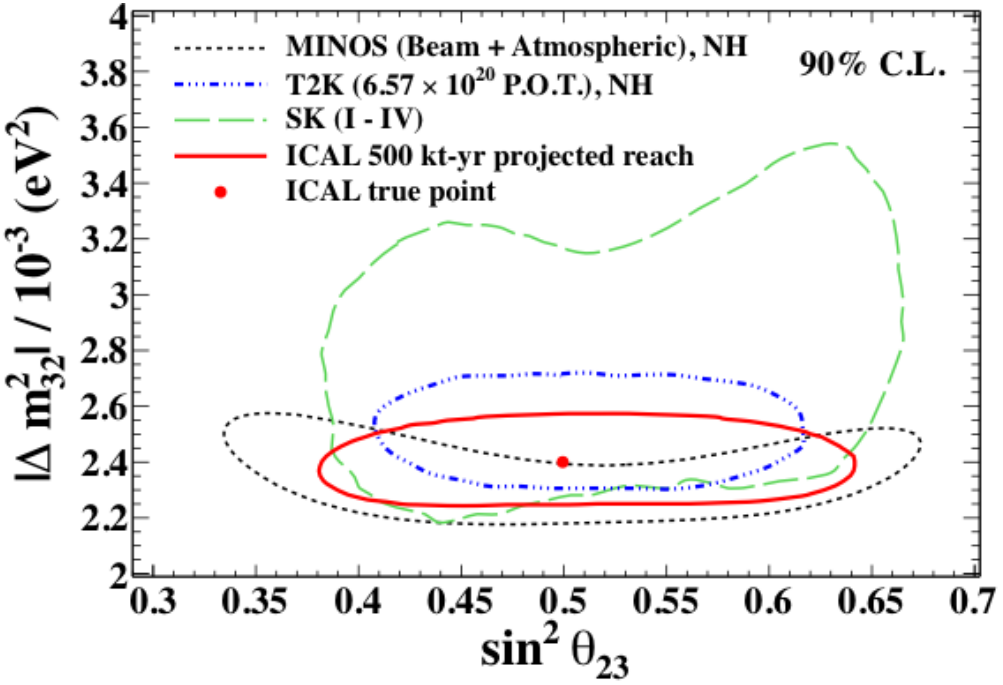
3σ Sensitivity can be achieved in 6 years

Devi, Thakore, Agarwalla, Dighe, work in progress

Precision measurements including hadron information



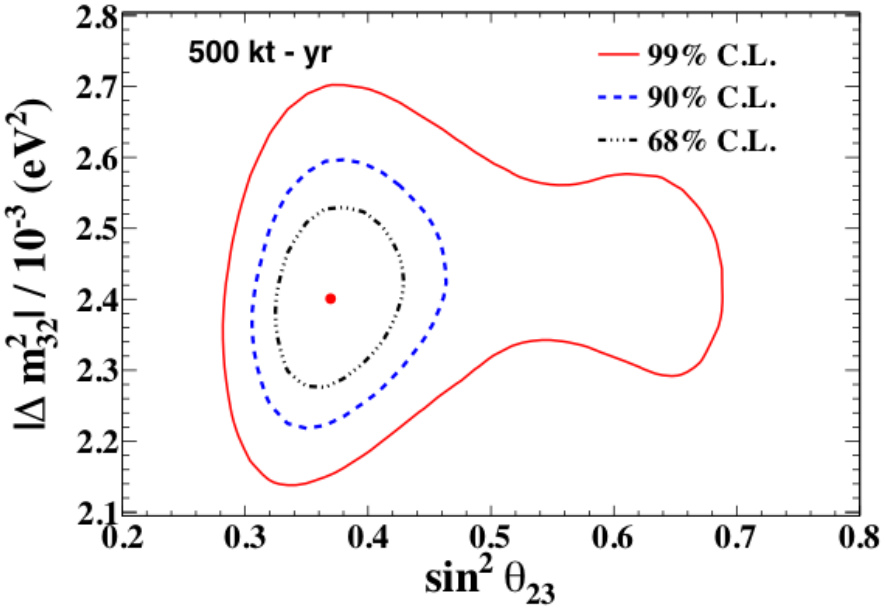


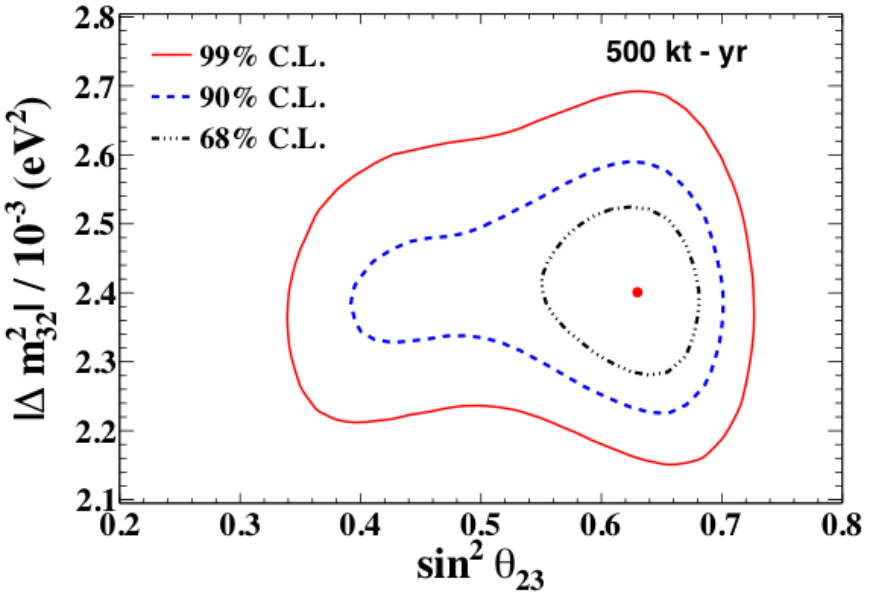


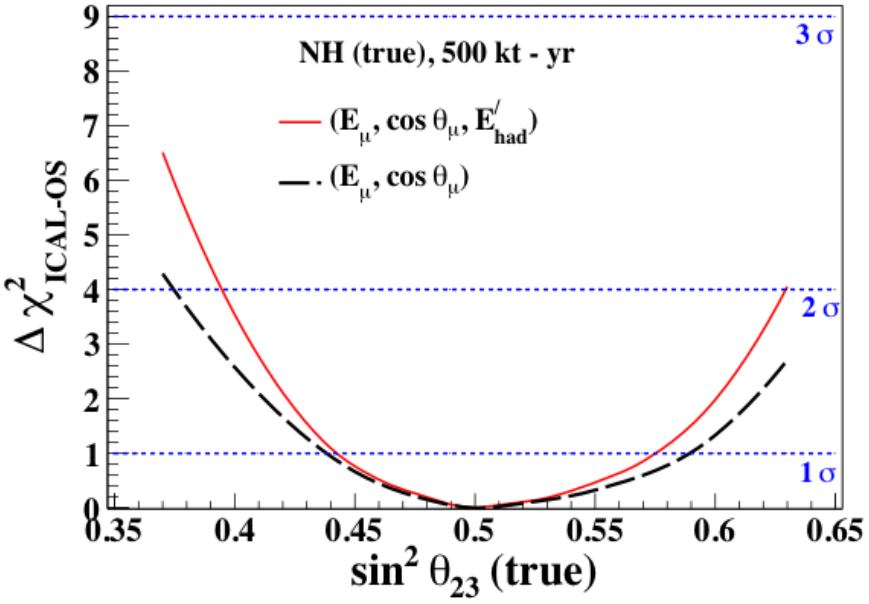
Factor of two improvement in $|\Delta m^2_{23}|$ precision with added hadron information

Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689

Octant sensitivity with hadron information





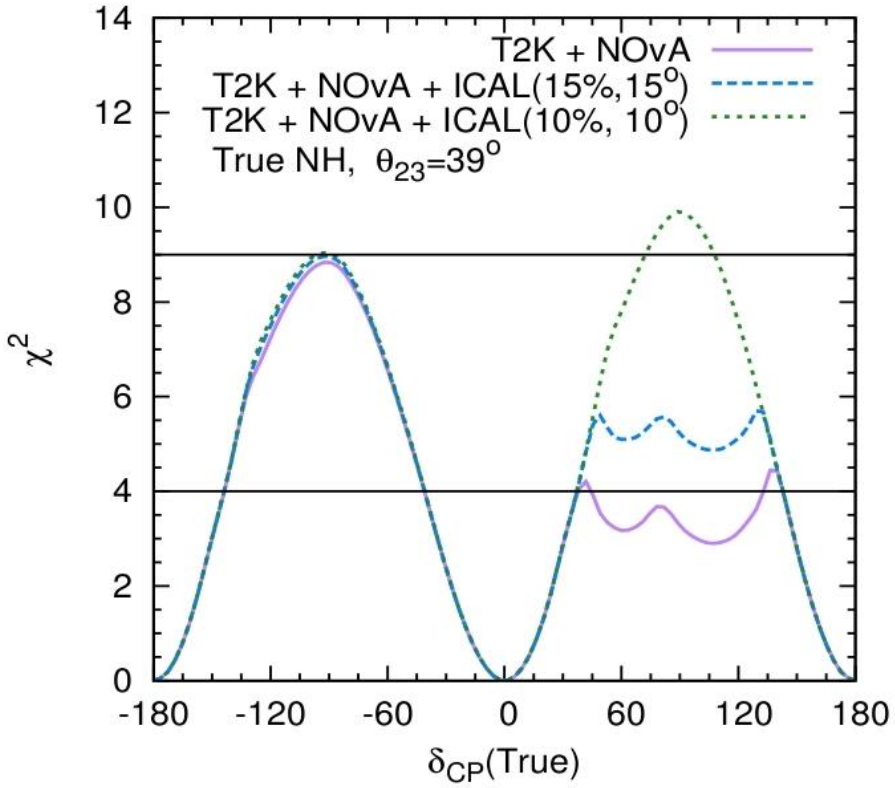


More than 2σ sensitivity to θ_{23} octant is possible if θ_{23} is sufficiently away from maximality

Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689

Synergy with other experiments: CPV

Monojit Ghosh, Pomita Ghoshal, Srubabati Goswami, Sushant Raut arXiv: 1306.2500



Hierarchy information from INO-ICAL helps the detection of CP violation, though INO itself is not sensitive to CP violation

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 complete.*
- *DPR for Detector & 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 clearance from PM's cabinet committee to start construction.*

5 questions

- Q1. (Theoretical relevance) What is according to you the theoretical relative urgency of the determination of the neutrino mass hierarchy,
  PMNS CP violating phase δ,
  θ_{23} octant
  existence of sterile neutrinos
  Dirac vs Majorana nature of the neutrino
  Compare, if relevant, to other attempts of measurement direct or indirect (e.g. in cosmology). Describe also synergies with other topics of science e.g. proton decay or neutrino astrophysics (supernova burst and relic, solar neutrinos,…).

- Q2. (Experimental Strategy) What is according to you the experimental strategy that needs to be deployed worldwide in order to answer the above questions? And in particular, how many experiments should there be worldwide, what complementarities or double check features should they exhibit?

INO : proposed to resolve neutrino mass hierarchy using atmospheric neutrinos and matter effect. It will be the only magnetised detector of its size available to make this measurement.

JUNO/RENO 50 : Proposed to use modulation of reactor anti-neutrino flux.

Q3. (Experimental readiness) Evaluate the readiness of the technology you are planning to use. Describe the phases (or R&D) towards its final validation. What are the risks associated. Is there place for global sharing and coordination of the R&D or validation effort? Are there industrial issues e.g. in procurement?

- R & D completed. Pilot production of RPC in industry to start soon.
- $1/8^{th}$ size prototype detector will be constructed in next one year.
- Possibility to make 100 kton (additional 50 kton) with international participation.

Q4. (Site issues) What are the optimisation criteria for the site you propose? What is the regional support for the site you propose? Is your proposal site specific? Could the same or better performances be obtained in another site in the same continent or some other region?

- We will be using atmospheric neutrinos in the energy range of 2-10 GeV and our sensitivity is site independent.
- Indian Govt. will fund the complete civil construction cost for the underground laboratory and other infrastructure.

Q5. (Financial and internationalisation issues) What is the cost of the experimental configuration (beam where relevant and detector)? What is your financial plan? What is the current level of international participation and what level of participation would be necessary to move to a construction decision? What models would you propose for international participation and at which parts of the beam or detectors? What would be the parts of the configuration whose leadership you would be willing to negotiate in exchange of international participation ?

- Total cost of infrastructure + 50 kton ICAL : 250 M USD. To be funded by Govt. of India.

- However the lab can accommodate 100 kton detector and we welcome international participation as equal partners to convert it into a 100 kton detector to increase its sensitivity.


Thank You for
your attention