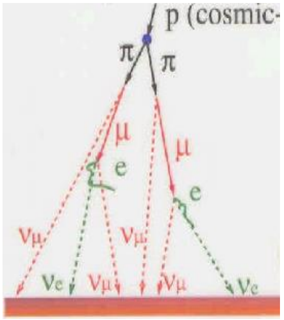
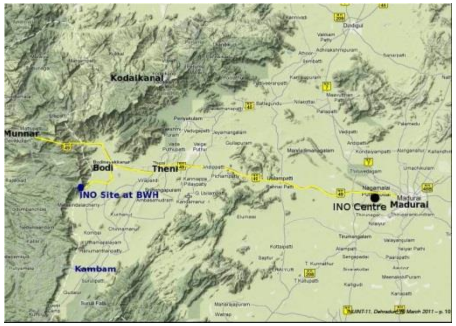
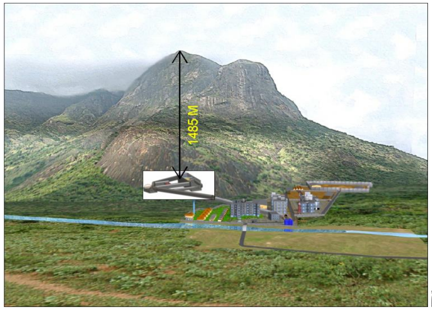
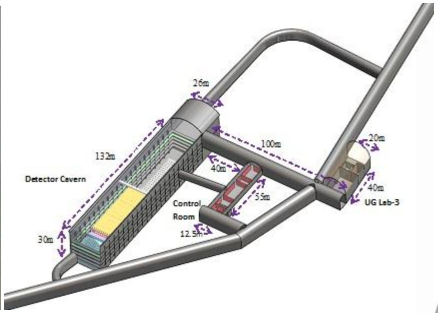
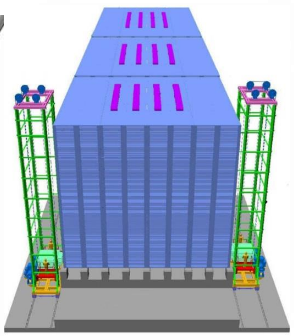
Status and perspectives of India based neutrino observatory (INO)









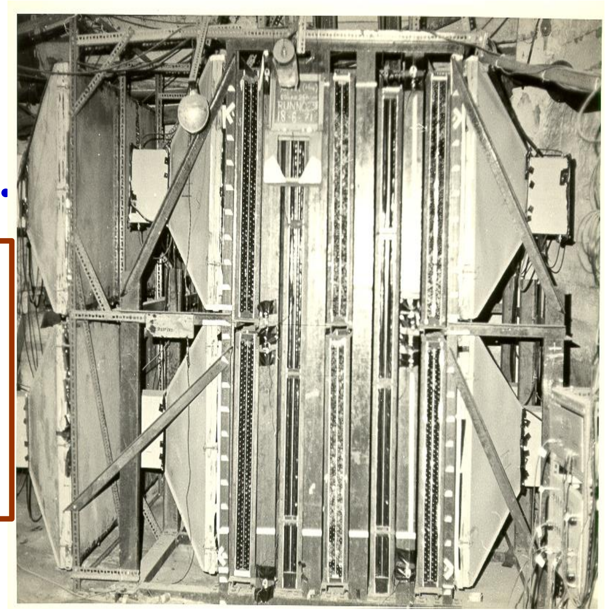


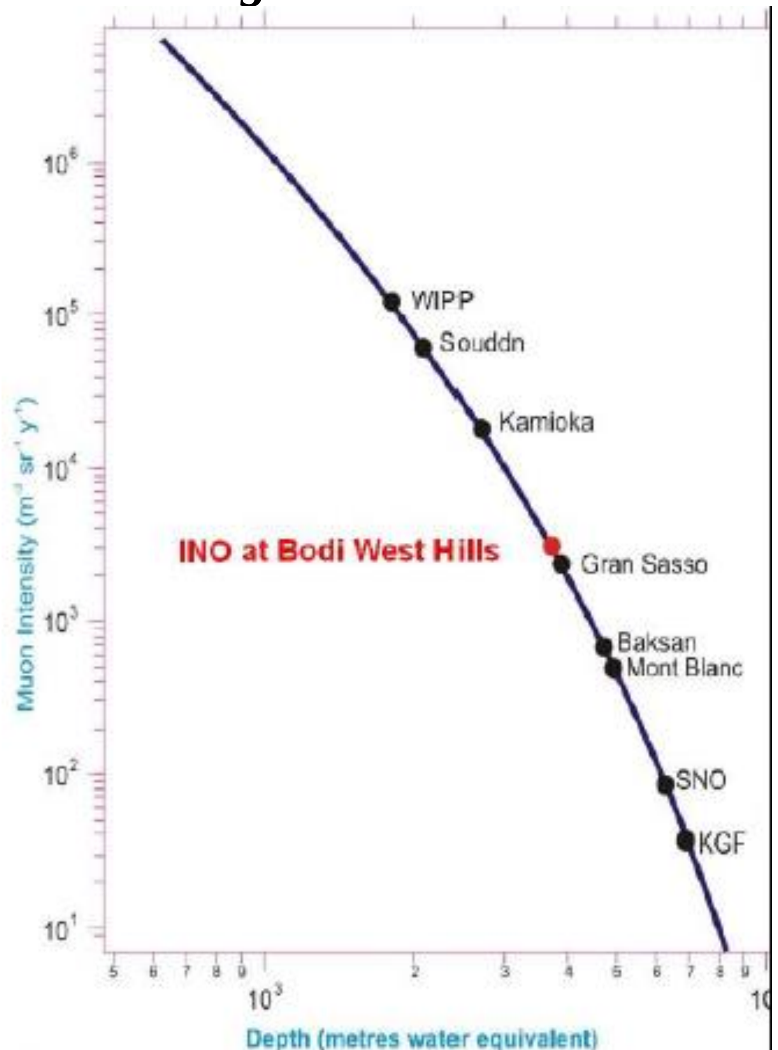
- Create experimental facility in the country where we can carry out front ranking experiments in the field of particle & astroparticle physics.
- Underground laboratory with ~1 km all-round rock cover accessed through a 2 km long tunnel. A large and several smaller caverns to facilitate many experimental programmes.
- 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 mass ordering.
- Will support several other experiments when operational. Neutrino-less Double Beta Decay and Dark Matter Search experiments foreseen in the immediate future.
- Open to International participation

First atmospheric neutrino was reported from Kolar Gold Field (KGF) at a depth of 2.3km way back in 1965 by the TIFR-Osaka-Durham group

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

- **We had a long tradition of carrying out experiments deep underground.**
- **KGF laboratory was the deepest underground laboratory during the period 1951-1992.**
- **KGF by TIFR-Osaka collaboration to look for proton decay.**
- **KGF mines closed its operation in 1992.**





~30 muon /year/m^2/sr at KGF, increased by a factor of ~100 at INO

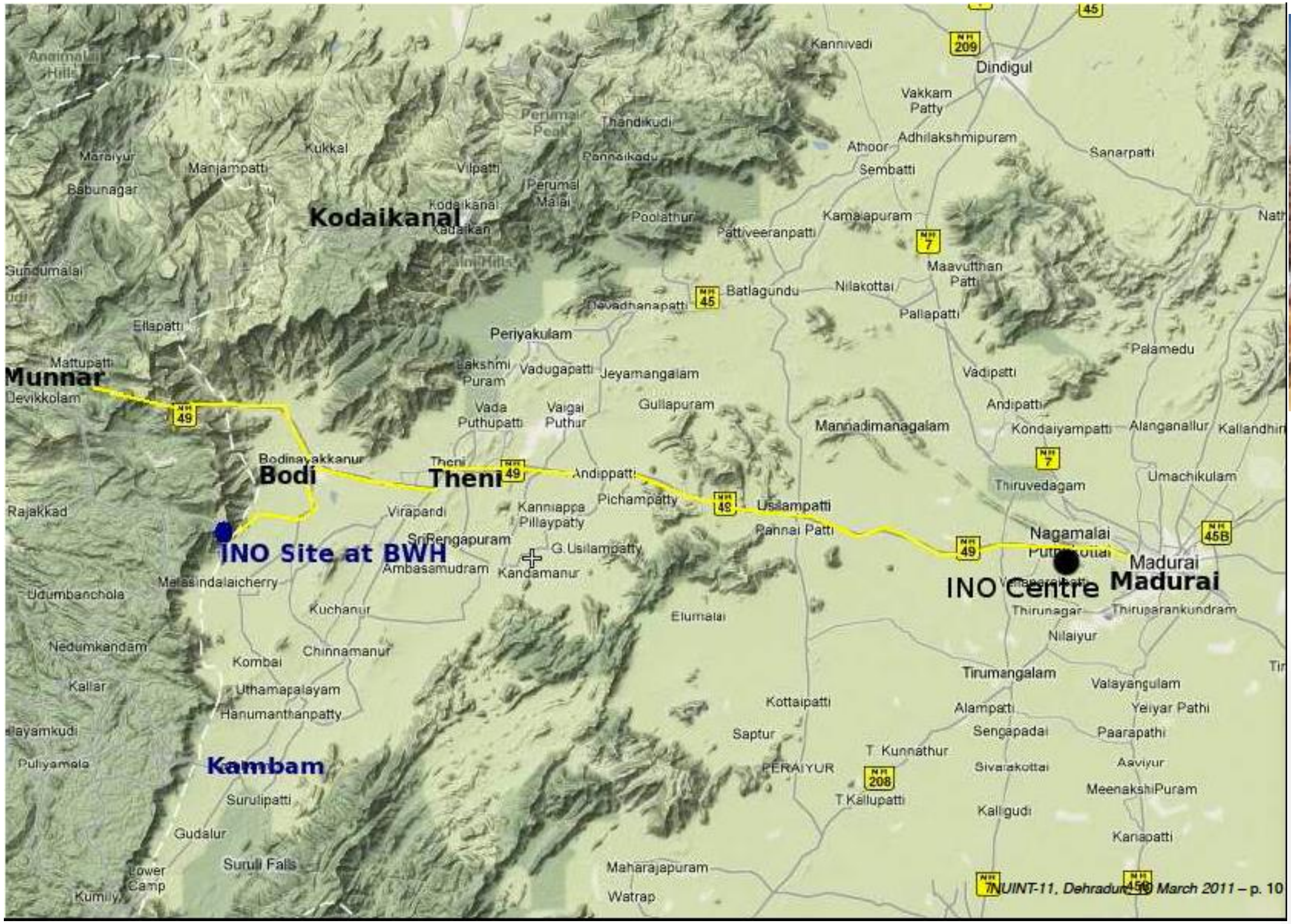
INO Collaboration

Ahmadabad: Physical Research Laboratory
Aligarh: Aligarh Muslim University
Allahabad: HRI
Bhubaneswar: IoP, Utkal University
Calicut: University of Calicut
Chandigarh: Panjab University
Chennai: IIT-Madras, IMSc
Delhi: University of Delhi
Kalpakkam: IGCAR
Kolkata: SINP, VECC, University of Calcutta
Lucknow: Lucknow University
Madurai: American College
Mumbai: BARC, IIT-Bombay, TIFR, CMEMS
Mysore: University of Mysore
Srinagar: University of Kashmir
Varanasi: Banaras Hindu University

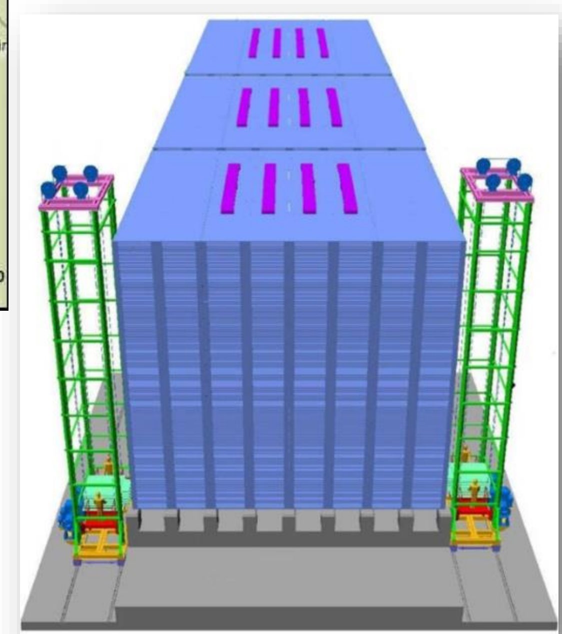
Nearly 100 scientists from 23 research institutes & universities all over India

One of the largest basic science projects in India in terms of man power and money

INO site : Bodi West Hills



~115 km from temple town Madurai



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

Warm, low rainfall area, low humidity throughout the year

Physics goal for a large mass detector with charge identification capability

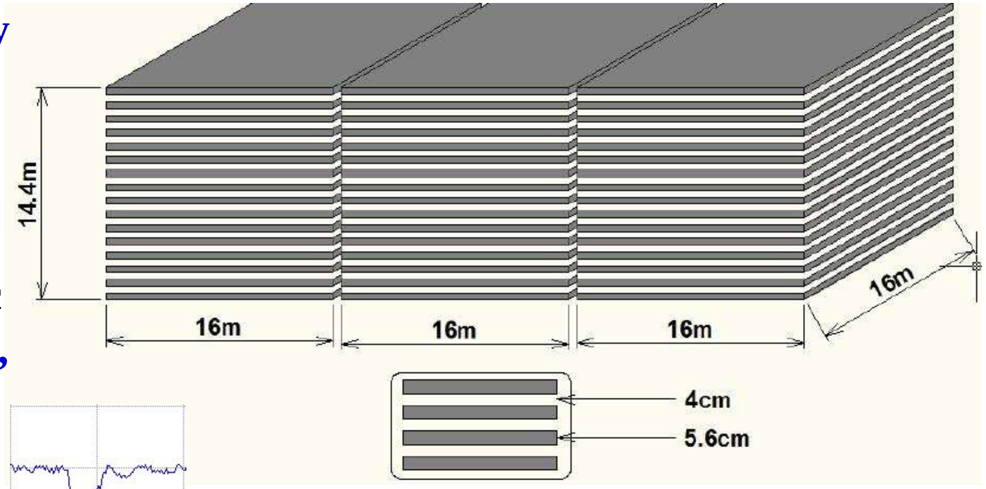
- Reconfirm atmospheric neutrino oscillation
- Improved measurement of oscillation parameters
- Search for potential matter effect in neutrino oscillation.
- Determining the sign of Δm^2_{23} using matter effect
- Measuring deviation from maximal mixing and octant of θ_{23}
- Probing Lorentz and CPT violation.
- Ultra high energy muons.
- ………………………..

Physics goals to be complementary to other experiments worldwide. There is a growing realization that both atmospheric and accelerator experiments are needed to obtain best values of the parameters.

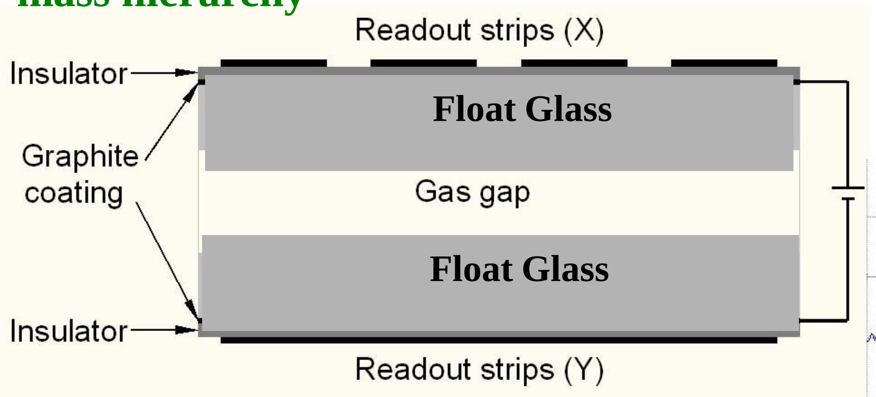
- **Accelerators : narrow range of L,E; high precision**
- **Atmospheric : Large range of L,E, not-so-high precision**

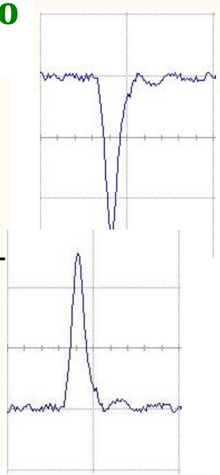
INO-ICAL detector

Fast and precise timing information to identify up-down ambiguity of muon: RPC is a the best choice to have 1ns precision with low cost



3cm strip pitch & strip multiplicity : ~5mm position resolution (along with ~1.3T magnetic filed) to identify bending of +ve and –ve muon, very crucial for the determination of neutrino mass hierarchy





- Total number of RPCs in the ICAL = 3 × 150 × 64 = 28,800
- Total gas volume = 28,800 × 190cm × 190cm × 0.2cm ~ 200 m^3
- Total surface area = 28,800 × 1.9m × 1.9m ~ 10^5 m^2
- Standard gas composition for the avalanche mode:
  - Freon, R134a($C_2H_2F_4$):Isobutane(i-C_4H_{10}):Sulphur Hexafluoride(SF_6)::95.5:4.3:0.2

INO-ICAL Detector

Parameter	ICAL	ICAL-Engineering module
No. of modules	3	1
Module dimensions	16.2m × 16m × 14.5m	8m × 8m × 2m
Detector dimensions	49m × 16m × 14.5m	8m × 8m × 2m
No. of layers	150	20
Iron plate thickness	56mm	56mm
Gap for RPC trays	40mm	40mm
Magnetic field	1.3Tesla	1.3Tesla
RPC dimensions	1950mm × 1910mm × 30mm	1950mm × 1910mm × 30mm
Readout strip pitch	30mm	30mm
No. of RPCs/Road/Layer	8	4
No. of Roads/Layer/Module	8	4
No. of RPC units/Layer	192	16
No. of RPC units	28,800 (107,266m^2)	320 (1,192m^2)
No. of readout strips	3,686,400	40,960

A journey through RPC road

Started with
10 cm × 30 cm Glass
RPC in Streamer mode

200 cm × 200 cm

30 cm × 30 cm

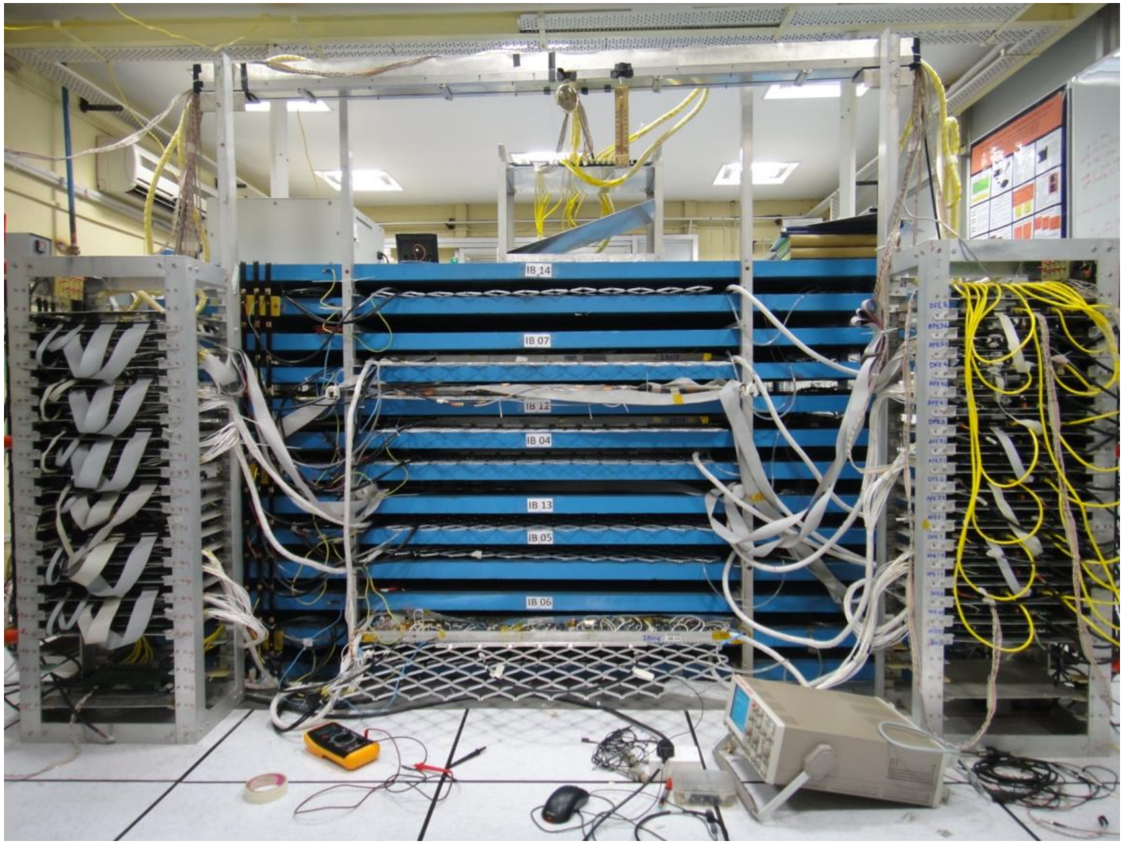
10 cm × 30 cm

100 cm × 100 cm

Now with 200 cm × 200 cm Glass RPC in Avalanche mode

Prototype Magnet & RPC setup

500AT : ~1.5 Tesla



- 35 Ton prototype with 12 gaps to house 1m × 1m RPCs
- Long term operational experience
- Operate both glass & bakelite RPCs
- Reconstructed muon track with & without magnetic fields.
- Stability & suitability of LV, HV & electronics.
- Lab environmental condition.

Running Prototype RPC Stack at TIFR

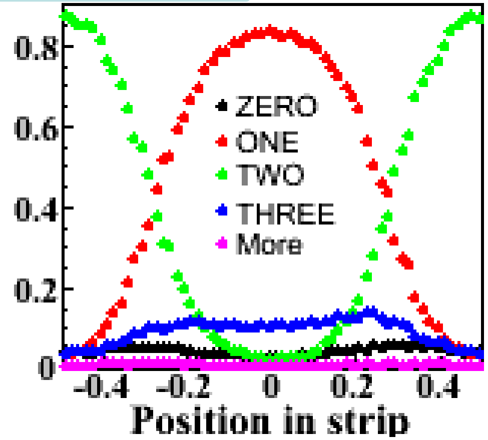
Operational since last six years

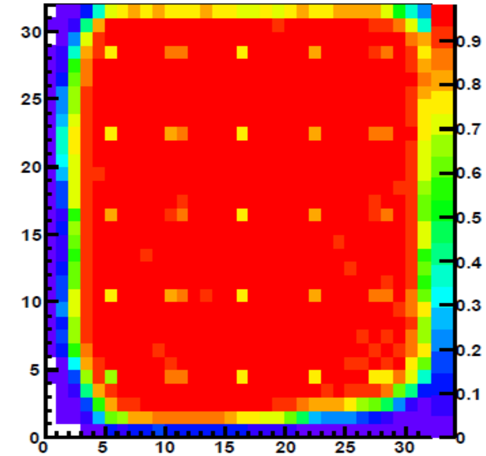
Now this system is used for developing/testing of ICAL electronics
Understood all aspects of RPC Gas gap and its signal, resolution, alignment/offset

Running Prototype RPC Stack at TIFR

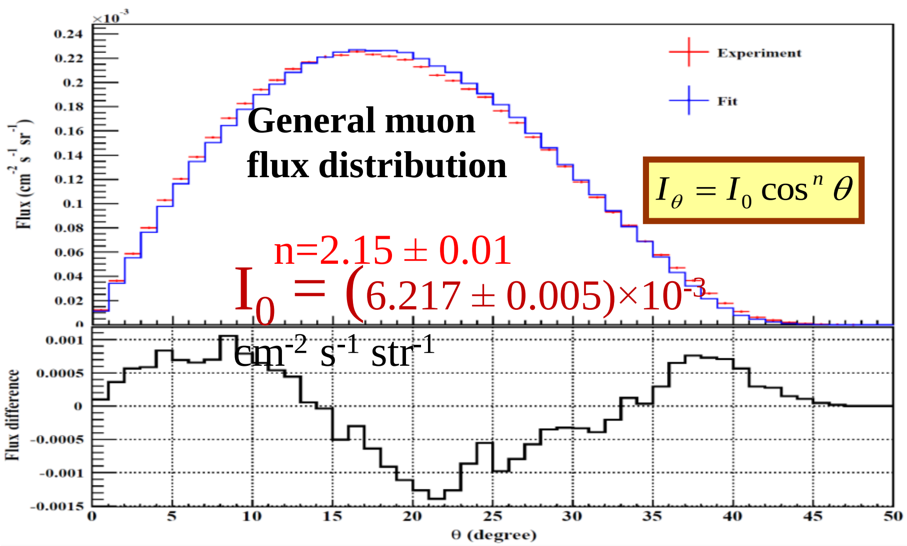
Multiplicity and position

Inefficiency due to button, dead strip, but edge effect also present

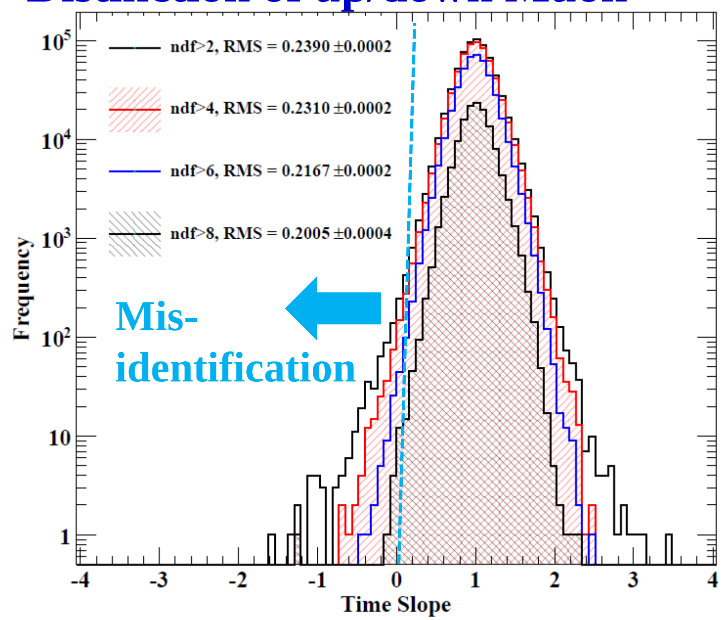




Zenith angle of muon, measurement of cosmic muon flux as well as it angular dependency

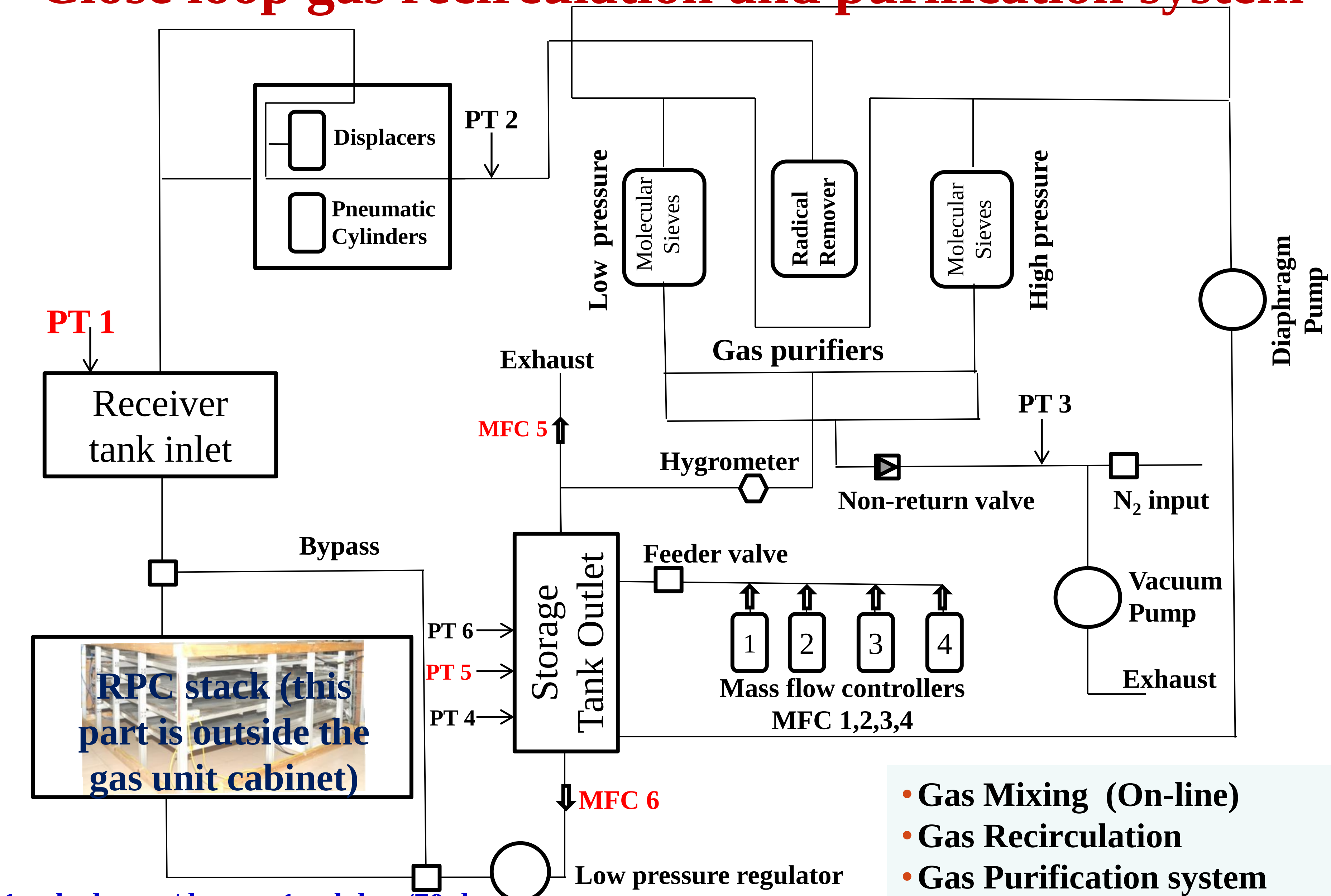


Distinction of up/down Muon



Input to detector simulation and digitisation

Close loop gas recirculation and purification system

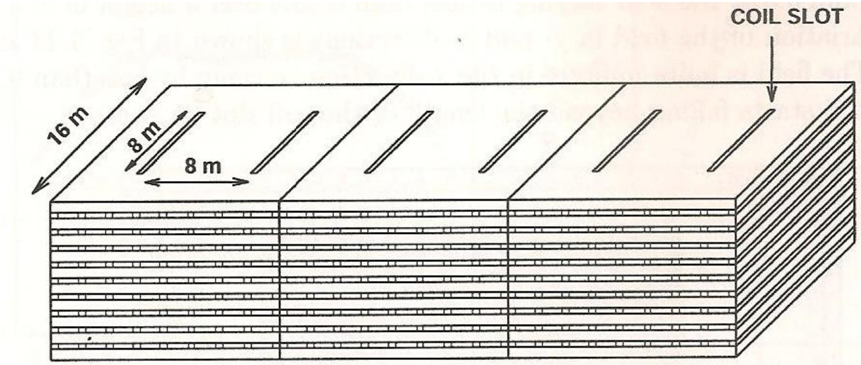


1 vol. change/day 1 vol. loss/70 days

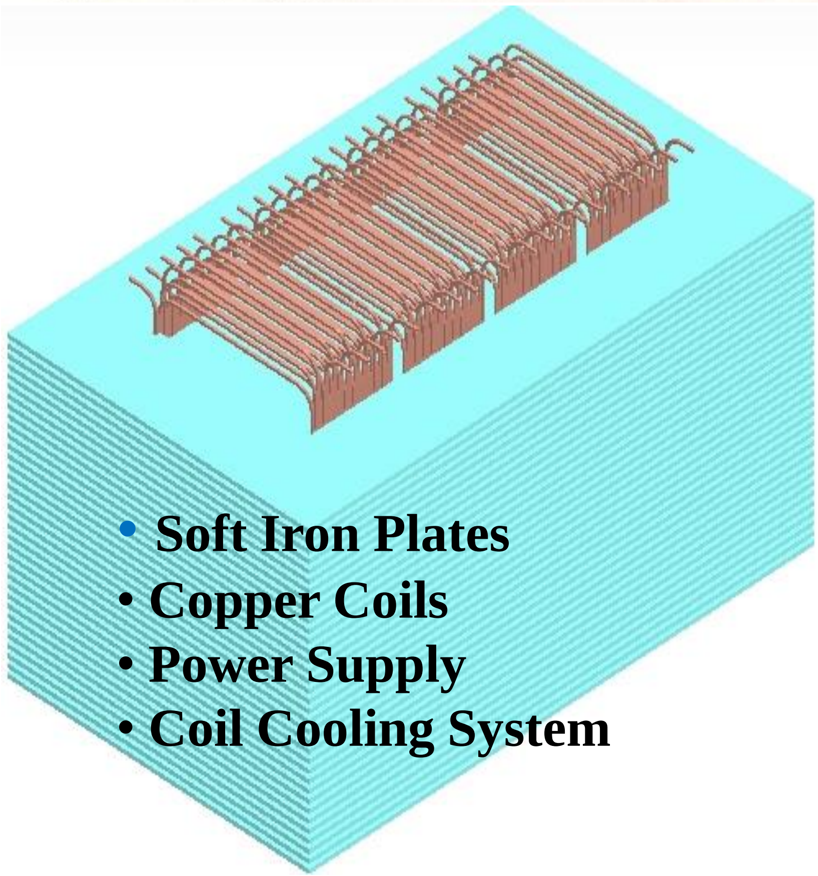
Automated pressure control, 1-3mbar above atm

- Gas Mixing (On-line)
- Gas Recirculation
- Gas Purification system
- Control System (PLC)

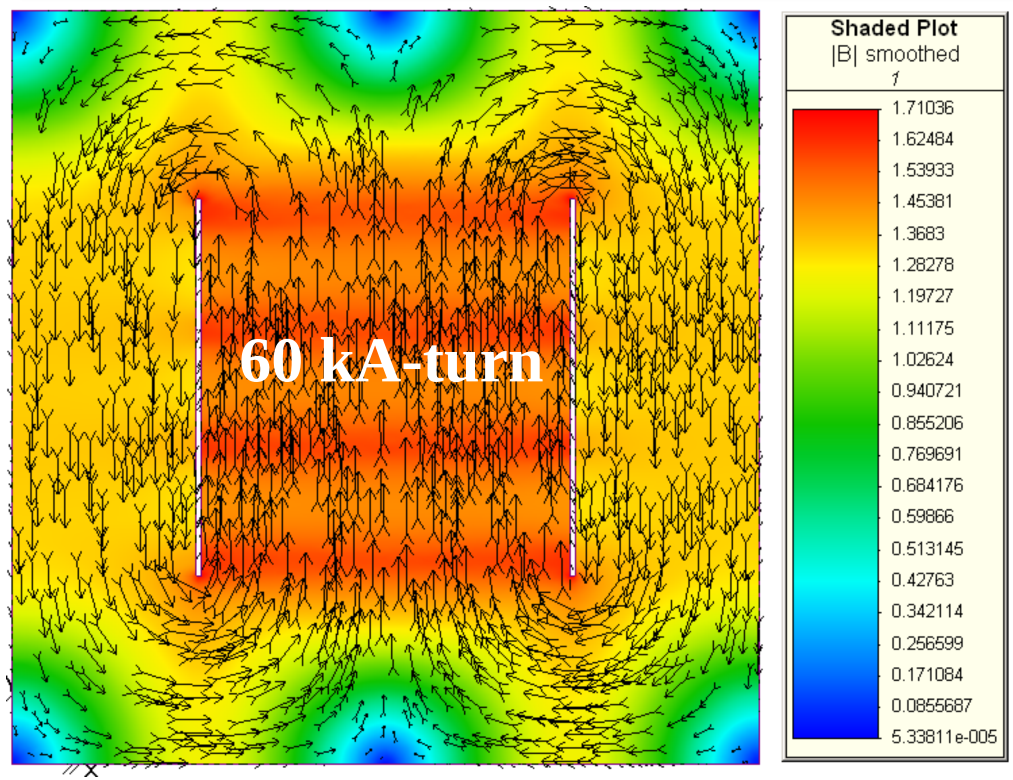
Magnet design



ICAL MAGNET QTY - 3
Size :- 16(L) × 16(W) × 15(H) meter
COIL SIZE :- 15m x 8m
Ampere-Turn :- 80,000 AT
Max. Design Value:- 100,000 AT
Max. Power requirements in each magnet:- <150KW (Coils & Power Supply)
Each coil gap = 1300mm x 80 mm



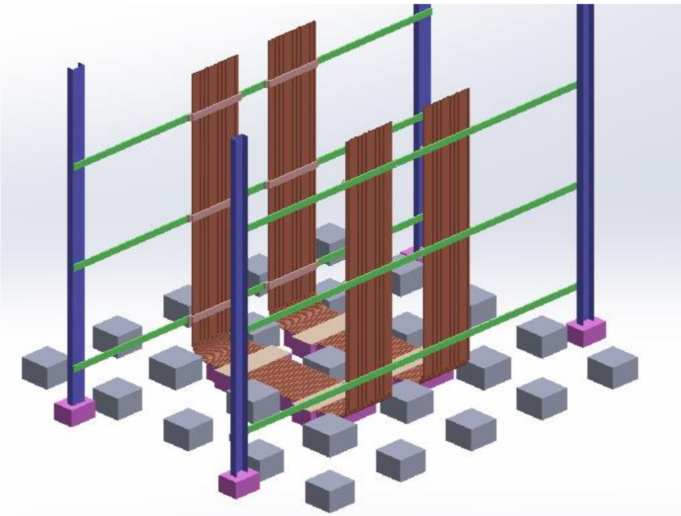
- **Soft Iron Plates**
- **Copper Coils**
- **Power Supply**
- **Coil Cooling System**

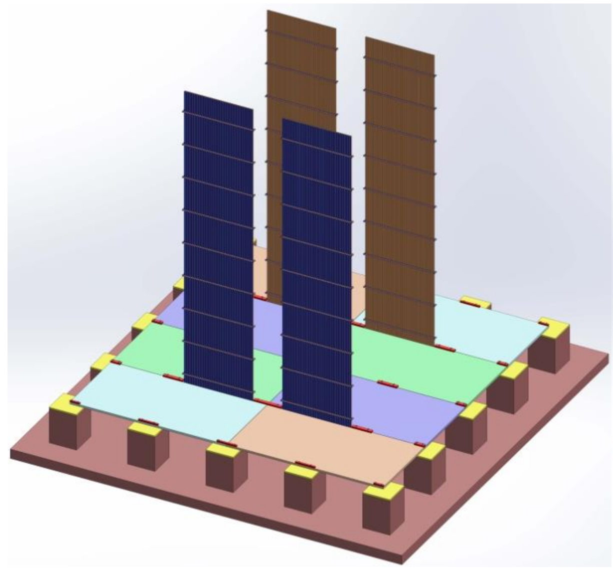


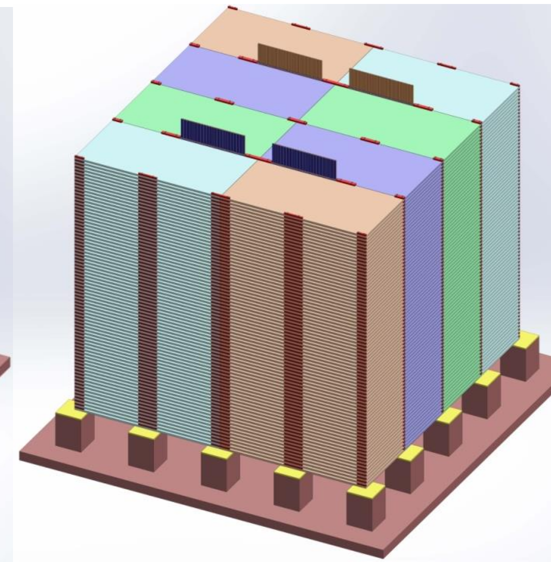
$20 \times 8 \times 8$ Prototype at Madurai

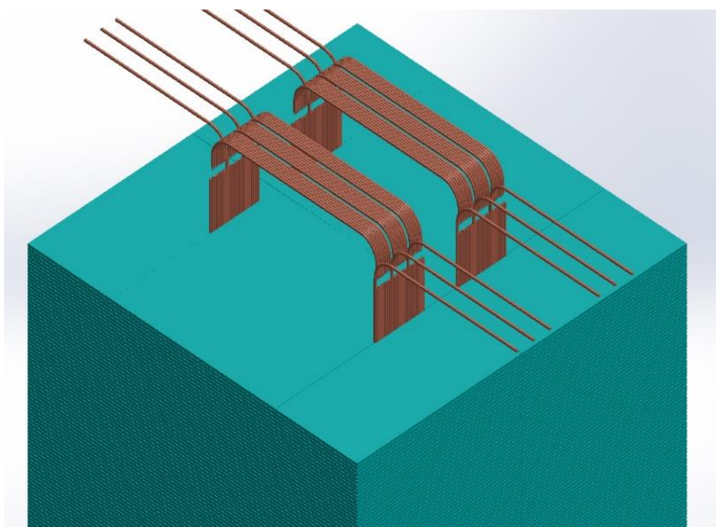
Mini ICAL to build and commission at ICHEP within 2.5 year

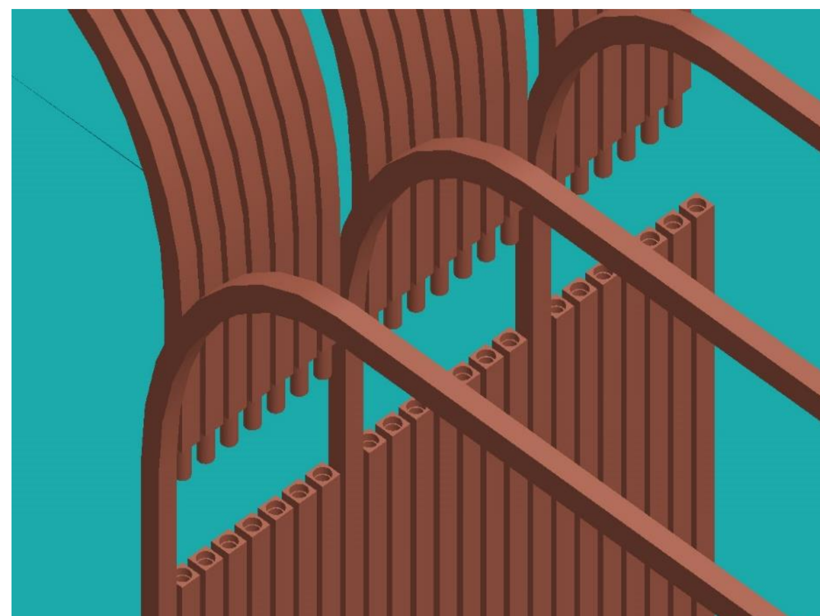
Only 20 layers of RPC







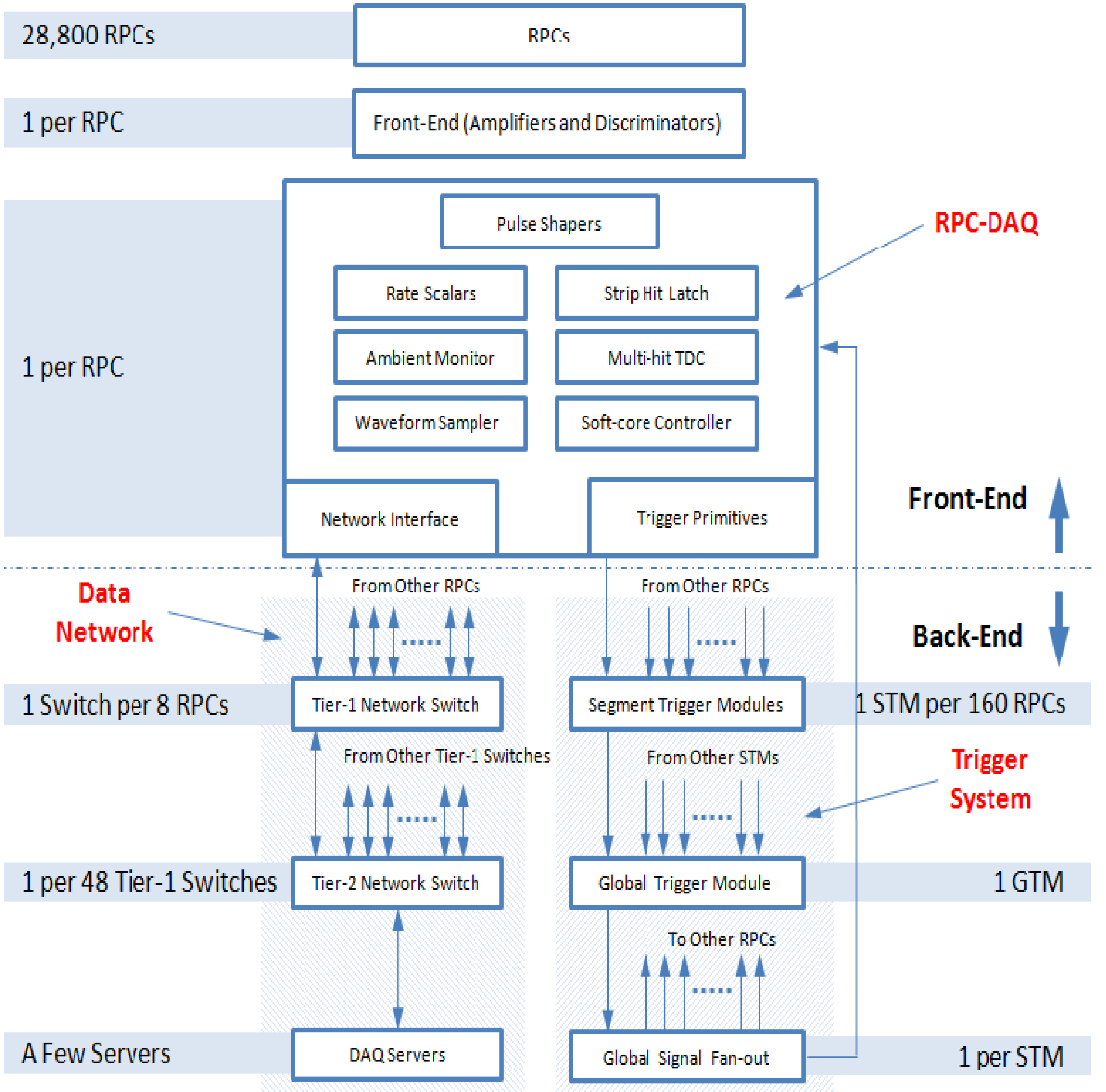




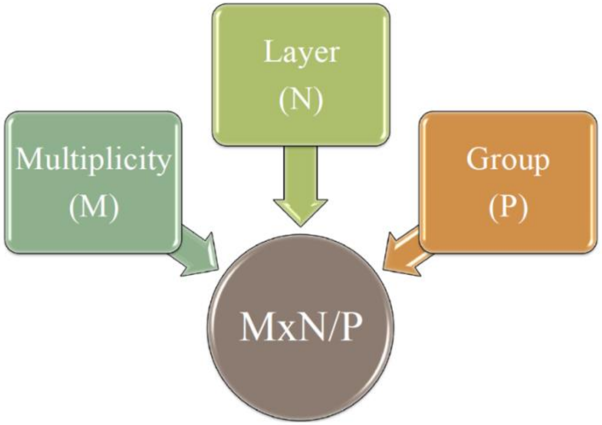
Electronics system for ICAL

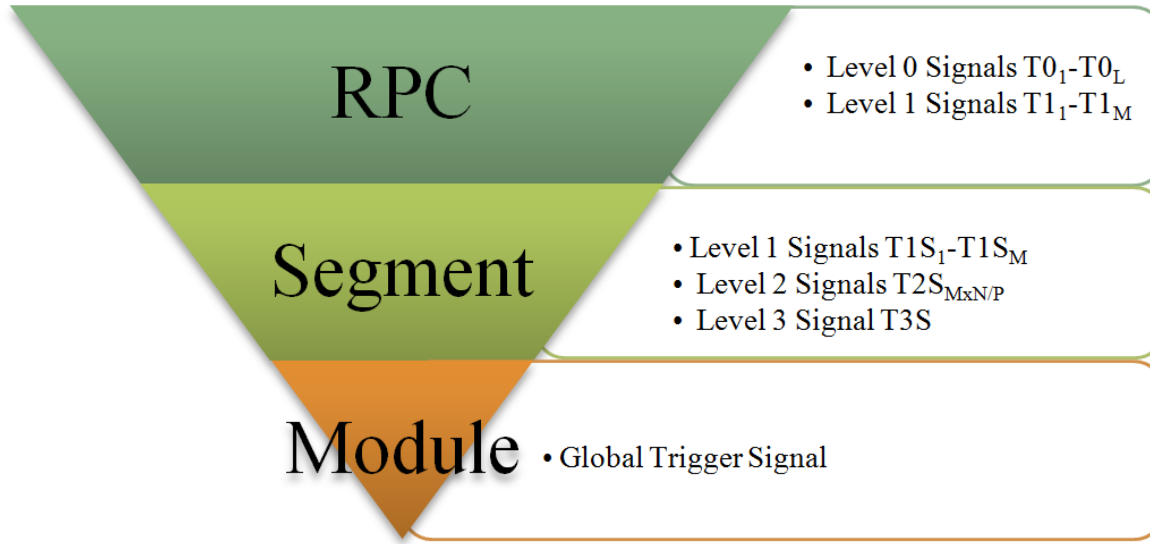
Major elements

- Front-end board
- RPCDAQ board
- Segment Trigger Module
- Global Trigger Module
- Global Trigger Driver
- Tier1 Network Switch
- Tier2 Network Switch
- DAQ Server
- VLSI, FPGA and ASIC chips; high density connectors

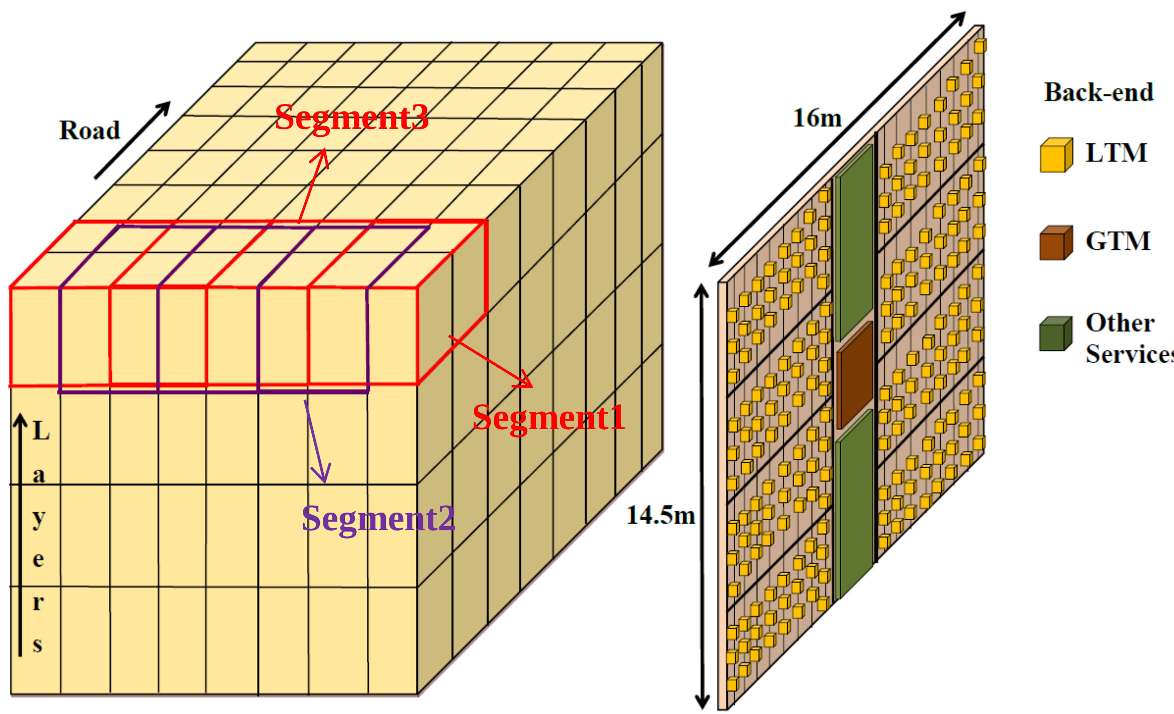


ICAL Trigger Scheme





- **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.**



Detector simulation and event reconstruction

GENIE : modified
3D neutrino flux,
Weighted evt

Neutrino Event Generation

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

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

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

GEANT

Event Simulation

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

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

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

Event Digitisation

(x,y,z,t) of A + B + ... + noise + detector efficiency + time resolution **from operational RPC in Mumbai**

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

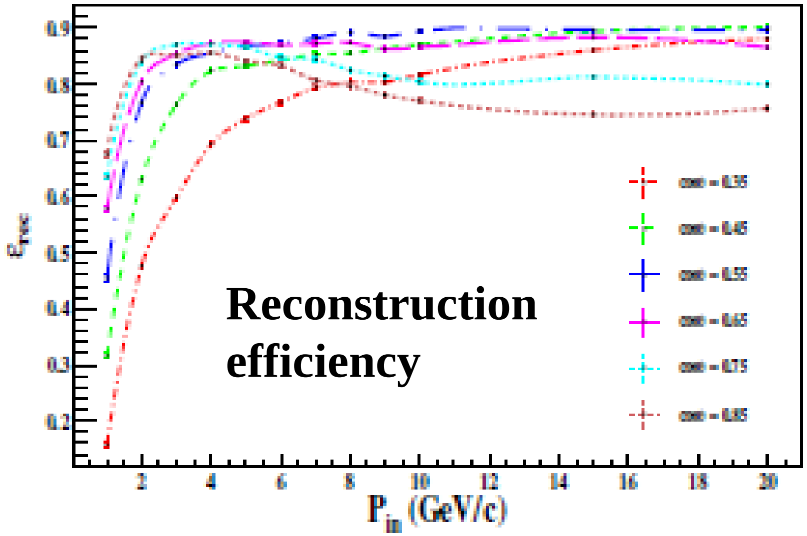
Event Reconstruction

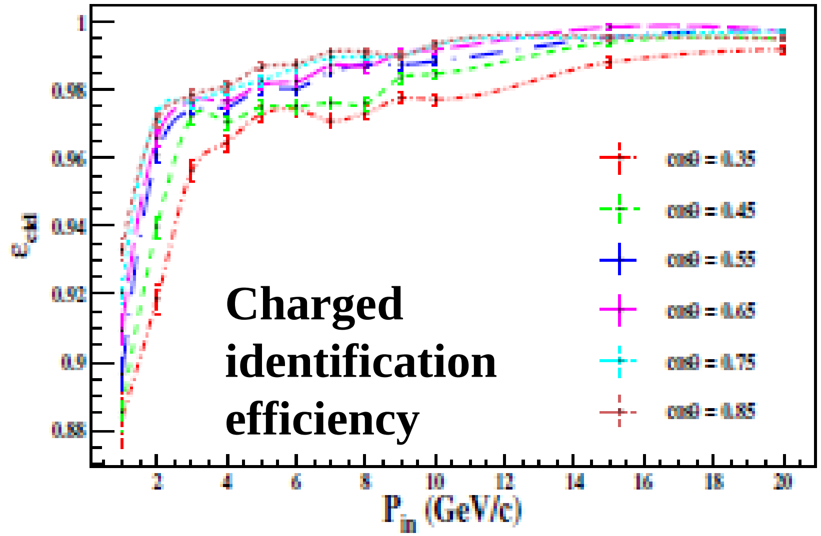
(E,p) of v + X = (E,p) of A + B + ...

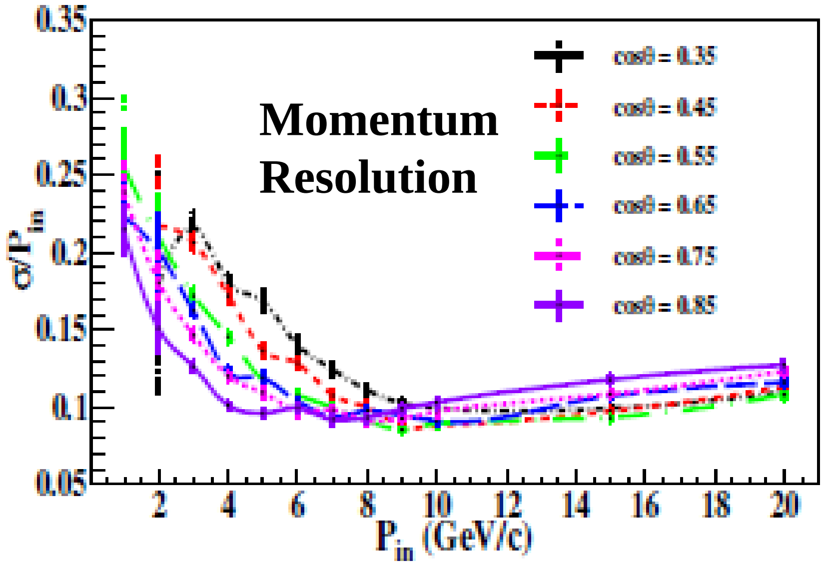
Fit the tracks of A + B + ... to get their energy and momentum.

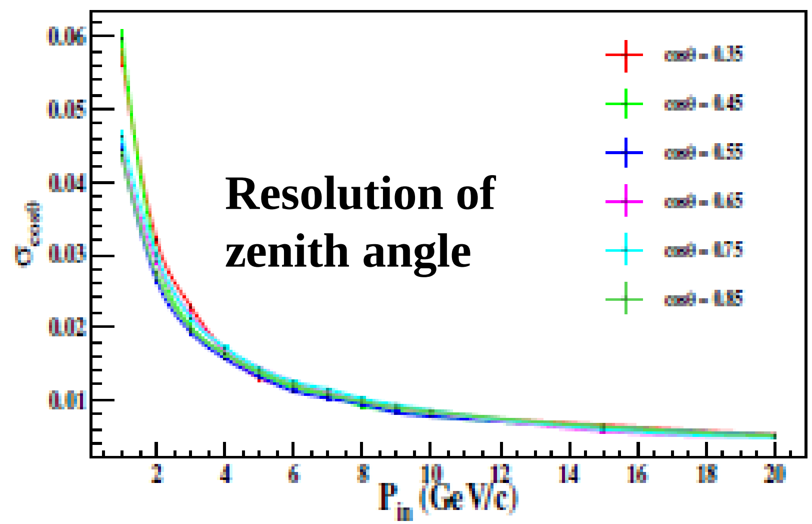
Output:
i) Energy & Momentum of the initial neutrino

ICAL detector performance : Muon



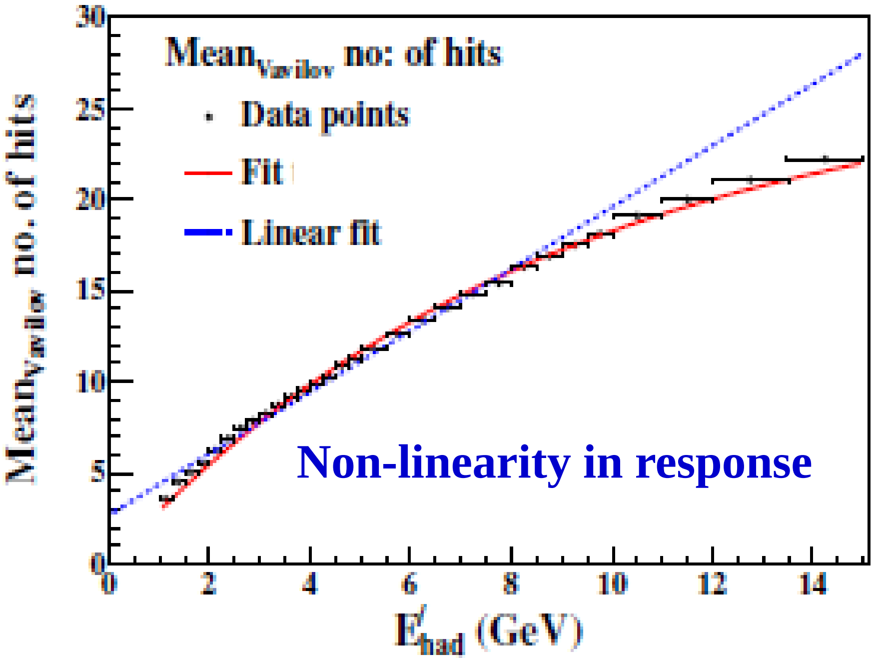


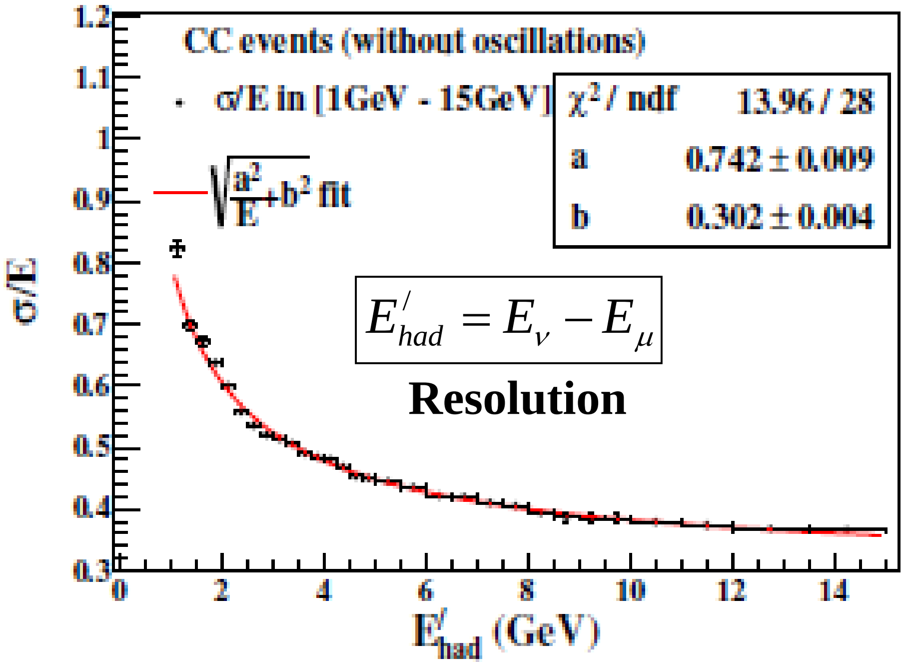




- **Fully contained event has better momentum resolution (upto 6% from pathlenght)**

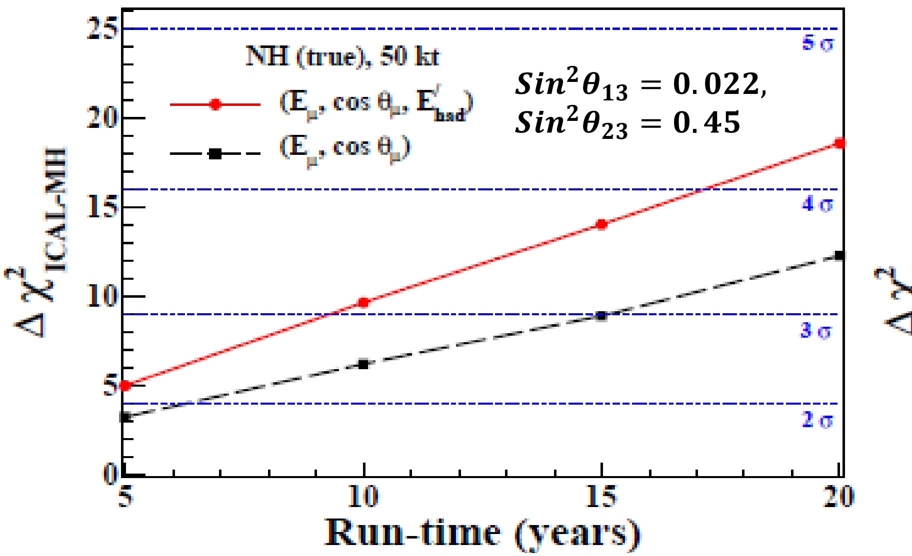
ICAL detector performance : Neutral

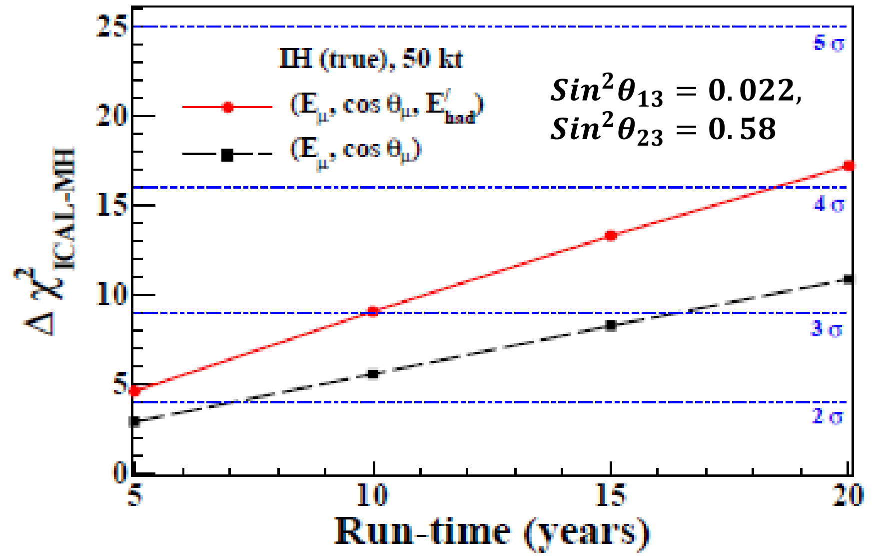


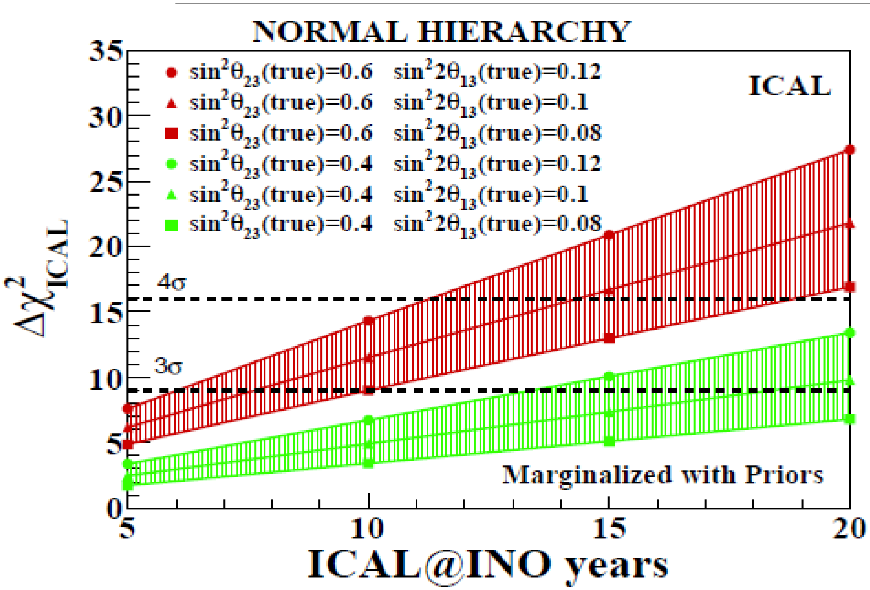


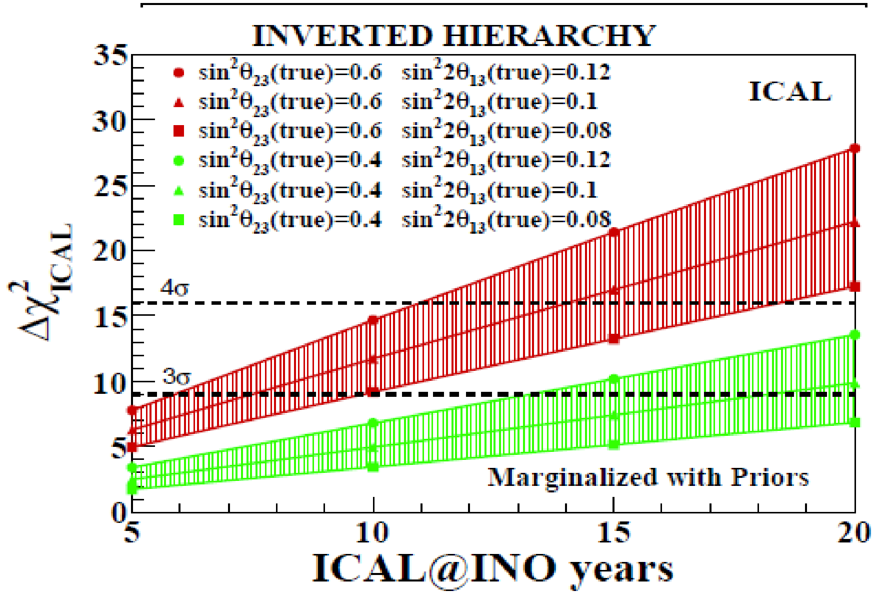
- **Momentum resolution is worse in neutral energy, which is expected.**
- **Neutrino physics analysis was done using only information of muon as well as combined information of muon and other neutral particles.**

Determination of neutrino mass hierarchy



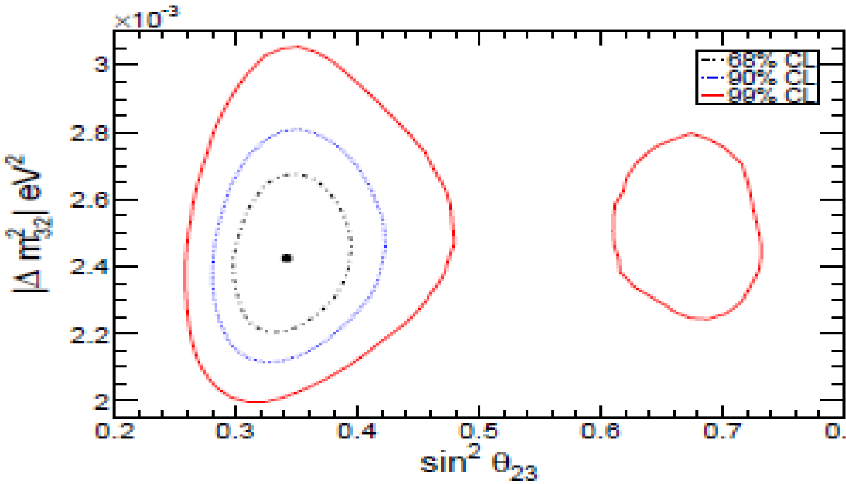




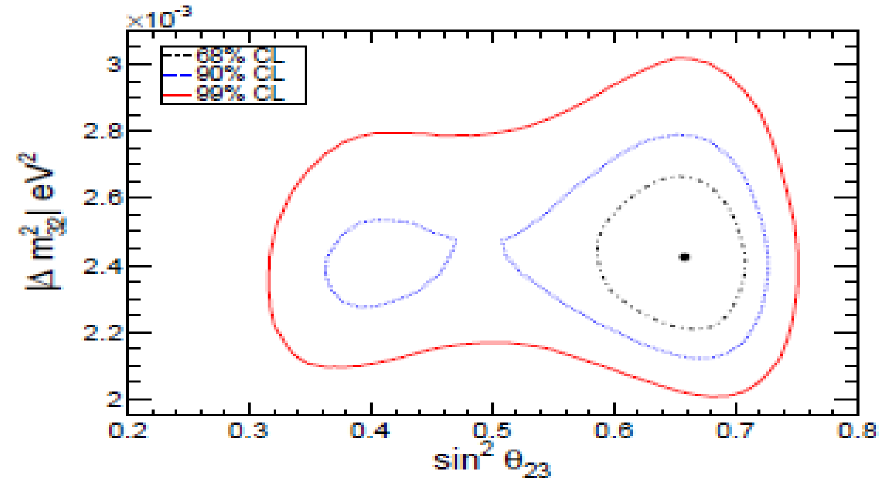


- **Hadronic information is added separately**
- **Larger value of $\sin^2\theta_{13}$, more confidence level/less year to have same CL**

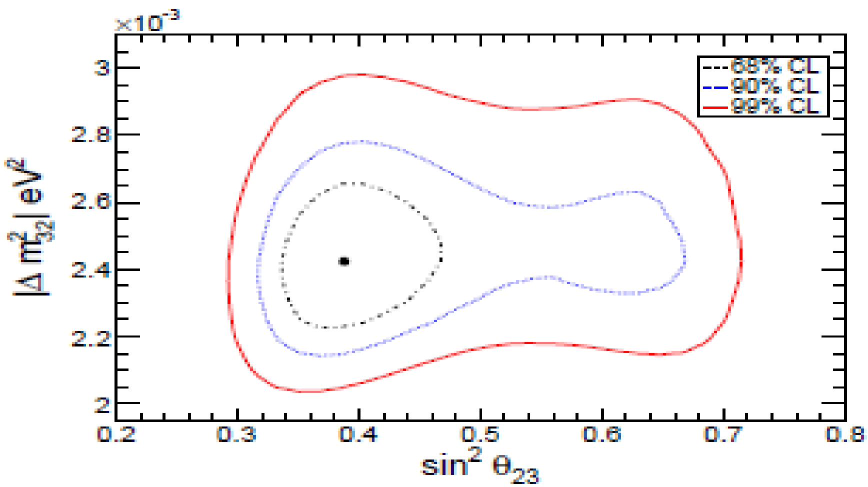
Octant of θ_{23}



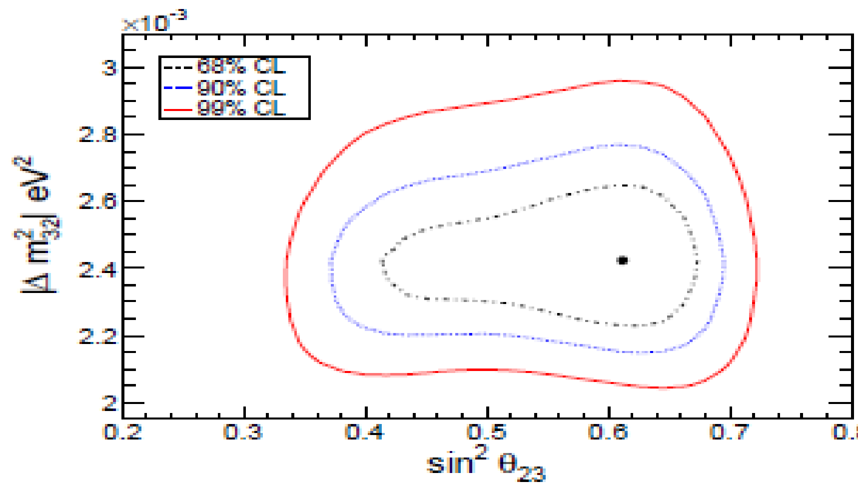
(a) $\sin^2 2\theta_{23} = 0.9$, first octant ($\sin^2\theta_{23} = 0.342$)



(b) $\sin^2 2\theta_{23} = 0.9$, second octant ($\sin^2\theta_{23} = 0.658$)



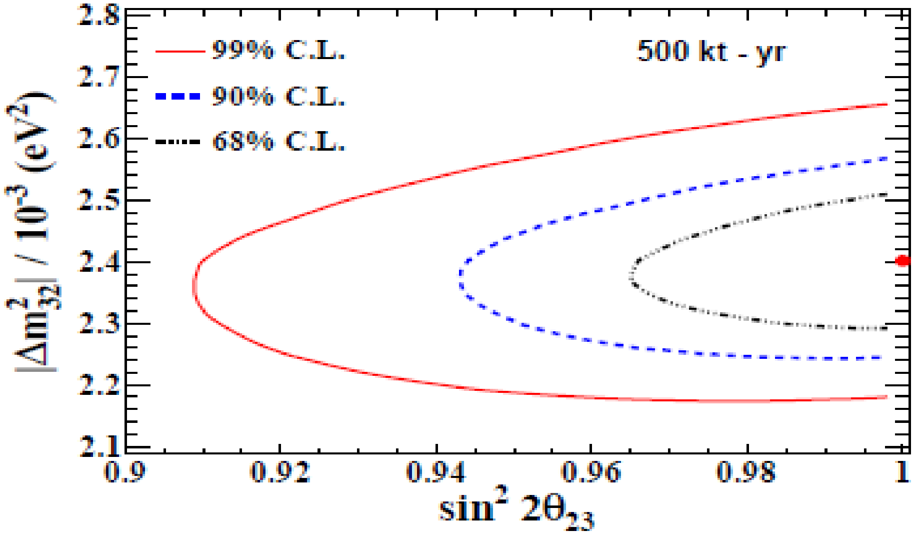
(c) $\sin^2 2\theta_{23} = 0.95$, first octant ($\sin^2\theta_{23} = 0.388$)

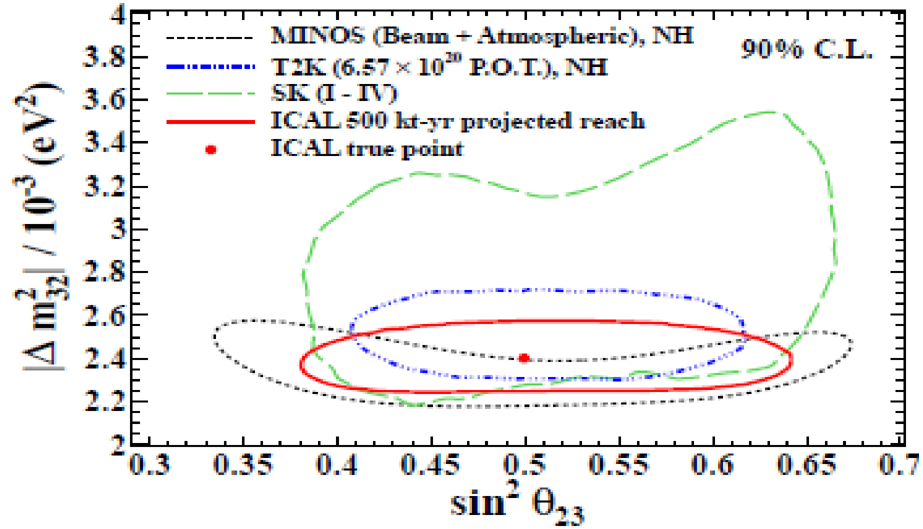


(d) $\sin^2 2\theta_{23} = 0.95$, second octant ($\sin^2\theta_{23} = 0.612$)

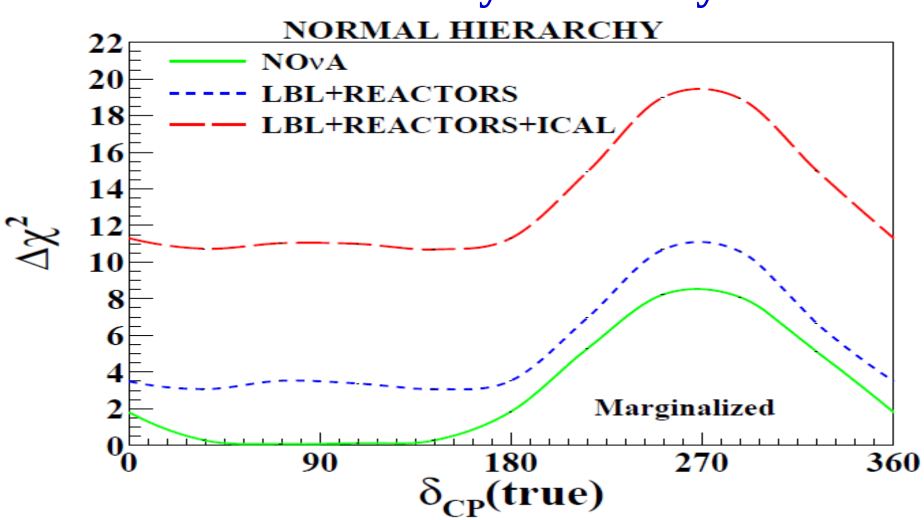
- **Identify the correct octant for lower value of $sin^2\theta_{23}$**
- **But certainly add values while combining result of NOνA and T2K**

Precision of neutrino mass matrix

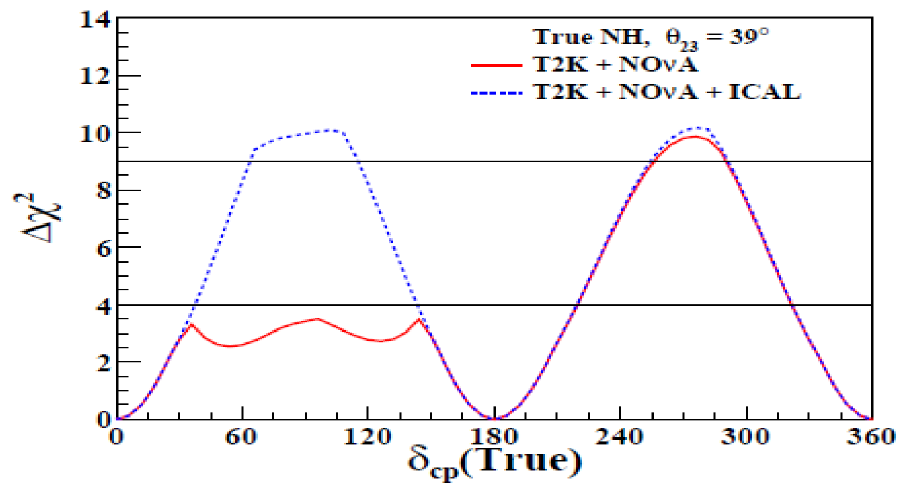




Mass hierarchy sensitivity

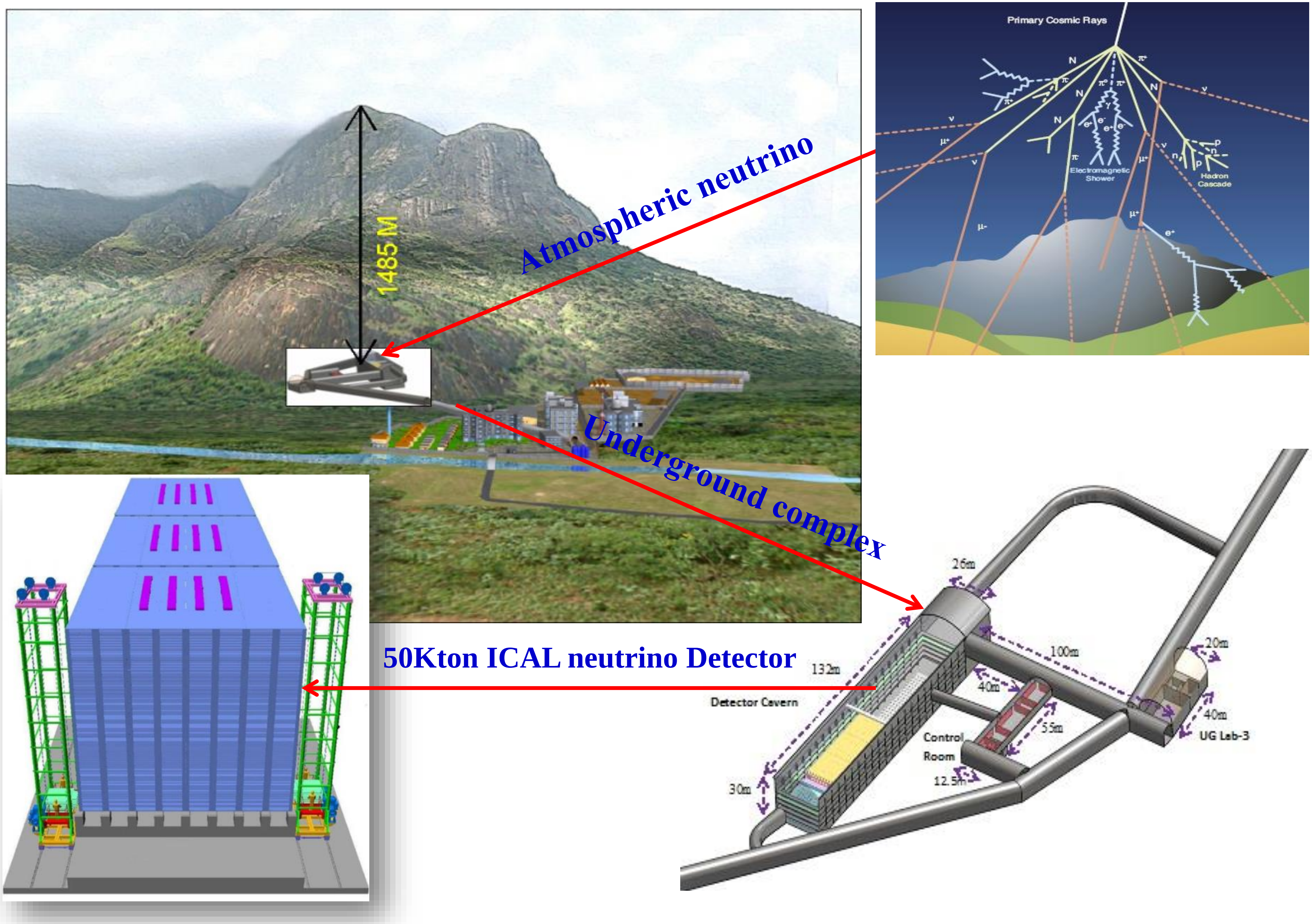


CPV discovery potential



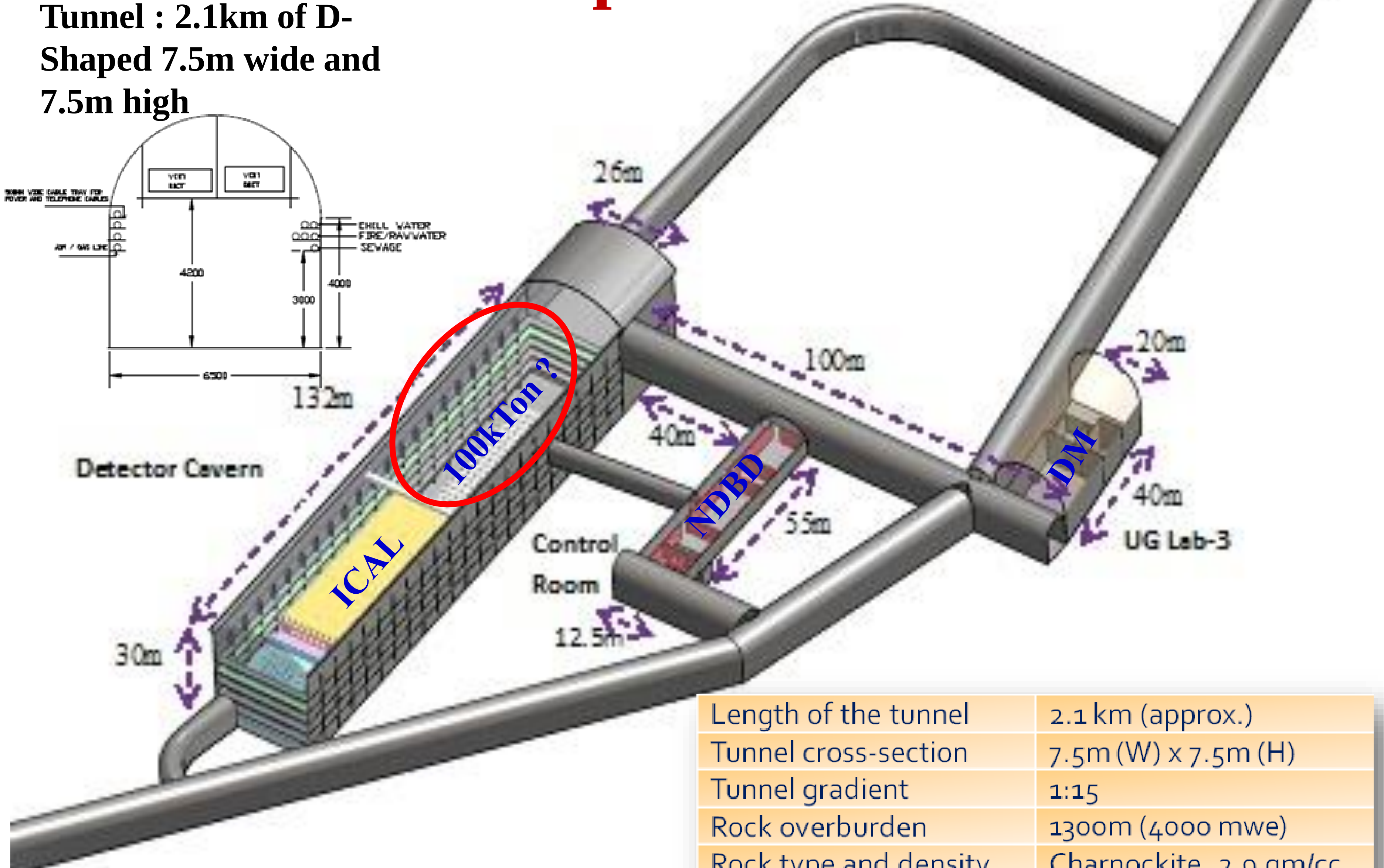
- **Hierarchy sensitivity of ICAL excludes the wrong-hierarchy minimum for the CPV discovery**
- **ICAL will play an important role to determine these parameter more precisely**

INO site at BodiHills



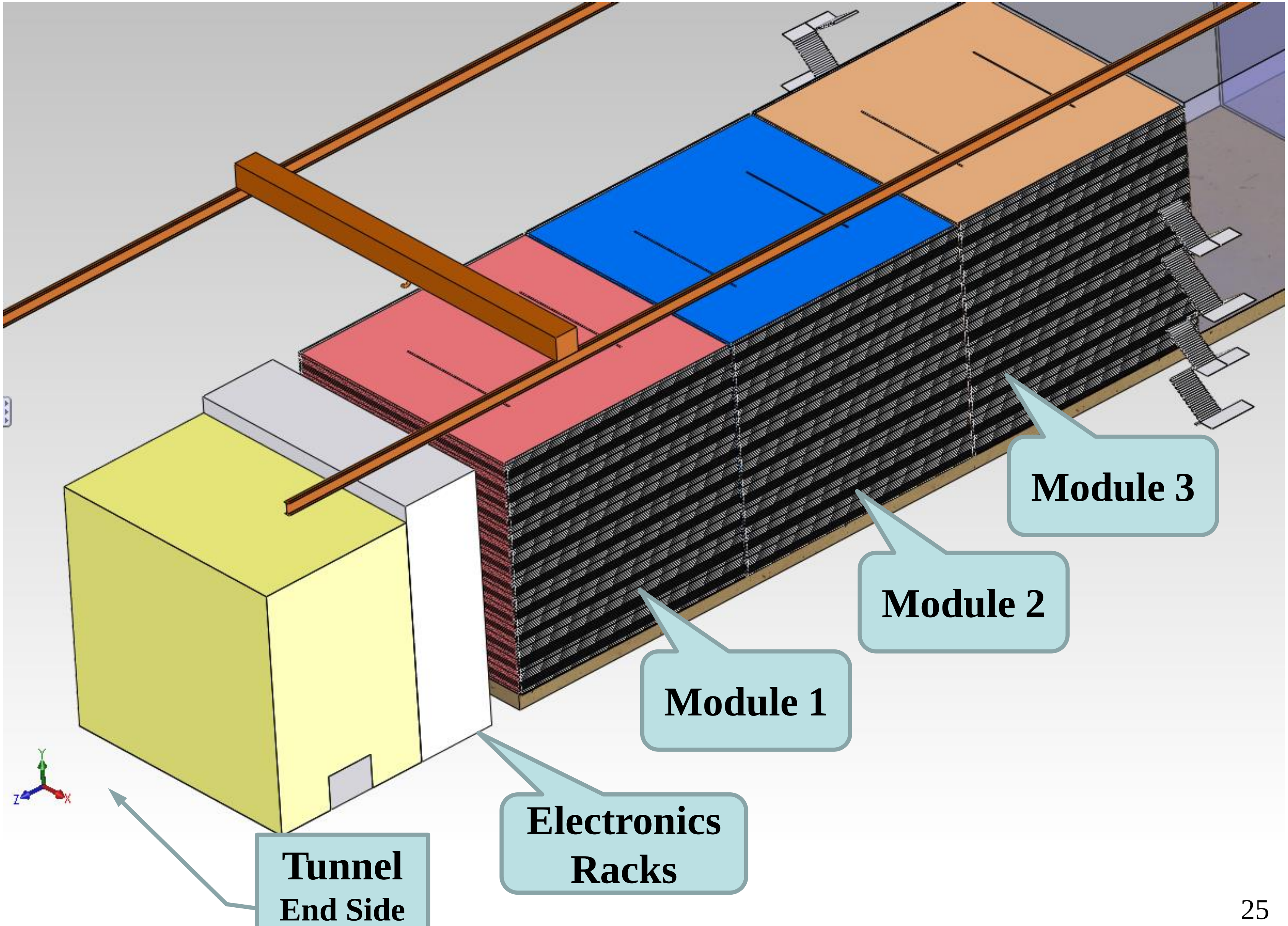
INO experimental hall

Tunnel : 2.1km of D-Shaped 7.5m wide and 7.5m high



Length of the tunnel	2.1 km (approx.)
Tunnel cross-section	7.5m (W) x 7.5m (H)
Tunnel gradient	1:15
Rock overburden	1300m (4000 mwe)
Rock type and density	Charnockite, 2.9 gm/cc
Number of caverns	3 (one big and two small)
Size of the main cavern	132m × 26m × 30m (H)

Under ground Lab : a Closer Look



Status of related activities@INO site

- **26.82.5 ha. of revenue land at Pottipuram village**
- **Civil Work – water, electricity, approach road has started**
- **Building for RPC test setup along with hostel/guest house, workshop, hostel**

Summary

- INO a well conceived project with pan-India presence of scientists.
- RPC as a choice for detector well suited and detector R&D matured for mass production.
- Electronics, DAQ, trigger etc, are in final stage of prototyping.
- Magnet : the 1/30 scale prototype work in progress, should be installed within 2 years.
- Simulation and physics studies in various stages of maturity, white paper is ready for submission.
- Expect construction of tunnel to begin by end of this year.
  - Tunnel and experimental hall : 3-4 years,
  - One module per year
- INO to be relevant to the world science in the coming decade.

Physics input in simulation

Parameter	Best-fit values	3σ ranges	Relative 1σ precision (in percent)
Δm^2_{21} (eV^2)	7.5×10^{-5}	$[7.0, 8.1] \times 10^{-5}$	$\sigma(\Delta m^2_{21}) = 2.4\%$
Δm^2_{31} (eV^2)	2.46×10^{-3} (NH)	$[2.32, 2.61] \times 10^{-3}$ (NH)	$\sigma(\Delta m^2_{31}) = 2.0\%$
Δm^2_{32} (eV^2)	-2.45×10^{-3} (IH)	$-[2.59, 2.31] \times 10^{-3}$ (IH)	$\sigma(\Delta m^2_{32}) = 1.9\%$
$\sin^2\theta_{12}$	0.3	$[0.27, \ 0.34]$	$\sigma(\sin^2\theta_{12}) = 4.4\%$
$\sin^2\theta_{23}$	0.45 (NH), 0.58 (IH)	$[0.38, \ 0.64]$	$\sigma(\sin^2\theta_{23}) = 8.7\%$
$\sin^2\theta_{13}$	0.022	$[0.018, \ 0.025]$	$\sigma(\sin^2\theta_{13}) = 5.3\%$
$\delta_{\mathrm{CP}}(^\circ)$	306	$[0, \ 360]$	–

$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} + \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{\mathrm{CP}}) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} + \alpha^2 \sin^2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} + \mathcal{O}(\alpha^3, \alpha^2 s_{13}, \alpha s^2_{13}, s^3_{13}) \,.$$

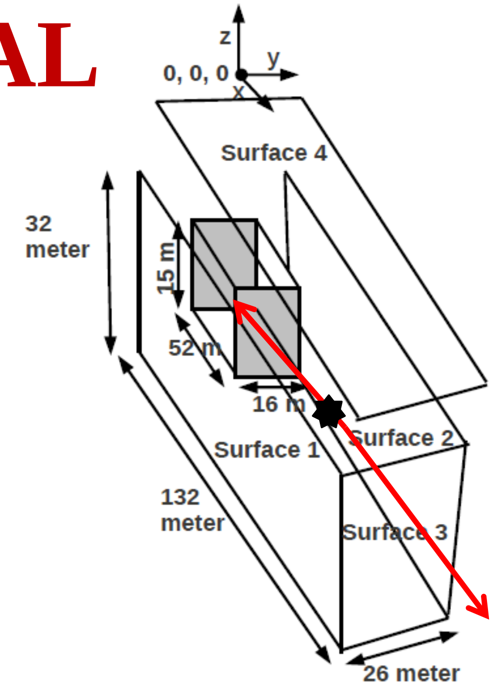
$$\hat{A} = \frac{2\sqrt{2}G_F n_e E}{\Delta m^2_{31}}$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

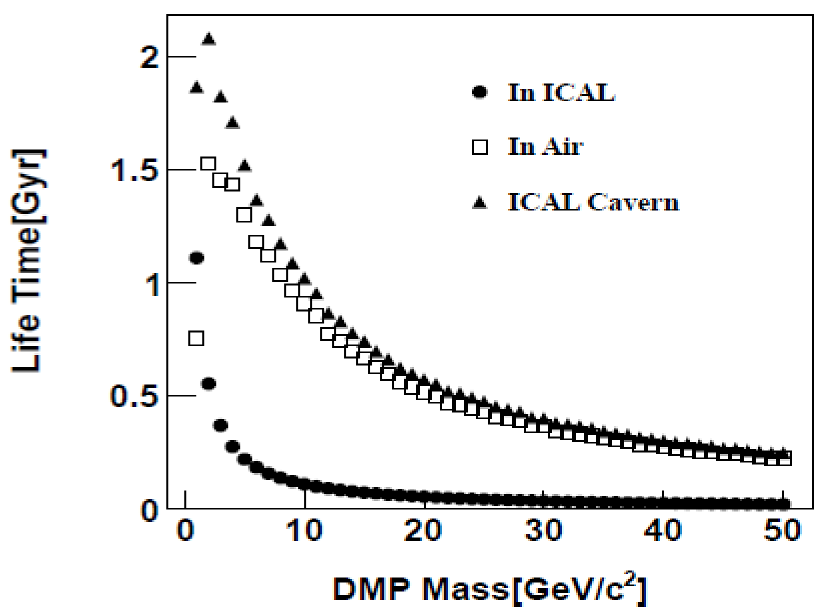
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

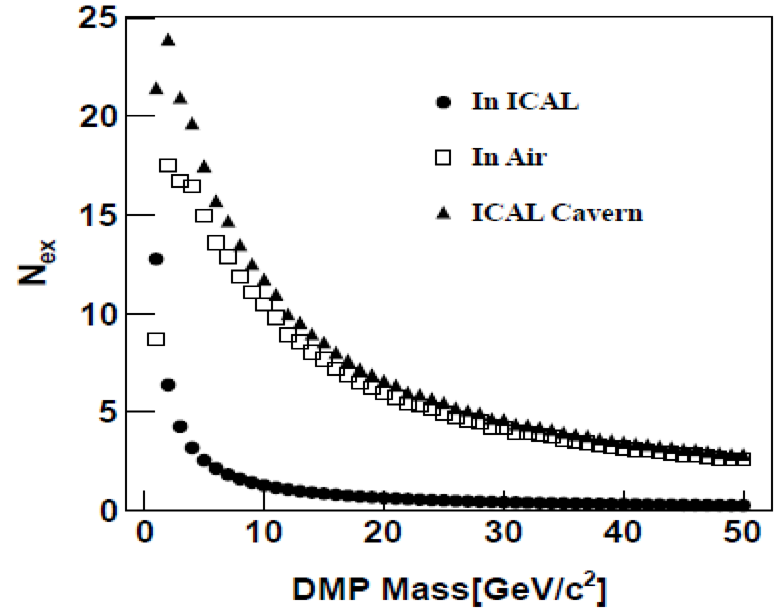
- **Error in systematic**
  - **Flux normalization : 20%**
  - **Cross section normalization : 20%**
  - **Energy dependent tilt factor 5%**

Dark Matter search with ICAL



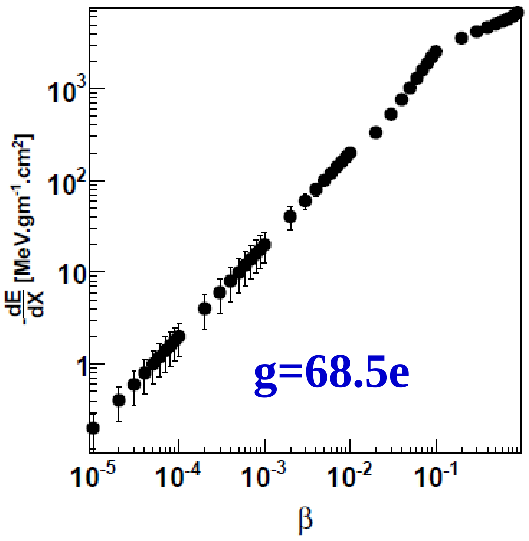
- Anomalous events in Kolar Gold Field (KGF) : Is it due to Dark Matter
- Many experiment tried to determine this
- Looked for $\Phi_{DM} \rightarrow l^{+}l^{-}\ (l = e, \mu, \tau)$
- Added extra scintillator/RPC detector in the wall of the cavern to detect second particle (increase the acceptance ranges)
- Either observe it or put an upper limit on it.



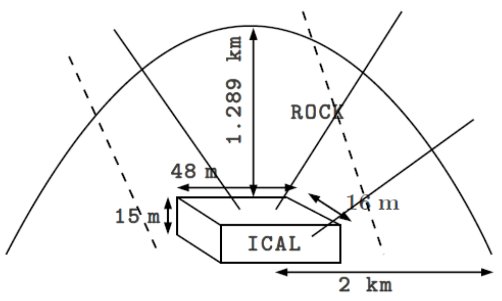


Search of Magnetic Monopole

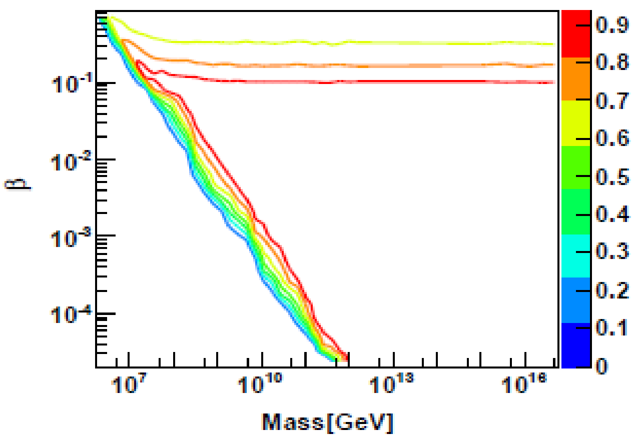
- No experimental evidence, but theoretically expected
- –dE/dx is very much different than charged(electric) particle
- Almost no background (large time gap between signal in consecutive layer, no bending)
- Need special trigger for this study



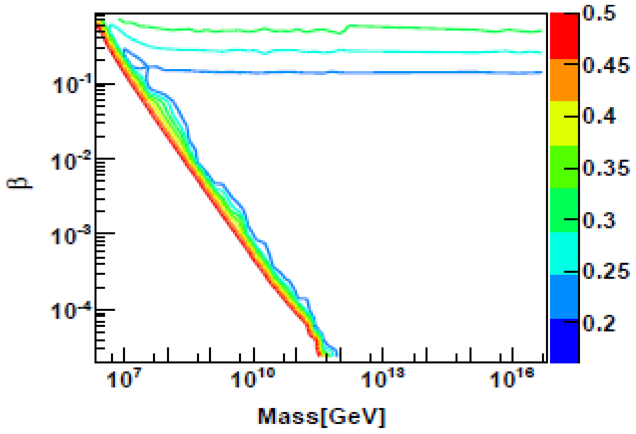
~1.3km rock on top of INO



Detection efficiency



In absence of signal in 10 years, upper limit of flux (10^{-15} cm^{-2} sr^{-1}s^{-1})



With larger year of ICAL data, either discover it or put more stringent limit than present one (MACRO)