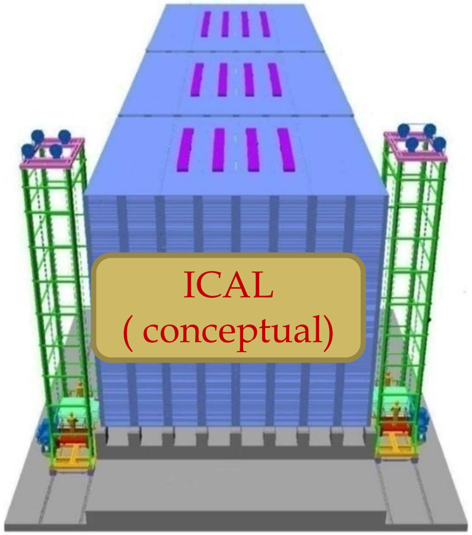
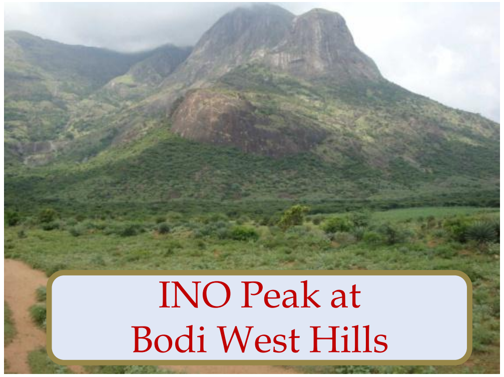
Status of India-Based Neutrino Observatory (INO)

B S Acharya,
Tata Institute, Mumbai
(on behalf of INO Collaboration)


ICAL (conceptual)

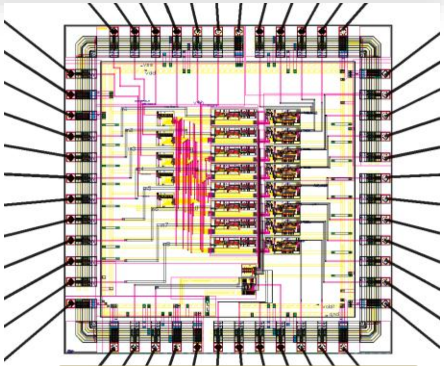

INO Peak at Bodi West Hills


RPC Test stand at TIFR

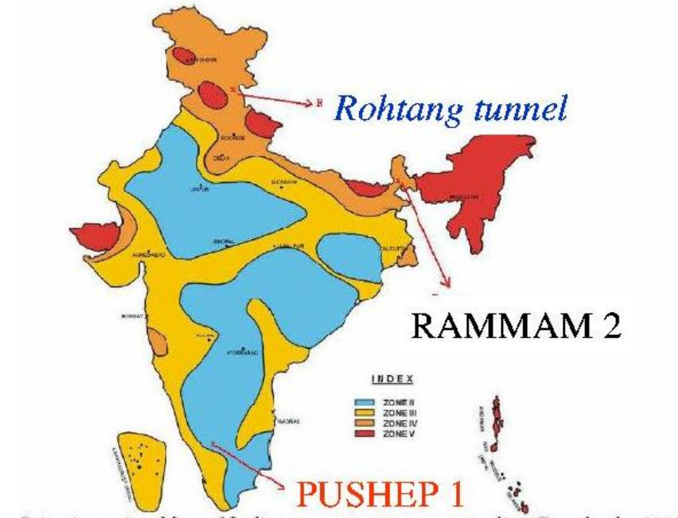

2mX2m RPC Test Stand at TIFR

Ahmedabad: Physical Research Laboratory (PRL); **Aligarh:** Aligarh Muslim University (AMU); **Allahabad:** Harish Chandra Research Institute (HRI); **Bhuwanewar:** Institute of Physics (IOP); Utkal University; **Calicut :** University of Calicut; **Chandigarh:** Panjab University (PU); **Chennai :** Indian Institute of Technology, Madras (IITM); The Institute of Mathematical Sciences (IMSc) ; **Delhi :** Delhi University (DU); Jawaharlal Nehru University (JNU); **Kolkata :** Saha Institute of Nuclear Physics (SINP); University of Calcutta (CU) ; Variable Energy Cyclotron Centre (VECC) ; **Lucknow :** Lucknow University (LU); **Madurai :** American College; **Mumbai :** Bhabha Atomic Research Centre (BARC) ; Indian Institute of Technology, Bombay (IITB) ; Tata Institute of Fundamental Research (TIFR); **Mysuru :** University of Mysore (MU) ; **Srinagar :** University of Kashmir; **Varanasi :** Banaras Hindu University (BHU)


Prototype ICAL at VECC


ASIC for RPC designed at BARC

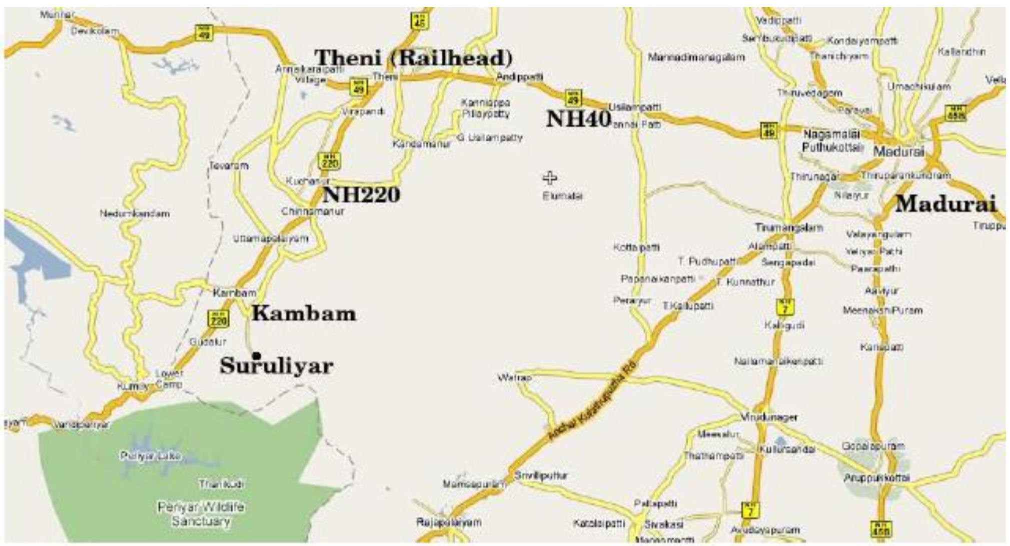
90+ Collaborators from
22 Institutions



Seismic zoning Map of India- issued by Bereau of Indian Standards, 2000

BWH (9°58' N, 77°16' E)
10 km from Theni (Railhead)
120 km from Madurai(Airport)

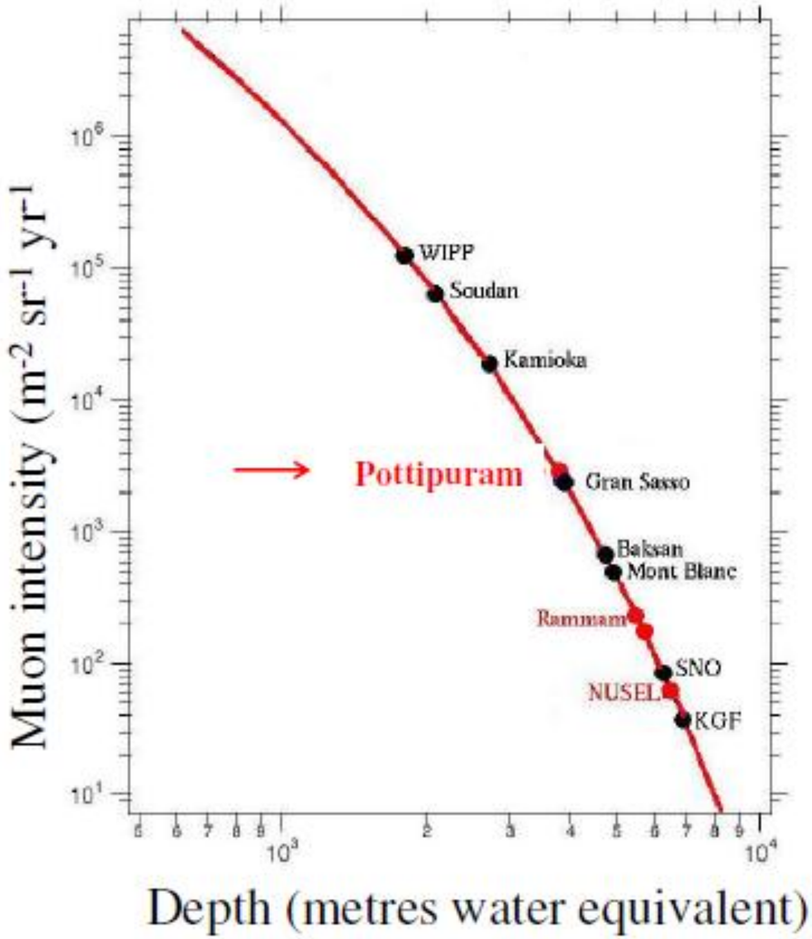
INO site at Pottipuram, Theni District



***Infrastructure at the site** for water, electricity, approach road and local area development Is going on.*

~13 ha. of land at Madurai city to establish the Inter Institutional Centre for High Energy Physics (IICHEP)

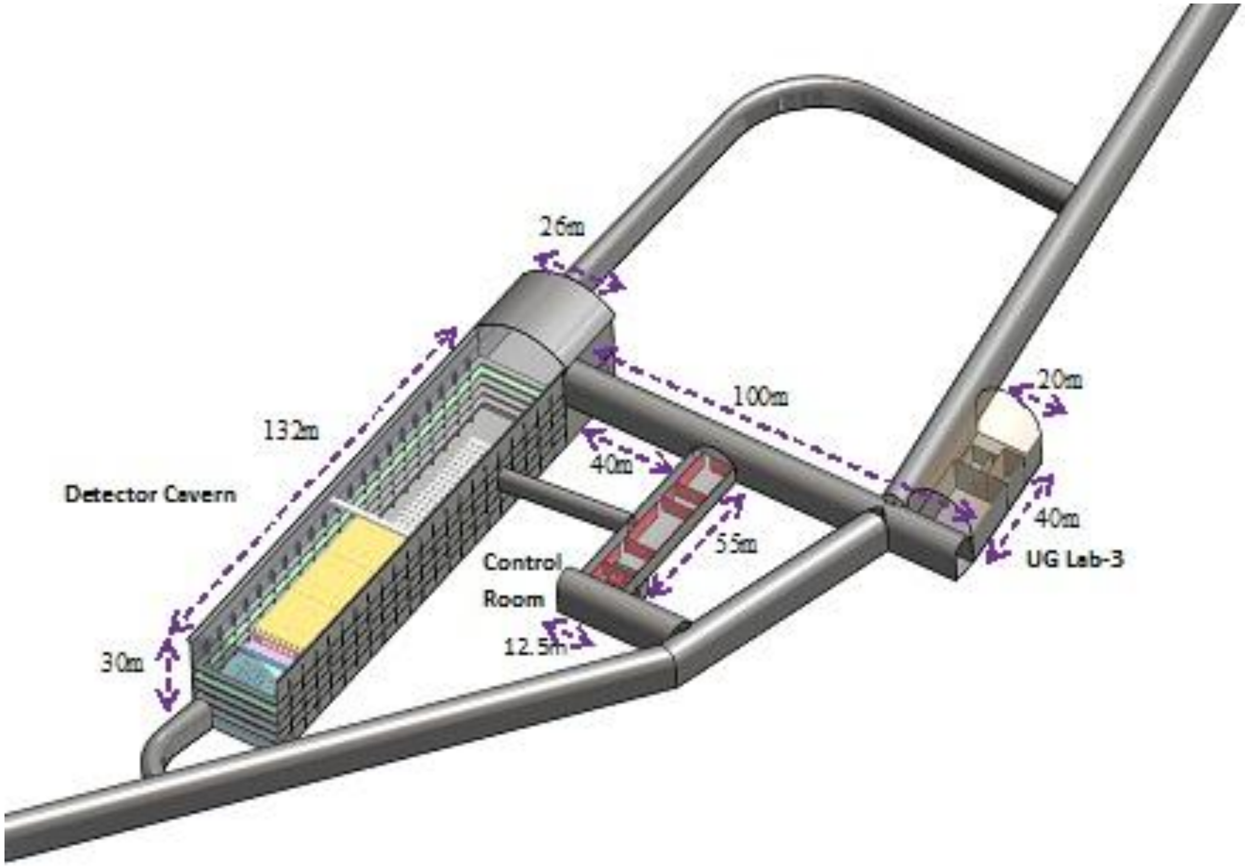
The INO site at Pottipuram



- Cavern set in Charnockite rock under 1580 m peak – Bodi West Hills mountain
- Cavern access through 2m long adit
- 1289 m Vertical cover (1000 m all-round)
- Warm , low rain-fall area, low humidity through out the year, unusual wind speed in some seasons
- Flat terrain with good access to major roads

Close to magic baseline (~7500 Km)
From CERN 7300 Km; JPARC 6500 Km;
RAL 7600 Km;

Underground Laboratory Layout



One large cavern for ICAL and 2 small cavern for other experiments such as Neutrino-less double beta decay (NDBD) and search for dark matter etc.

ICAL@ INO

Magnetized Iron Calorimeter (ICAL)

charge identification capability and good energy resolution

Excellent muon energy measurement, muon direction reconstruction and charge identification

Hadron shower reconstruction allows access to neutrino energy and high energy cosmic rays

Motivation:

Atmospheric neutrinos provide wider range for E and L than any artificial neutrino sources

An ability to discriminate between neutrinos and anti-neutrinos enables efficient determination of neutrino mass ordering.

ICAL@ INO

ICAL – The physics goals

Determination of neutrino mass hierarchy

Accurate determination of atmospheric neutrino oscillation parameters
Reconfirm neutrino oscillations from distortion in L/E dependence,
Measure $|\Delta m^2_{31}|$ and $\sin^2 2\theta_{23}$

Deviation of θ_{23} from maximality and octant of θ_{23}

Non-standard interactions , sterile neutrinos, CPT violations, LIV, long range forces, Ultra high energy muon fluxes etc.

Determination of CP violation in the lepton sector (with a future long baseline experiment with neutrino factory)

INO-ICAL Detector Concept

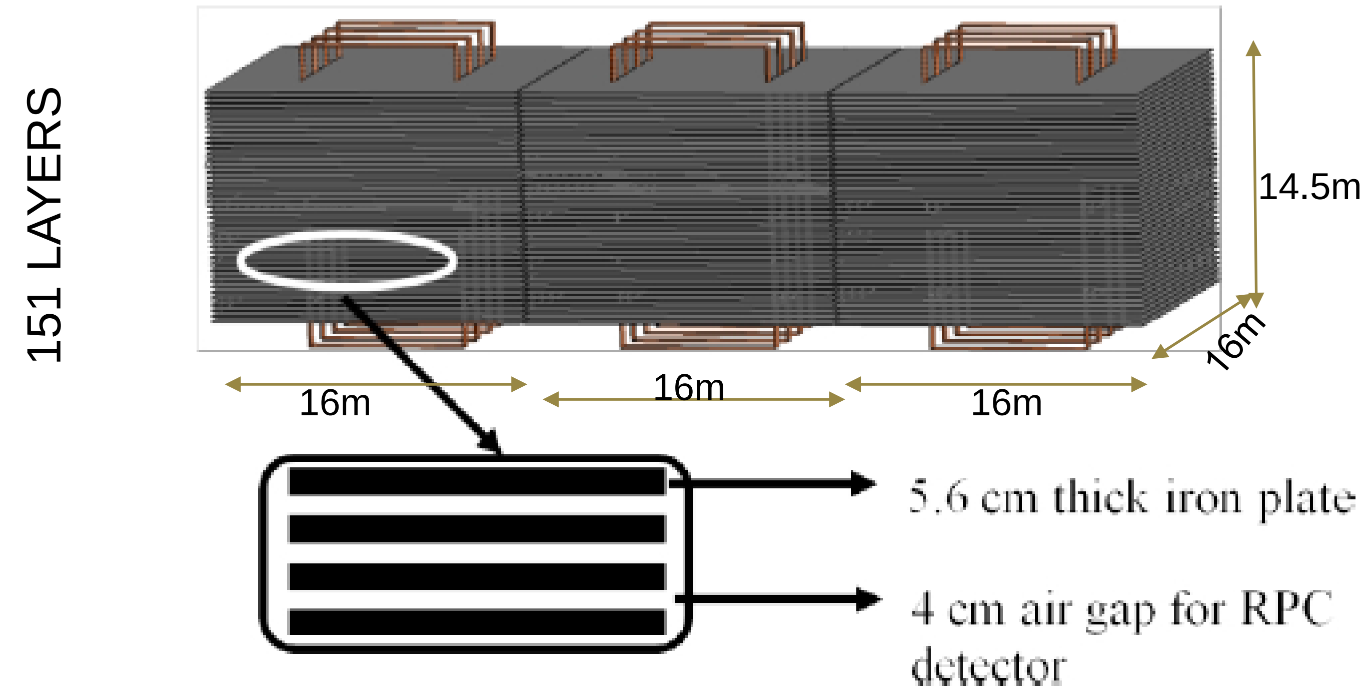
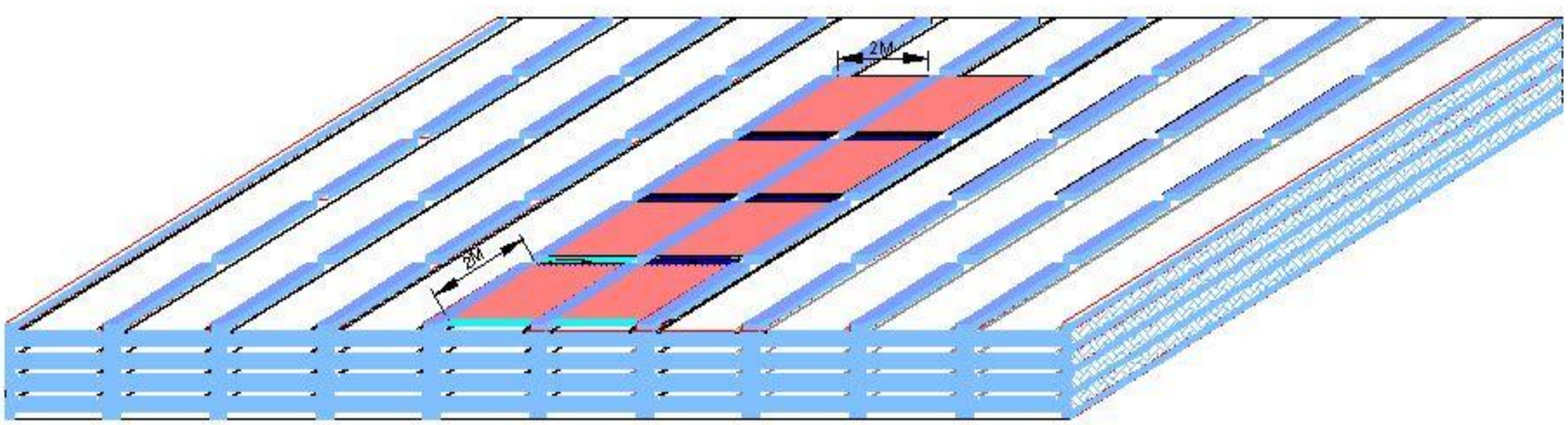


Figure 1.3: Schematic view of the 50 kt ICAL detctor

50 k ton
Magnetized
Iron
calorimeter



INO-ICAL Detector Specifications

No of modules	3 (50 k ton)
Module dimensions	16 m X 16 m X 14.5 m
Detector dimensions	48.4m X 16 m X 14.5 m
No of layers	151
Iron plate thickness	56 mm
Gap for RPC trays	40 mm
Magnetic field	1.5 Tesla
RPC unit dimensions	195 cm X 184 cm X 24 mm
Readout strip pitch	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	28,992 (= 104,023 m^2)
No of readout strips	3.710,976 (3.7 million)

Simulation Framework

NUANCE

Neutrino Event Generation

ν_ℓ + N -> ℓ + X

Generates particles that result from a random interaction of a neutrino with matter using theoretical models for both neutrino fluxes and cross-sections.

Output:

i) Reaction Channel

ii) Vertex Information

Iii) Energy & Momentum of all final state particles

GEANT

Event Simulation

ℓ + X through simulated ICAL

Simulate propagation of particles through the ICAL detector with RPCs and magnetic field.

Output:

i) *x, y, z, t* of the particles as they propagate through the detector

ii) Energy deposited

iii) Momentum information

DIGITIZATION

Event Digitization

(*x,y,z,t*) of final state particles including noise and detector efficiency

Add detector efficiency and noise to the hits

Output:

i) Digitised output of the previous stage (simulation)

ANALYSIS

Event Reconstruction

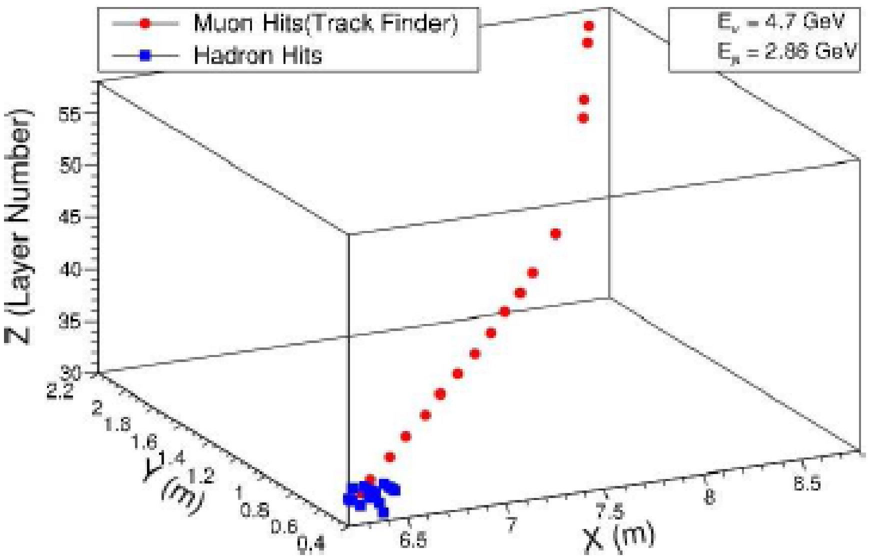
(E,p) of ℓ + X (total hadrons)

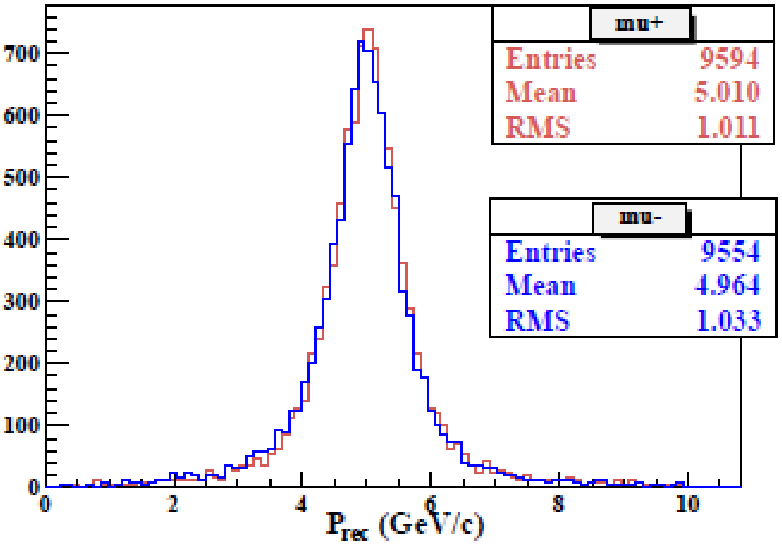
Fit the muon tracks using kalman filter techniques to reconstruct muon energy and momentum, use hits in hadron shower to reconstruct hadron information.

Output:

i) Energy & Momentum of muons and hadrons, for use in physics analysis.

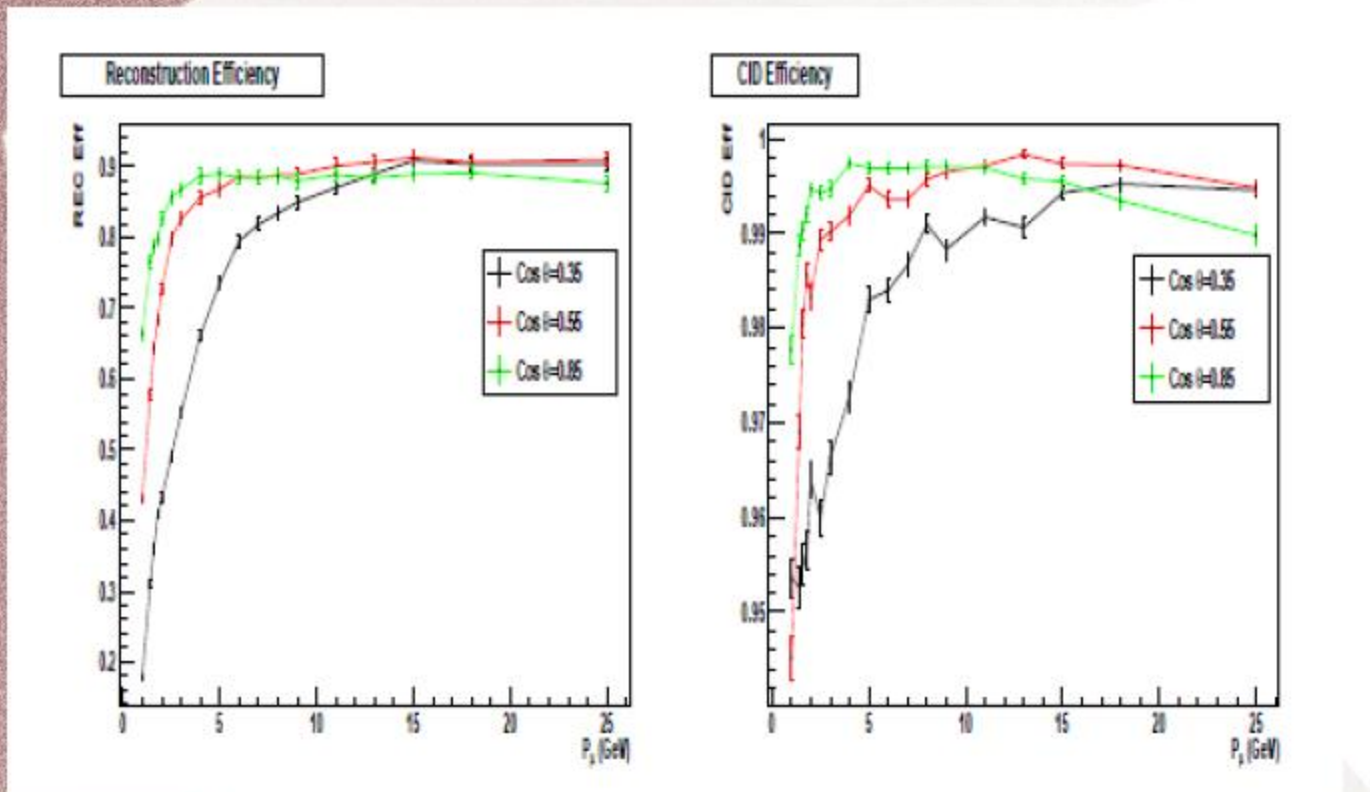
ICAL Simulations





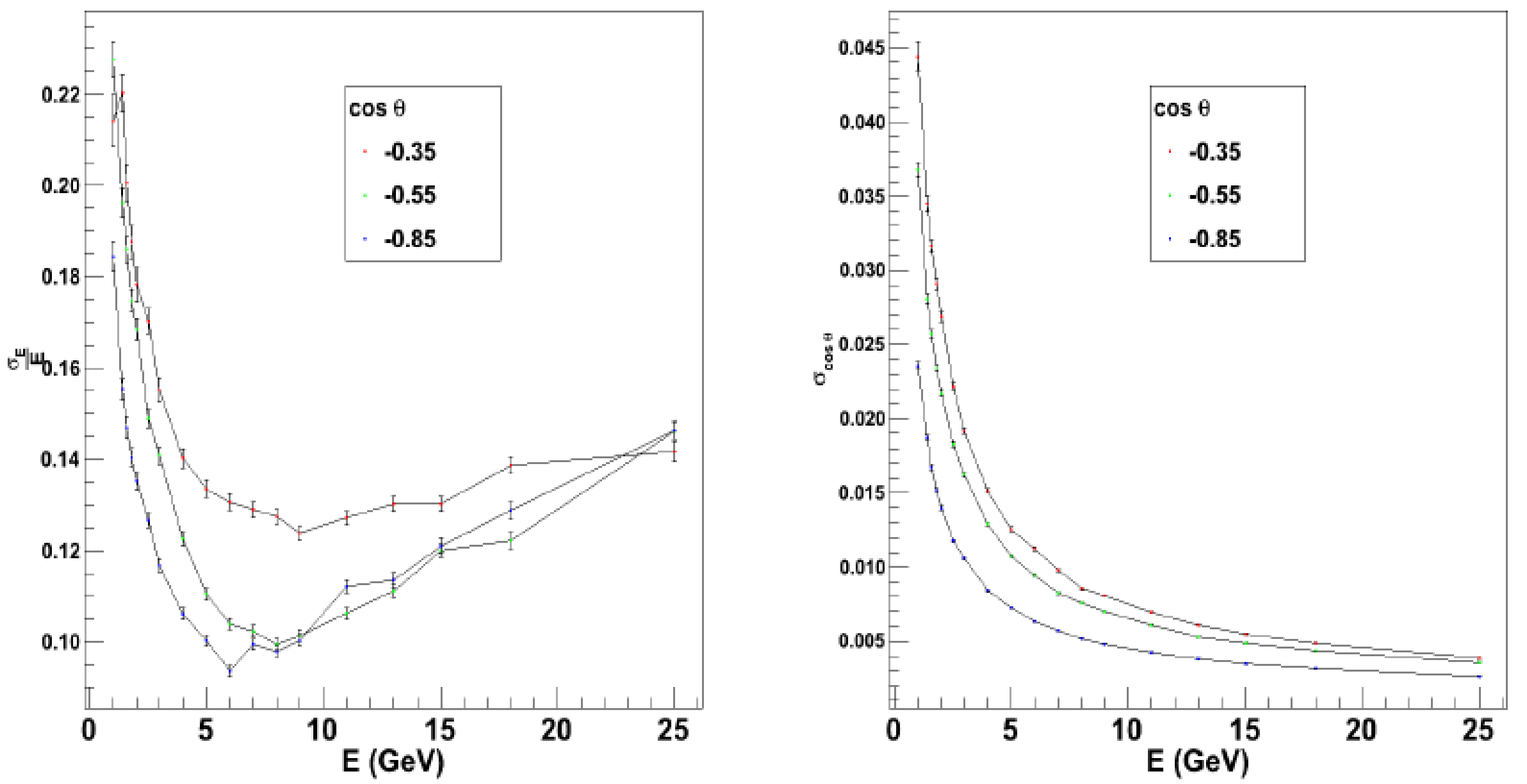
- GEANT4-based simulation of ICAL detector. Magnetic field map through simulations using MAGNET6.0 code.
- Neutrino events generated using NUANCE neutrino generator
- Muons leave long, clean tracks in detector. Calibrated through range or bending in magnetic field (Kalman filter)
- Hadrons are calibrated through the hits they leave: do not traverse many iron layers

Detector performance: efficiencies



μ-

Detector performance : resolutions



μ^-

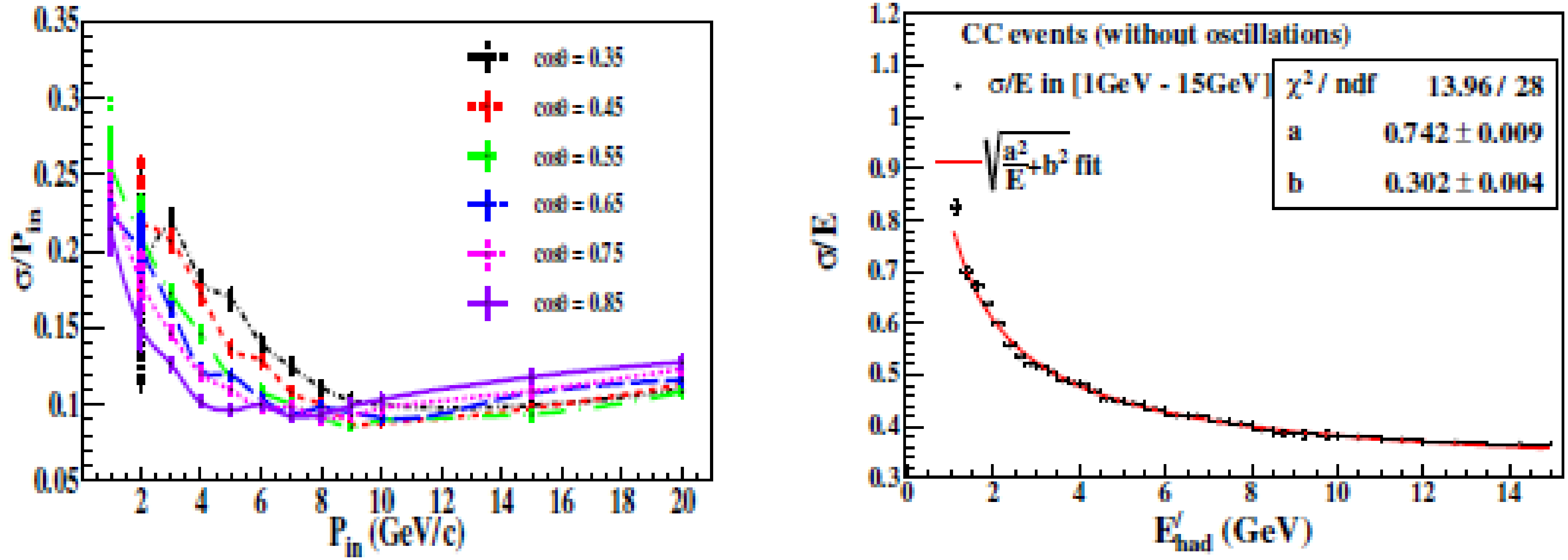


Figure 1: Left panel shows the momentum resolution of muons produced in the region $0 < \phi < \pi/4$ (see Sec. 4.1), as functions of the muon momentum in different zenith angle bins [8]. Right panel shows the energy resolution of hadrons (see Sec. 4.2) as functions of $E'_{\rm had}$, where events have been generated using NUANCE in different $E'_{\rm had}$ bins. The bin widths are indicated by horizontal error bars [9].

	μ^-	μ^+
Unoscillated	14311	5723
Oscillated	10531	4188
After Applying Reconstruction and CID Efficiencies	4941	2136
After Applying $(E, \cos\theta)$ Resolutions	5270	2278

Table 5.1: Number of muon events produced in CC ν_μ interactions at various stages of the analysis for an exposure of 50 kt $\times$ 10 years in the energy range 0.8–10.8 GeV.

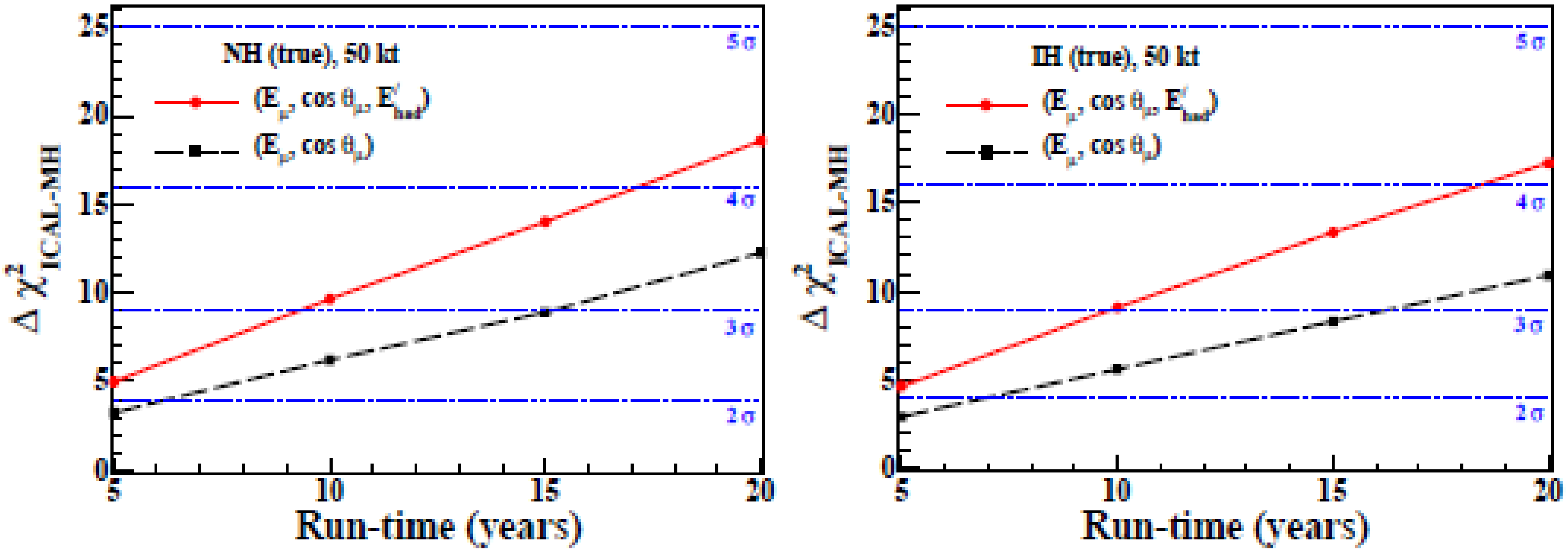


Figure 2: The hierarchy sensitivity of ICAL with input normal (left) and inverted (right) hierarchy including correlated hadron energy information, with $|\Delta m^2_{\rm eff}|$, $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$ marginalised over their 3σ ranges [14]. Improvement with the inclusion of hadron energy is significant.

Identifying mass hierarchy at all $\delta_{\rm CP}$ values

The large range of path length of the atmospheric neutrinos makes ICAL insensitive to the CP phase $\delta_{\rm CP}$, as a result its reach in distinguishing the hierarchy is also independent of the actual value of $\delta_{\rm CP}$ [18]. On the other hand the sensitivity of fixed-baseline experiments such as T2K and NOνA is extremely limited if $0 < \delta_{\rm CP} < \pi$. However adding of the ICAL information ensures that the hierarchy can be identified even in these unfavoured $\delta_{\rm CP}$ regions [11]. Of course in the $\delta_{\rm CP}$ regions favourable to the long baseline experiments, the ICAL data can only enhance the power of discriminating between the two hierarchies.

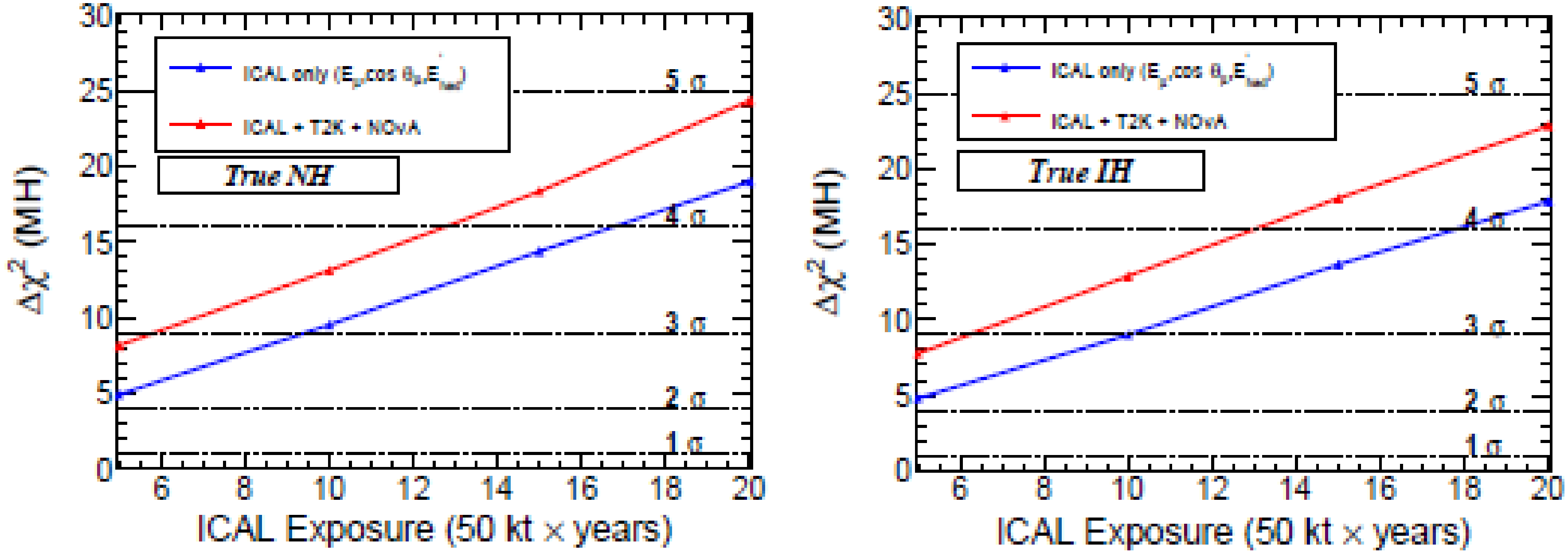


Figure 4: Preliminary results on the hierarchy sensitivity with input normal (left)and inverted (right) hierarchy when ICAL data is combined with the data from T2K (total luminosity of 8×10^{21} pot in neutrino mode) and NOνA (3 years running in neutrino mode and 3 years in antineutrino mode) [17].

Determination of the CP phase

Though ICAL itself is rather insensitive to δ_{CP}, data from ICAL can still improve the determination of δ_{CP} itself, by providing input on mass hierarchy. This is especially crucial in the range $0 \leq \delta_{CP} \leq \pi$, precisely where the ICAL data would also improve the hierarchy discrimination of NOνA and other experiments [19].

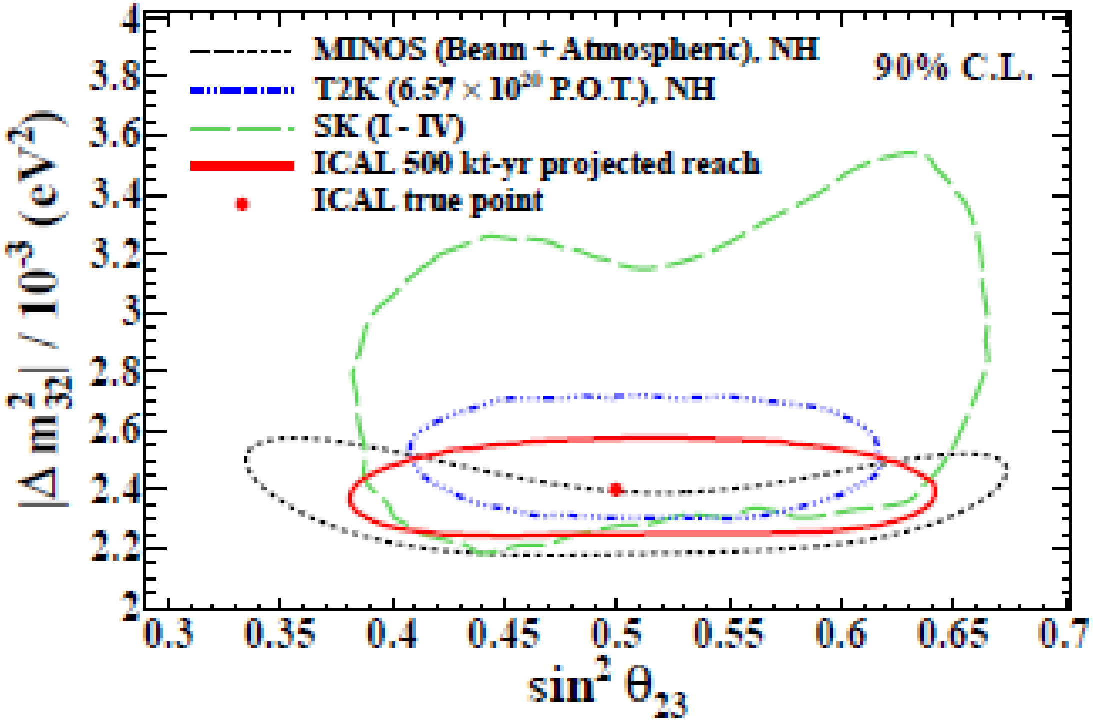


Figure 3: The precision reach of ICAL in the $\sin^2\theta_{23}$–Δm^2_{32} plane, in comparison with other current and planned experiments [14]. Information on hadron energy has been included.

With a non-maximal true value of θ_{23}, the bounds on $\sin^2\theta_{23}$ range would be asymmetric about 0.5. Figure 5.18 shows the sensitivity of ICAL for $\sin^2 2\theta_{23} = 0.93$ (i.e. $\sin^2\theta_{23} = 0.37$, 0.63). It may be observed that for θ_{23} in the lower octant, the maximal mixing can be ruled out with 99% C.L. with 500 kt-yr of ICAL data. However, if θ_{23} is closer to the maximal mixing value, or in the higher octant, then the ICAL sensitivity to exclude maximal mixing would be much smaller.

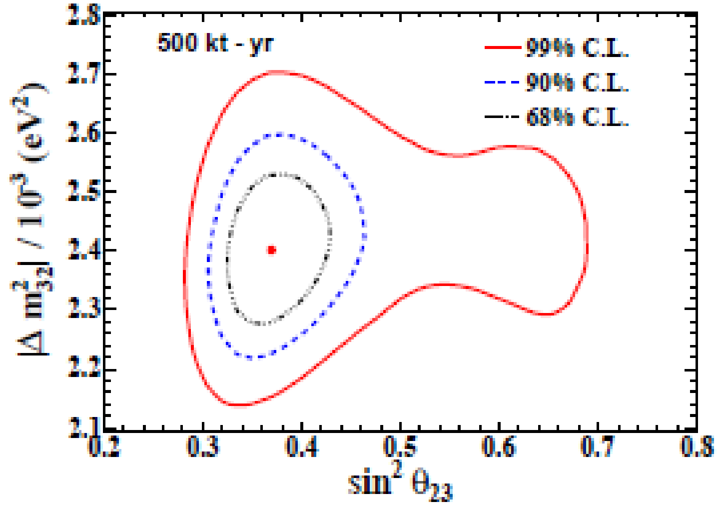


Figure 5.18: $\Delta\chi^2_{\rm ICAL-PM}$ confidence level contours in the the $\sin^2\theta_{23}$–$|\Delta m^2_{32}|$ plane, for $\sin^2\theta_{23}$(true) = 0.37 (left panel) and $\sin^2\theta_{23}$(true)= 0.63 (right panel), using the hadron energy information. Here the true hierarchy is NH [14].

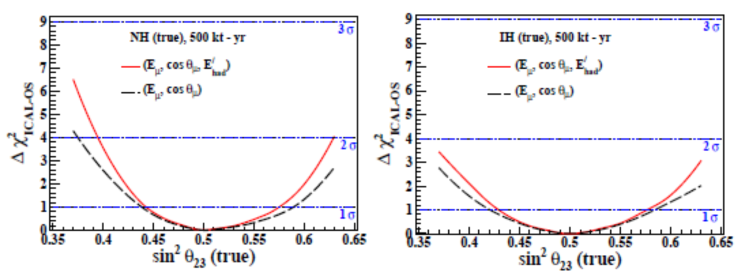
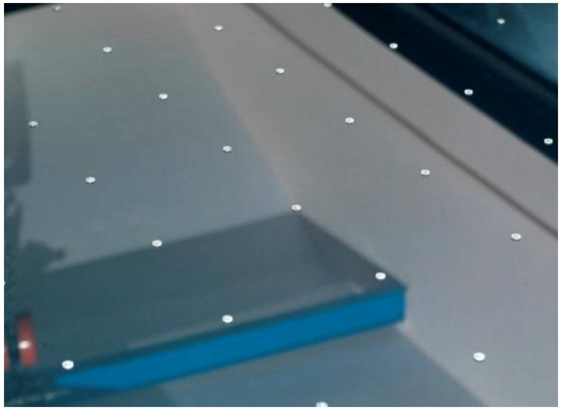


Figure 5.19: $\Delta\chi^2_{\rm ICAL-OS}$ for octant discovery potential as a function of true $\sin^2\theta_{23}$. The left panel (right panel) assumes NH (IH) as true hierarchy. The line labelled $(E_\mu, \cos\theta_\mu)$ denotes results without including hadron information, while the line labelled $(E_\mu, \cos\theta_\mu, E'_{\rm had})$ denotes improved results after including hadron energy information. ICAL exposure of 500 kt-yr is considered [14].

RPC Development work at TIFR

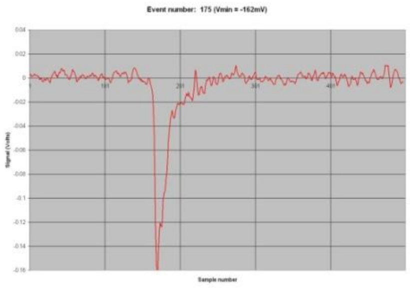


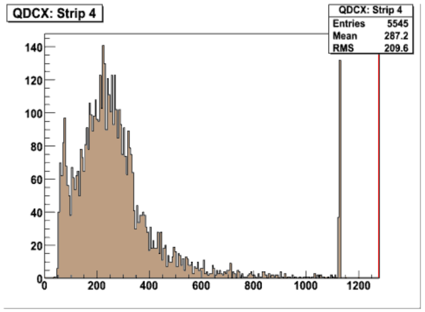
Developing tools for large scale RPC production

2m X 2m RPC Test Stand at TIFR

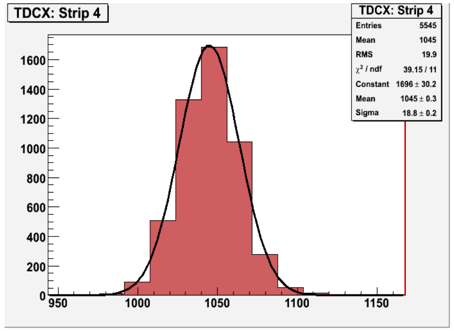
Testing of RPCs using cosmic ray muons

Gas mixing unit





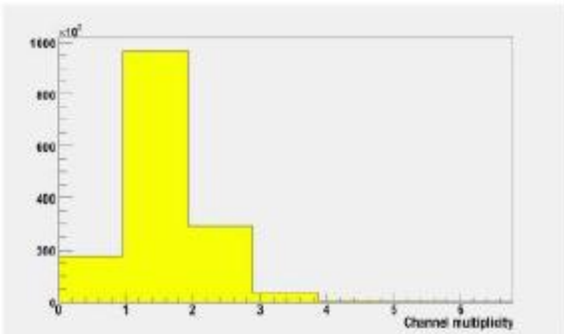
Charge distribution



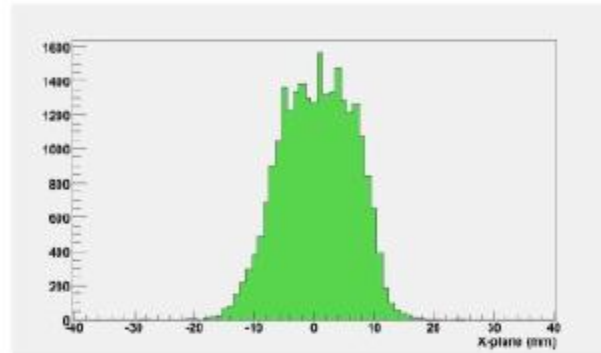
Timing distribution

Streamer mode: HF134a: A : Isobutane:: 62:30:8
Avalanche mode: A : Isobutane: SF6::95.5:4.5:0.3

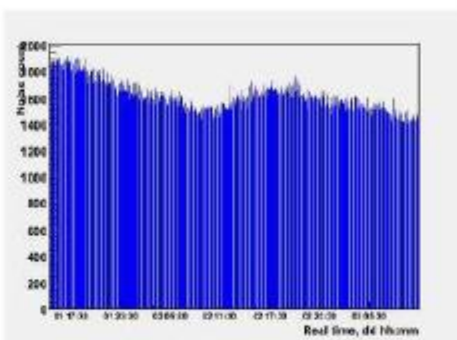
RPC performance with cosmic rays



Strip Multiplicity due to crossing muons



Track residue in mm



Strip noise rate vs time

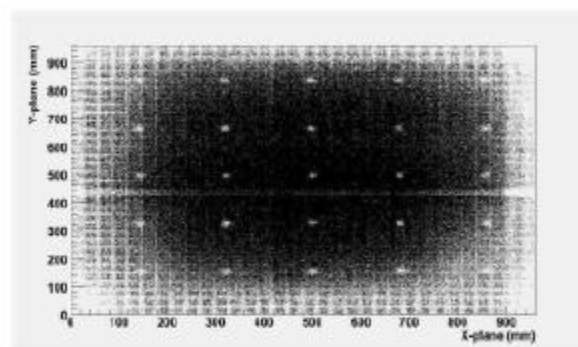
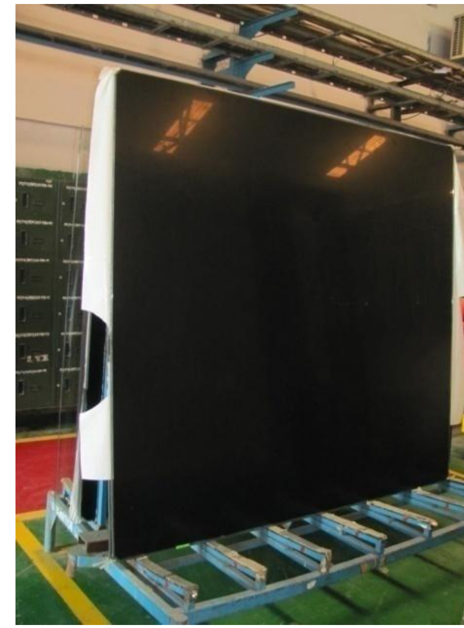
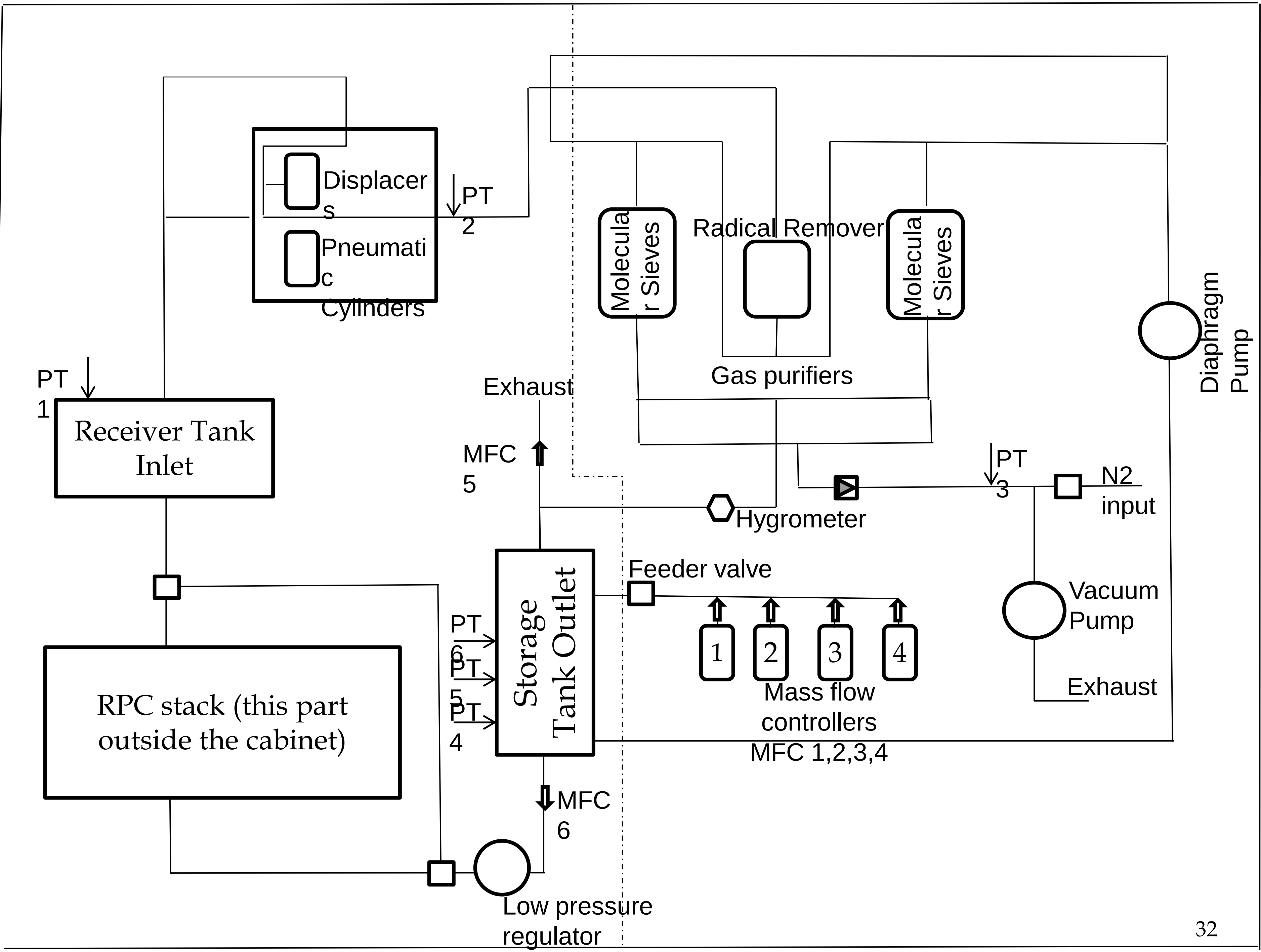


Image of a RPC using muons

RPC Fabrication at Asahi Float Glass Ltd. Mumbai





Displacers
Pneumatic Cylinders
PT 2
Molecular Sieves
Radical Remover
Molecular Sieves
Diaphragm Pump
Gas purifiers
PT 1
Receiver Tank Inlet
Exhaust
MFC 5
PT 3
N2 input
Hygrometer
Feeder valve
Vacuum Pump
Storage Tank Outlet
PT 6
PT 5
PT 4
1
2
3
4
Mass flow controllers MFC 1,2,3,4
Exhaust
RPC stack (this part outside the cabinet)
MFC 6
Low pressure regulator

Newly developed gas recirculation system

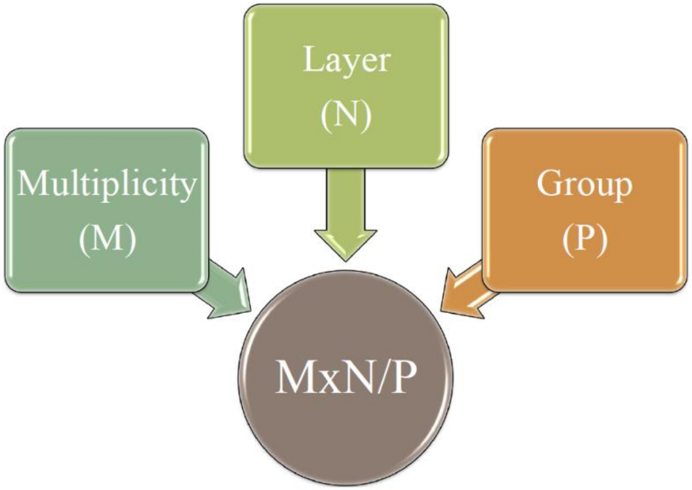
Gas Recirculation System:

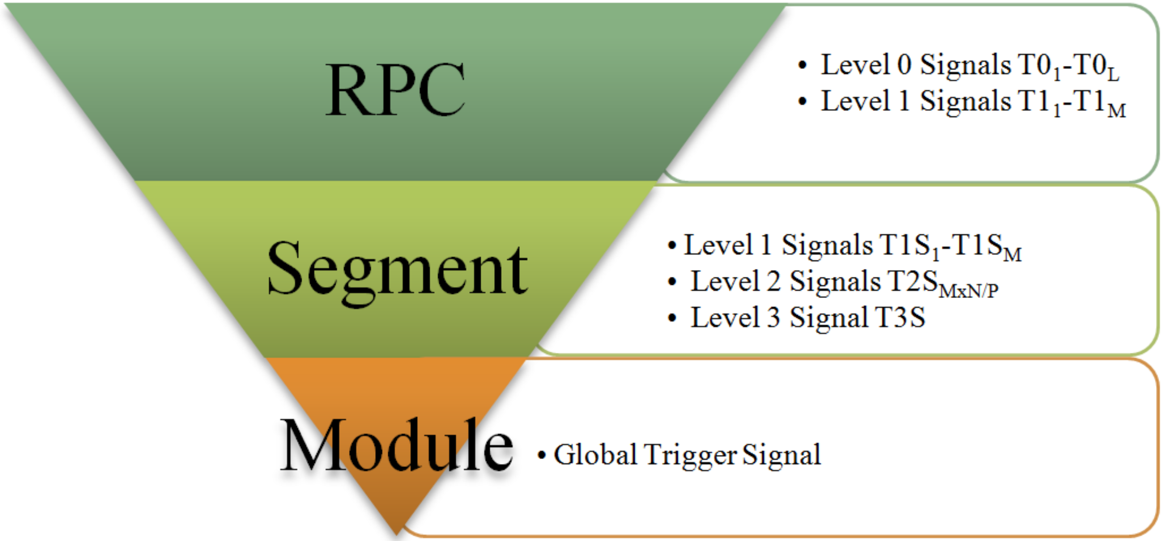
- *Prototype close loop gas recirculation system is under test at TIFR RPC lab.*

Electronics/Daq for RPC system

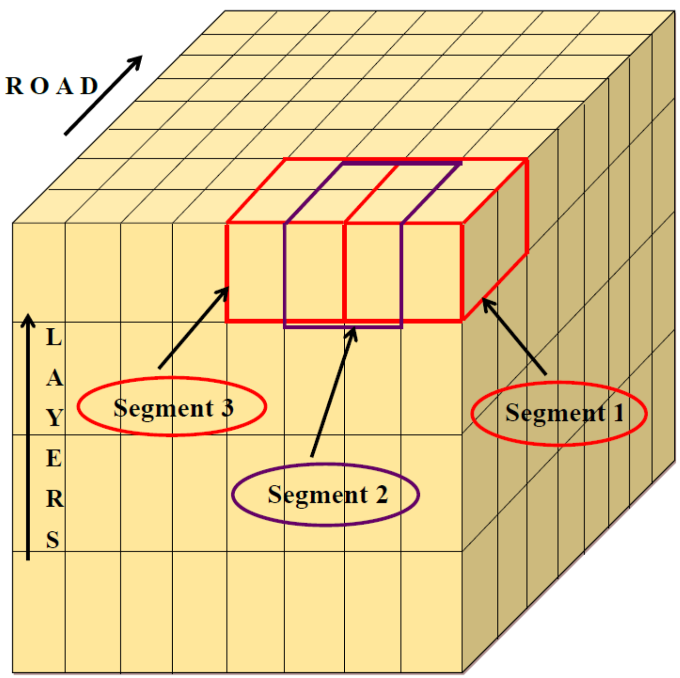
- *An in-house front end amp-disc ASIC front end has been designed by the BARC electronics team and fabricated by Euro Practice IC Services. Tested the first version and a revised version has now been fabricated. It is under test.*
- *Overall electronics and DAQ architecture under discussion. Designate RPC as the minimum stand alone unit.*
- *High performance FPGA (featuring a μC softcore), TDC and waveform sampler based RPC-DAQ board is being prototyped.*
- *Data network architecture and hardware being designed to transmit digitized data to the back-end using RPC-DAQ network interface.*
- *Integration of electronics and DAQ hardware with the RPC detector is being finalised. The entire ICAL detector becomes a large Ethernet LAN, suitably segmented, with RPC units as LAN hosts together with the back end DAQ computers*
- *1st version of ICAL trigger scheme in place. Many implementation aspects tested, integration issues being addressed.*

ICAL Trigger Scheme

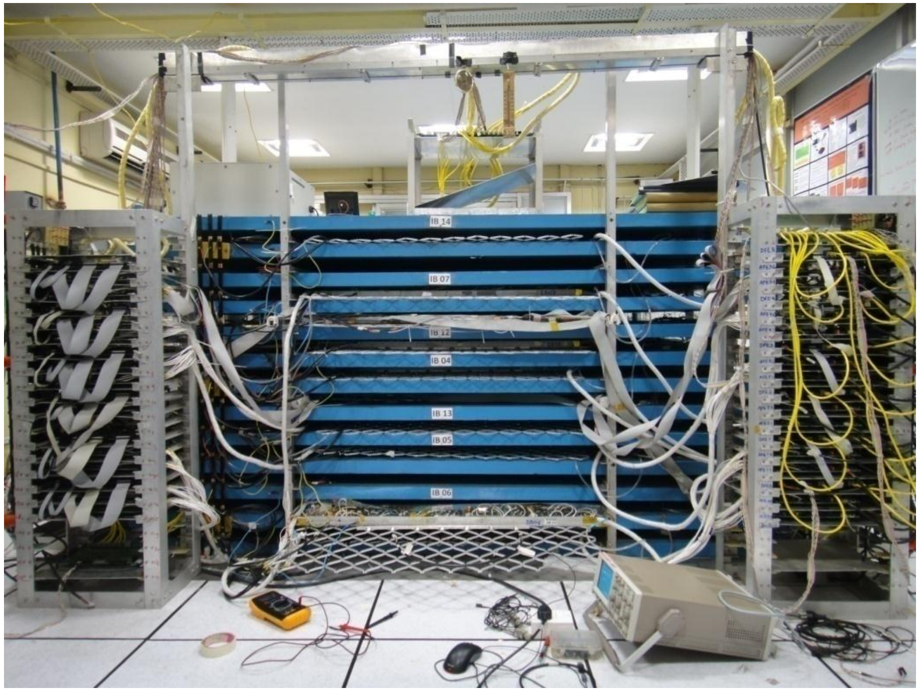




- ➢ **Trigger criteria based on event topology alone.**
- ➢ **Distributed and hierarchical architecture.**
- ➢ **Detector module segmented to generate local trigger.**
- ➢ **Combination of local triggers produces global trigger.**
- ➢ **Global trigger latches event data.**

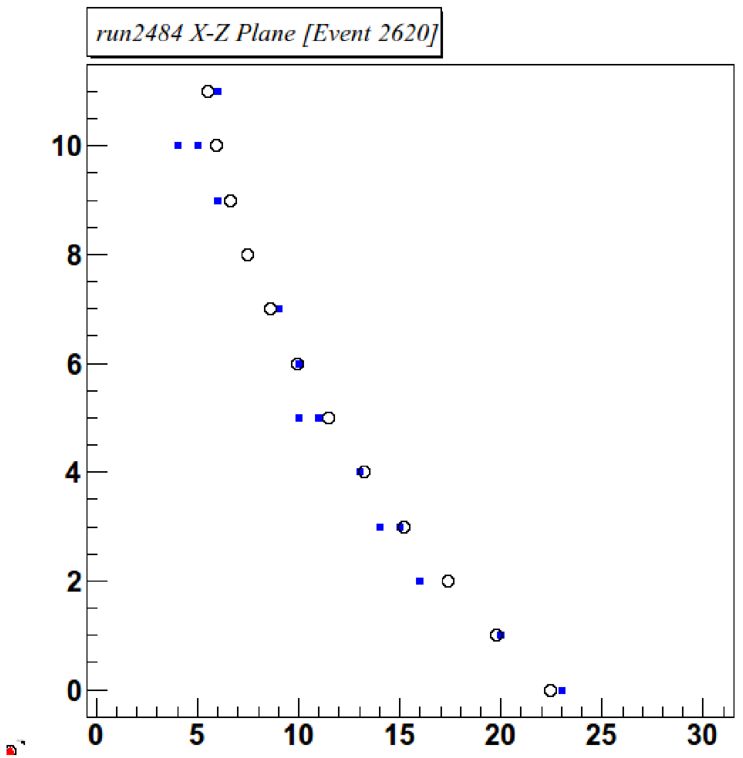


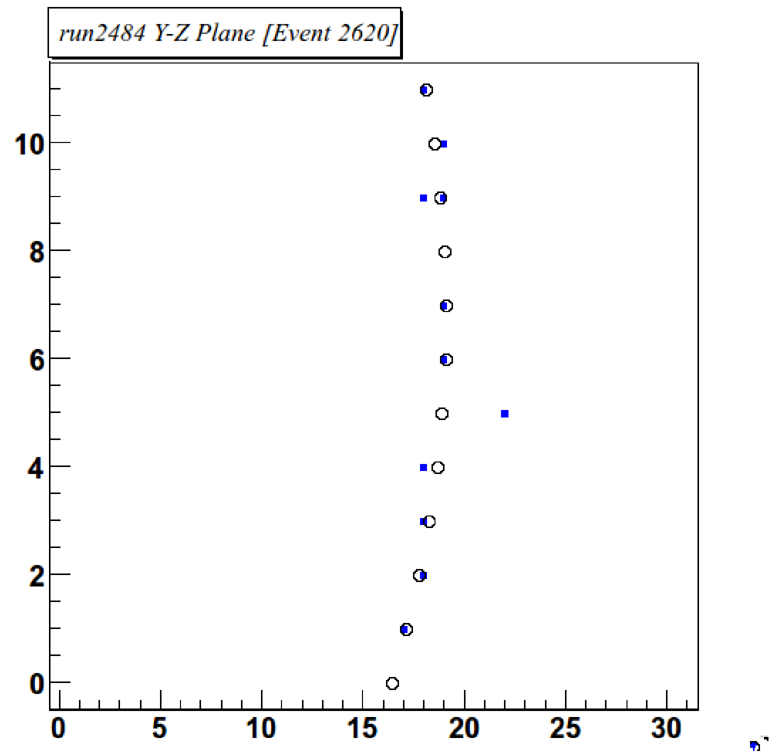
INO Prototype magnet at VECC



• 35 Ton prototype with 12 gaps to house 1mX1m RPCs
•Long term operational experience
•Operate both glass & bakelite RPCs
•Muon track reconstruction with & without magnetic fields.
•Stability & suitability of LV & HV electronics.
•Lab environmental condition studies and student training
•Will be taken to CERN for beam tests and calibration

Cosmic muon tracks seen in the prototype

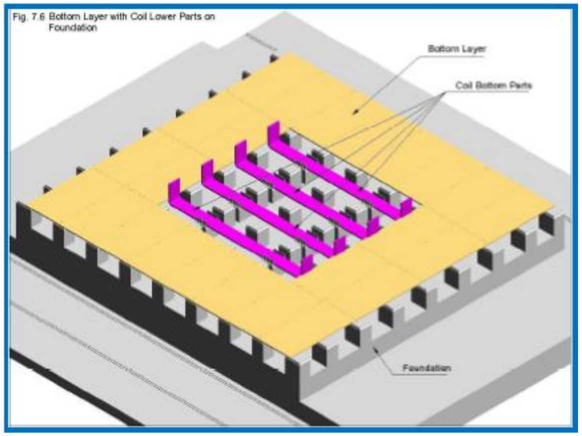


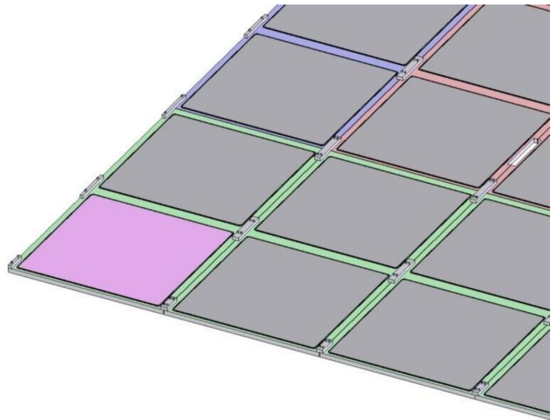


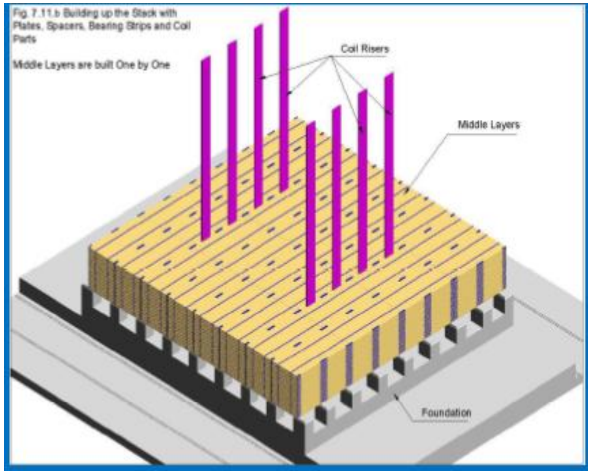
Hits and fitted points on a bent track for data taken with magnetic field ON condition

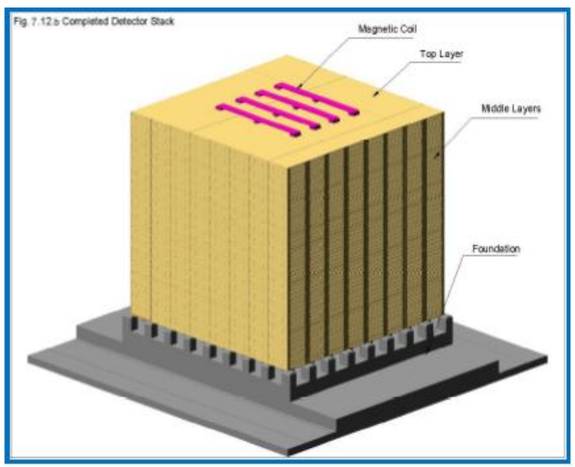
Next: 800 ton Engineering poto-type module (8mX8mx20 layers; 400 RPCs).

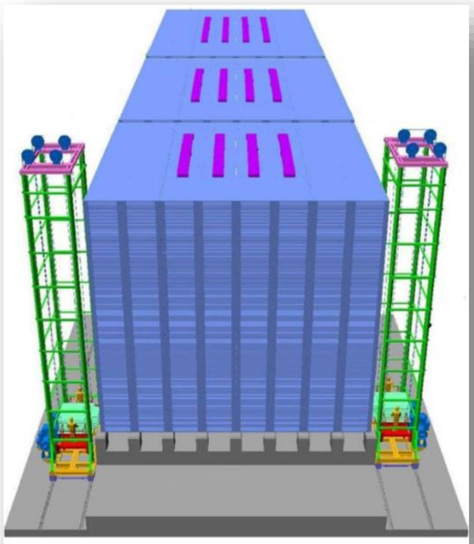
Construction of ICAL Magnet

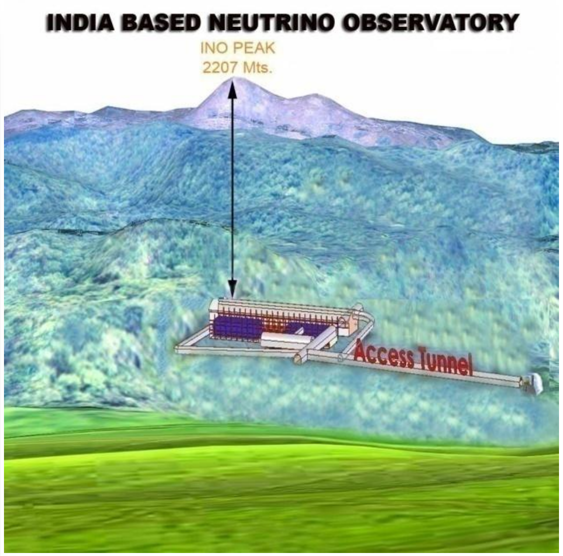












Concepts from DPR prepared by TCE

Summary - Current Status

Pre-project activities were started with an initial grant of USD ~ 10 Million
Infrastructure development of the Site
Development of IICHEP at Madurai (110 km from INO lab)
Detector R & D is now complete; DPR for Detector is ready

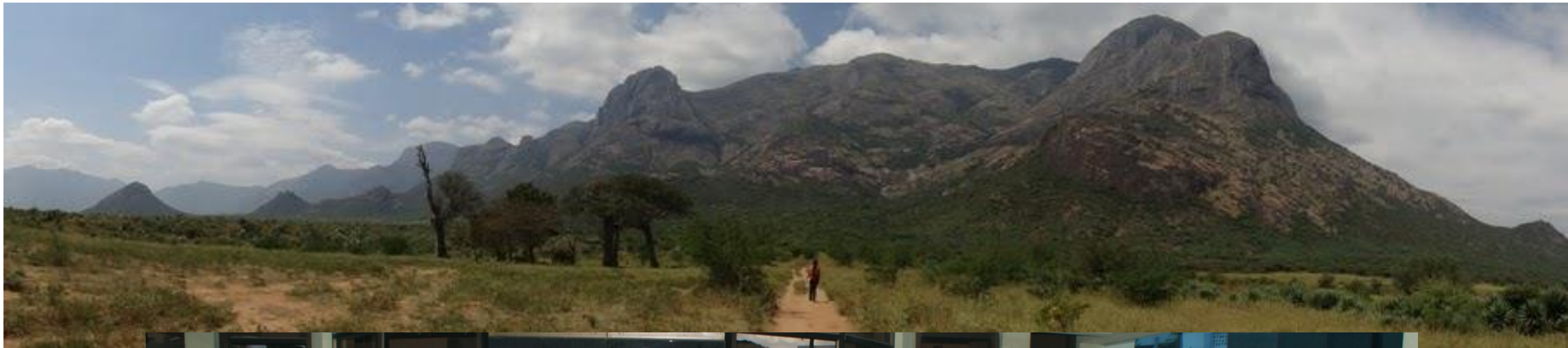
DPR for DAQ system is getting ready
Industrial production of RPCs and associated electronics to start soon
Geo-technical survey for construction of tunnel & cavern to start

Construction of engineering prototype module at Madurai (in surface lab), to test all aspects of construction of detector, efficiency of industrially produced RPCs apart from physics studies, logistics of operation.

Full project was approved the funding agencies,(~250M$) got the clearance in the beginning of this year (2015) from the central government for disbursing the funds and start construction

We have a strong physics programme , all eager to begin.
Hopefully, by 2020 detector should be operational at the site.

Thank You



Collaborators are welcome
http://www.ino.tifr.res.in/ino