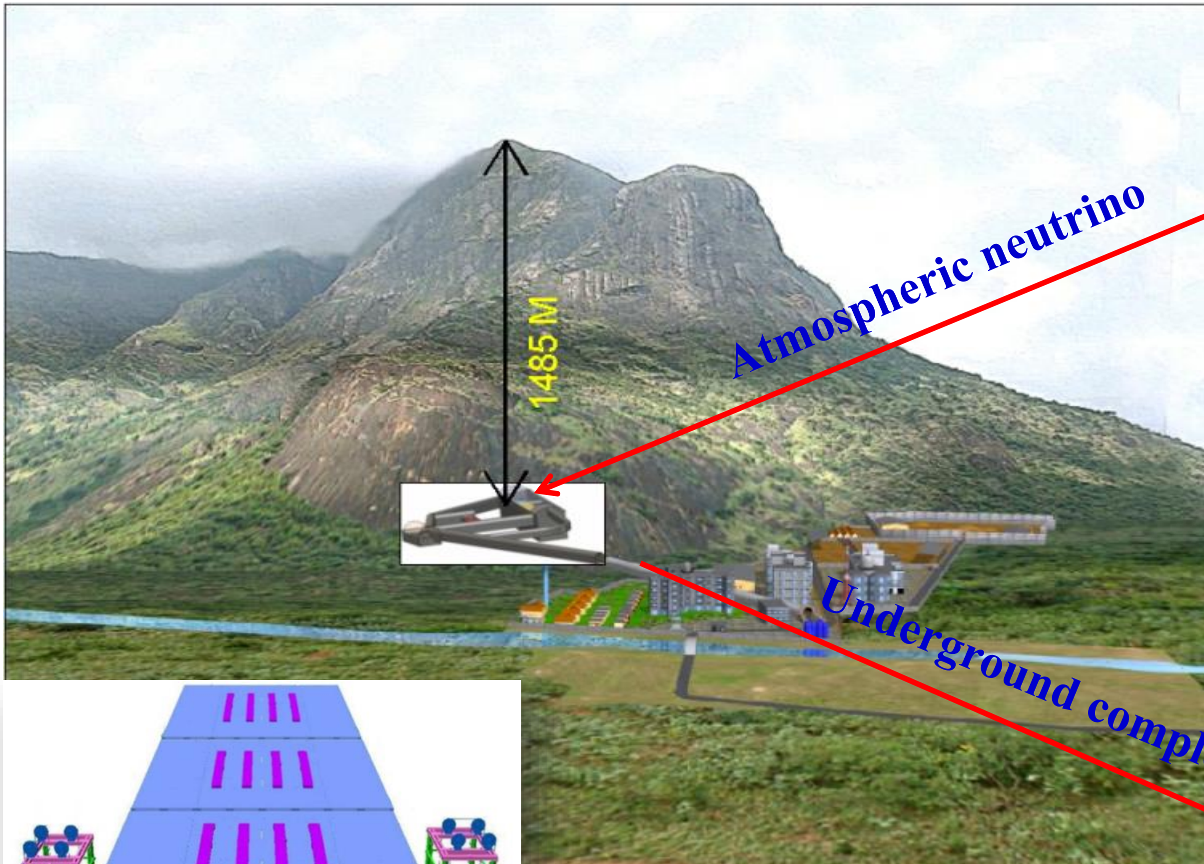
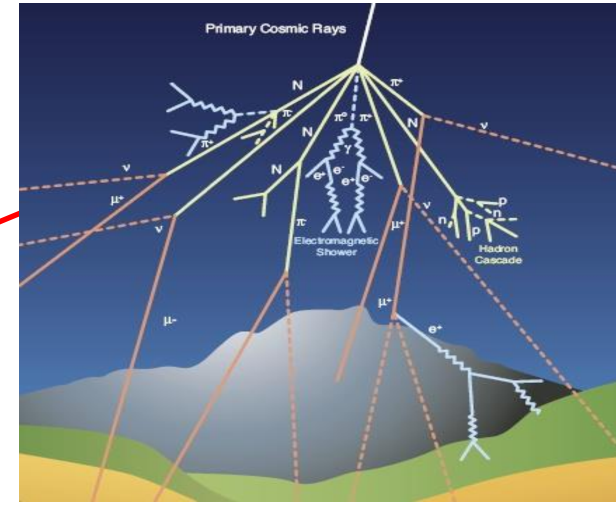
India based neutrino observatory (INO)

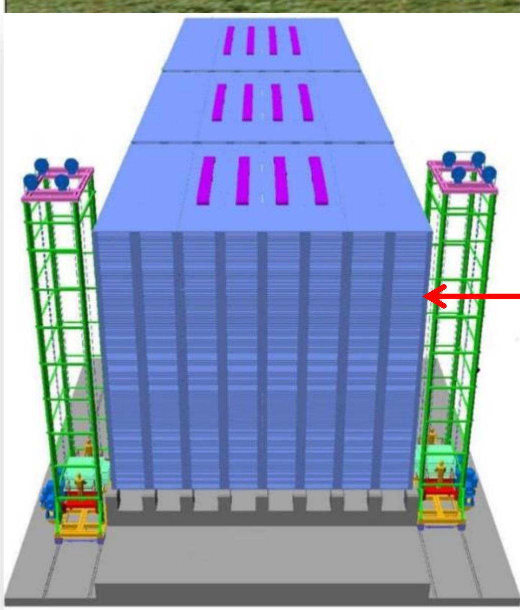
- Create experimental facility in the country where we can carry out front ranking experiments in the field of particle & astroparticle physics.
- Underground laboratory with ~1 km all-round rock cover accessed through a 2 km long tunnel. A large and several smaller caverns to facilitate many experimental 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, to address questions about the neutrino mass ordering.

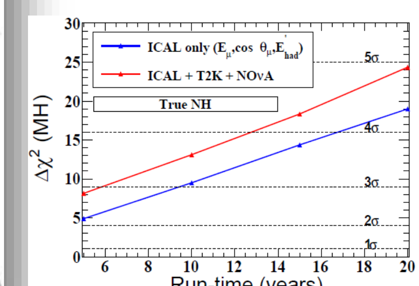
Proposed India based Neutrino Observatory at BodiHills

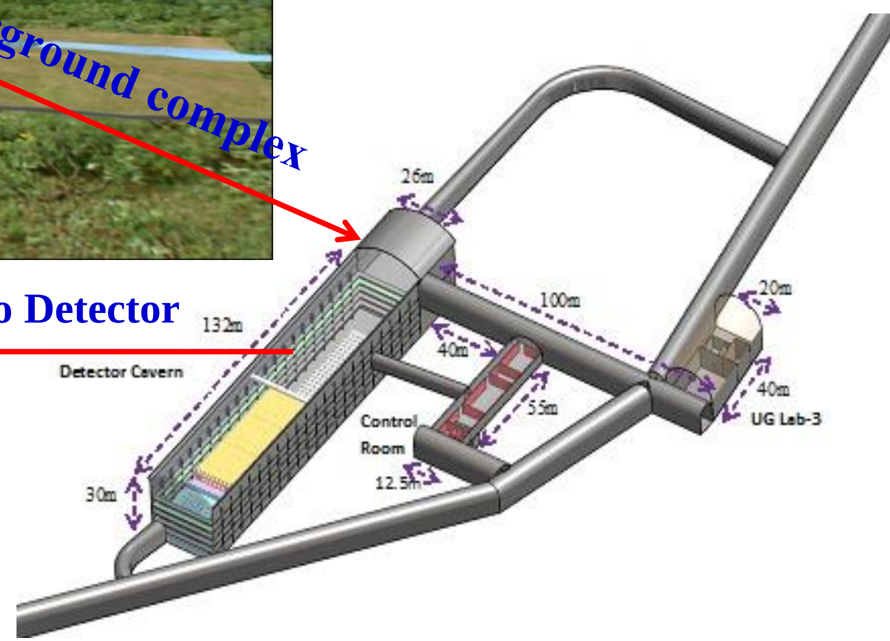




50Kton ICAL neutrino Detector

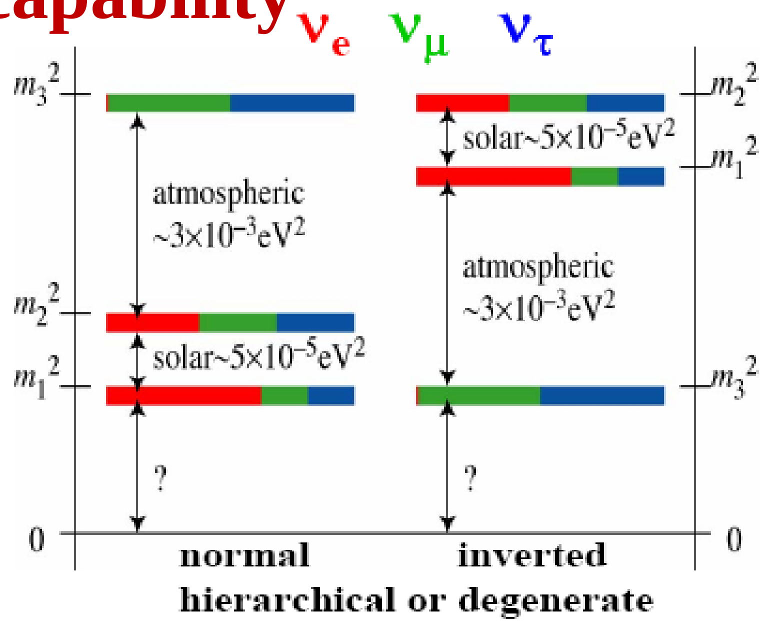






ICAL : Physics goal for a large mass detector with charge identification capability

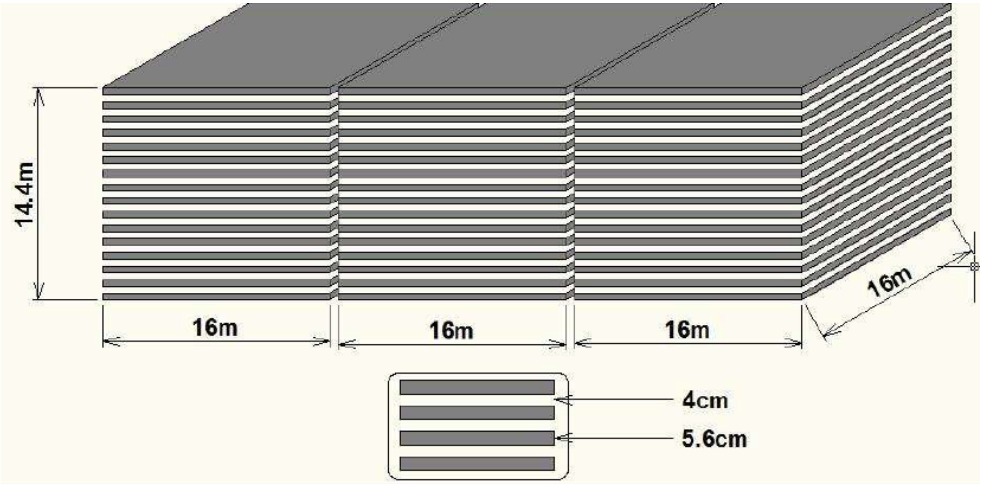
- Reconfirm atmospheric neutrino oscillation
- Improved measurement of oscillation parameters
- Search for potential matter effect in neutrino oscillation.
- Determining the sign of Δm^2_{23} using matter effect
- Measuring deviation from maximal mixing and octant of θ_{23}
- Probing Lorentz and CPT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

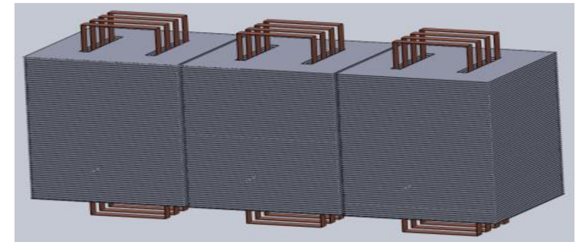


Physics goals to be complementary to other experiments worldwide. There is a growing realization that both atmospheric and accelerator experiments are needed to obtain best values of the parameters.

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

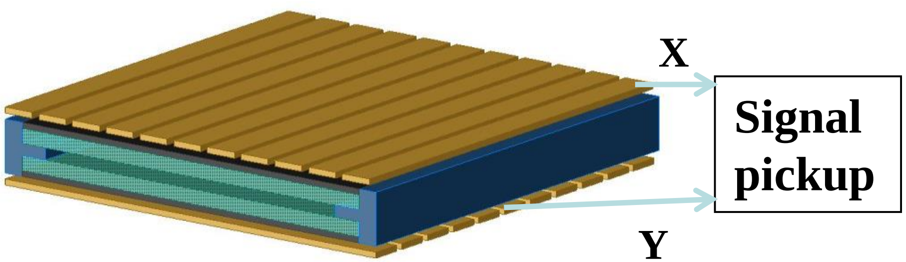
Schematic of Iron Calorimeter at INO





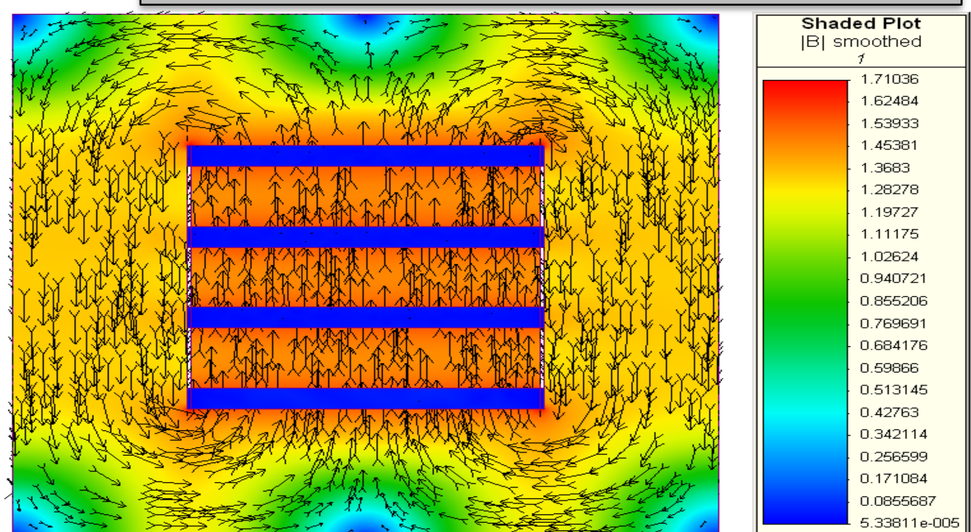
ICAL MAGNET QTY - 3
Size :- 16(L) ×16(W) × 15(H) meter
COIL SIZE :- 15m × 8m
Ampere-Turn :- 80,000 AT
Max. Design Value:- 100,000 AT
Max. Power requirements in each magnet:- <150KW (Coils & Power Supply)
Each coil gap = 1300mm x 80 mm

51 kt world's largest electromagnet



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

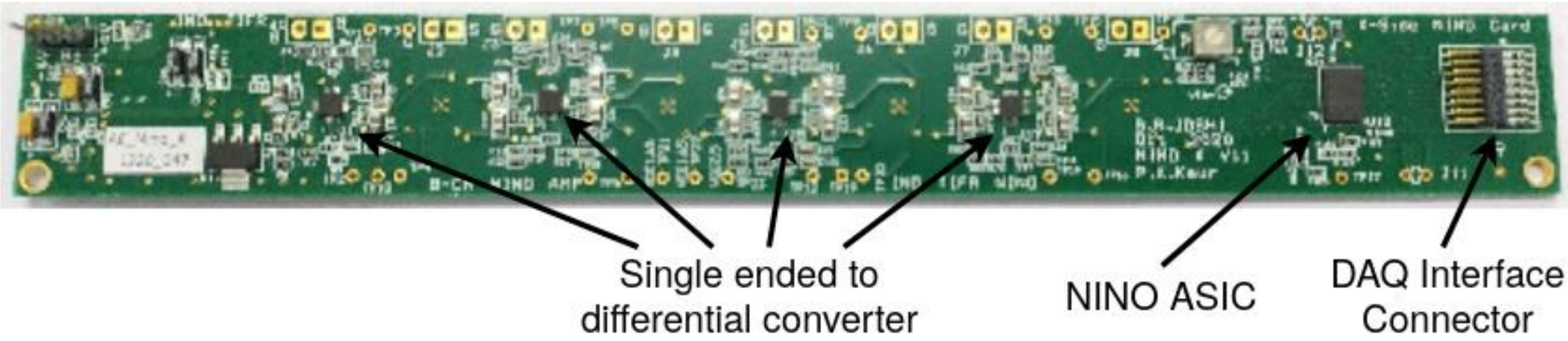
~4 times the surface area of all RPC detectors used in HEP



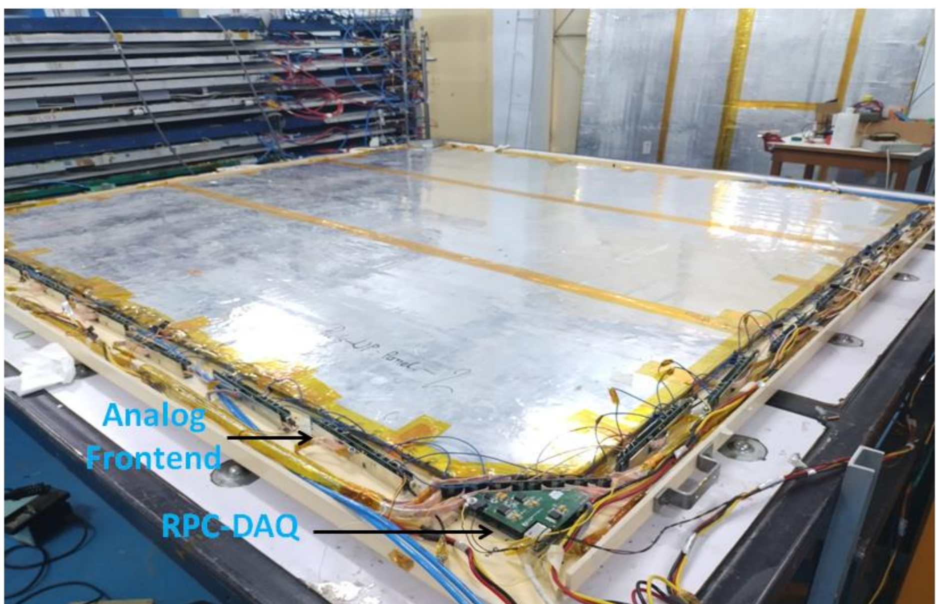
B-field for 60 kA-turns, typical low C steel

A fully assembled RPC

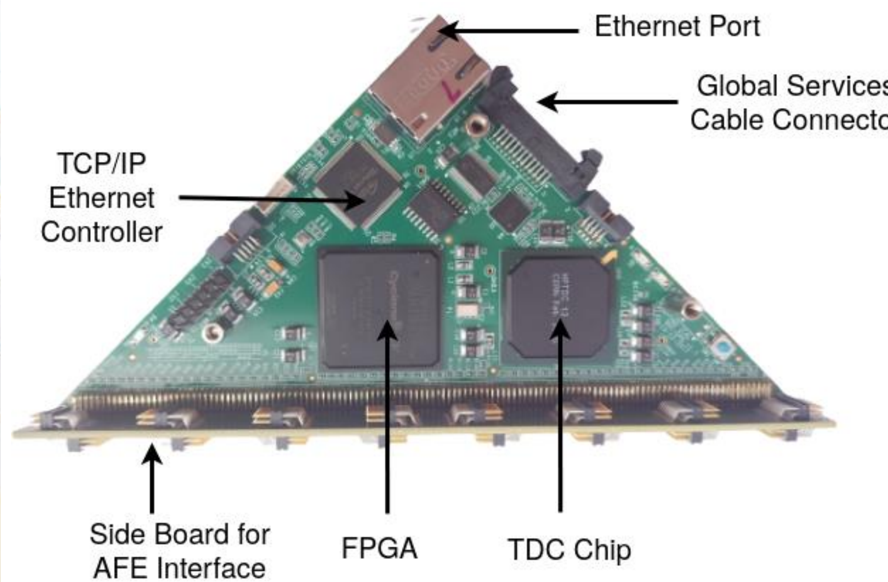
The analog Front-End Board



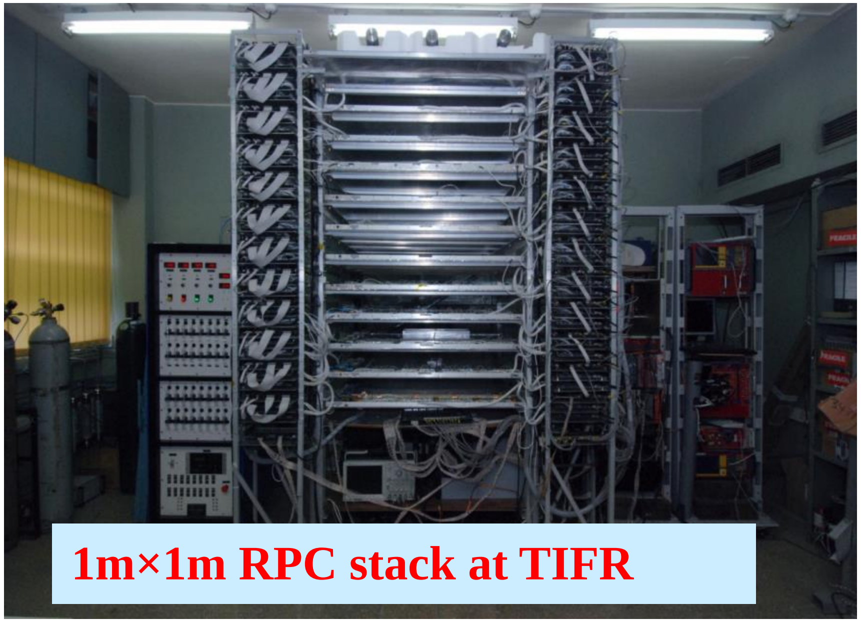
Assembled RPC on table



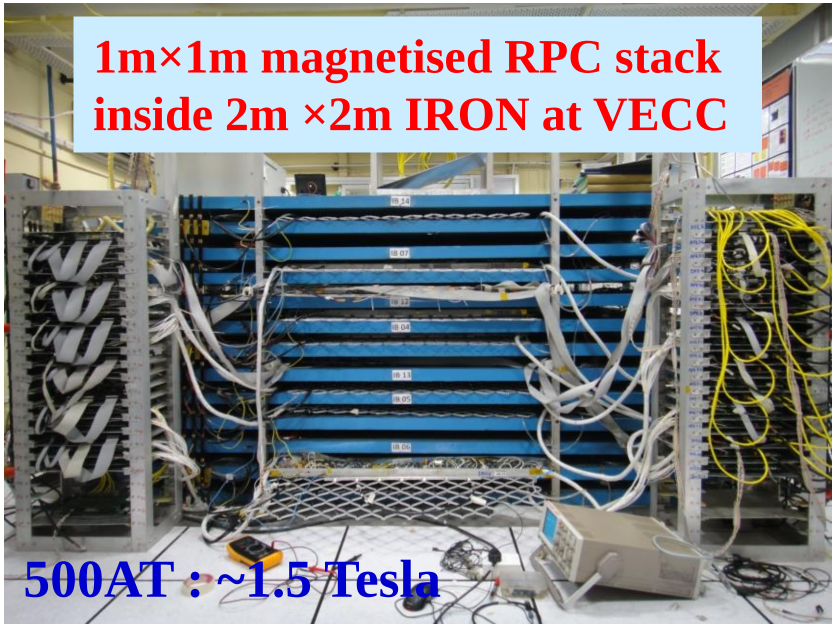
The digital Front-End Board



Development of RPC detector

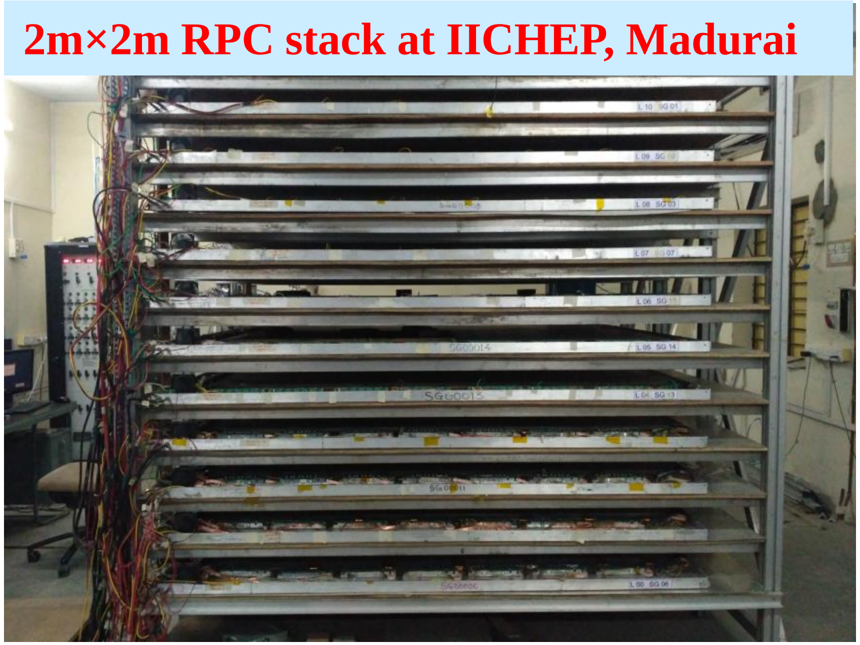


1m×1m RPC stack at TIFR

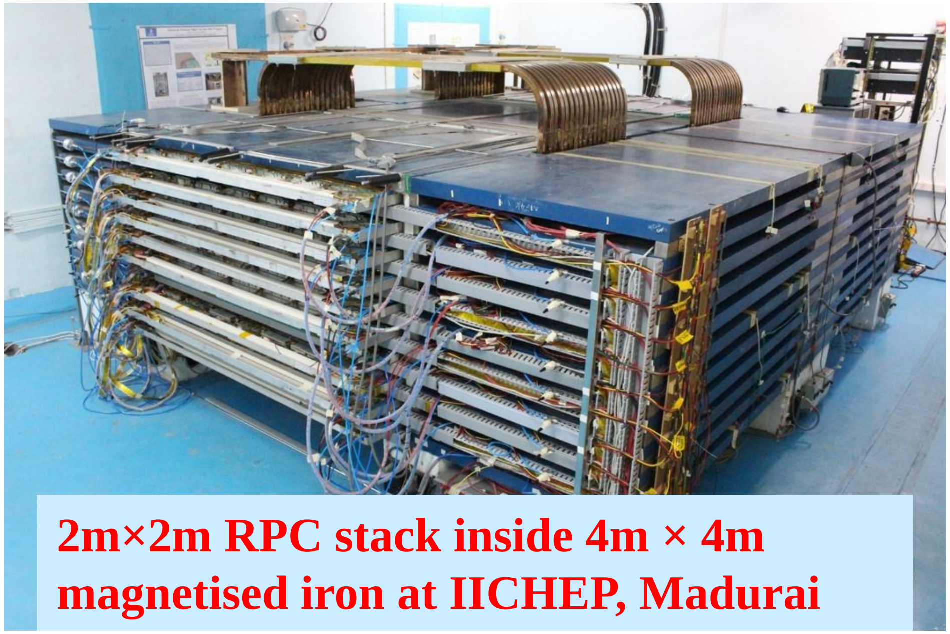


1m×1m magnetised RPC stack inside 2m ×2m IRON at VECC

500AT : ~1.5 Tesla

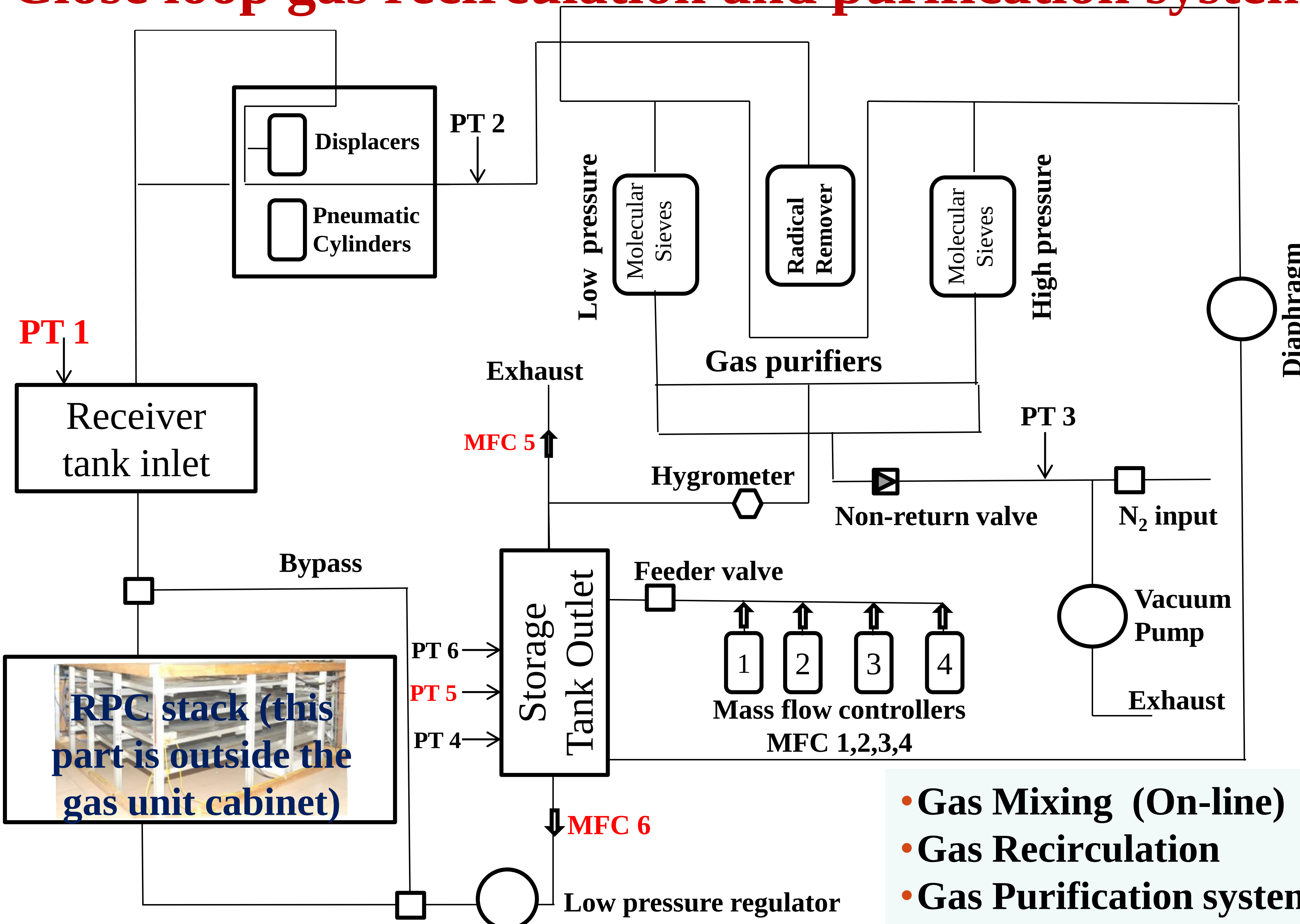


2m×2m RPC stack at IICHEP, Madurai



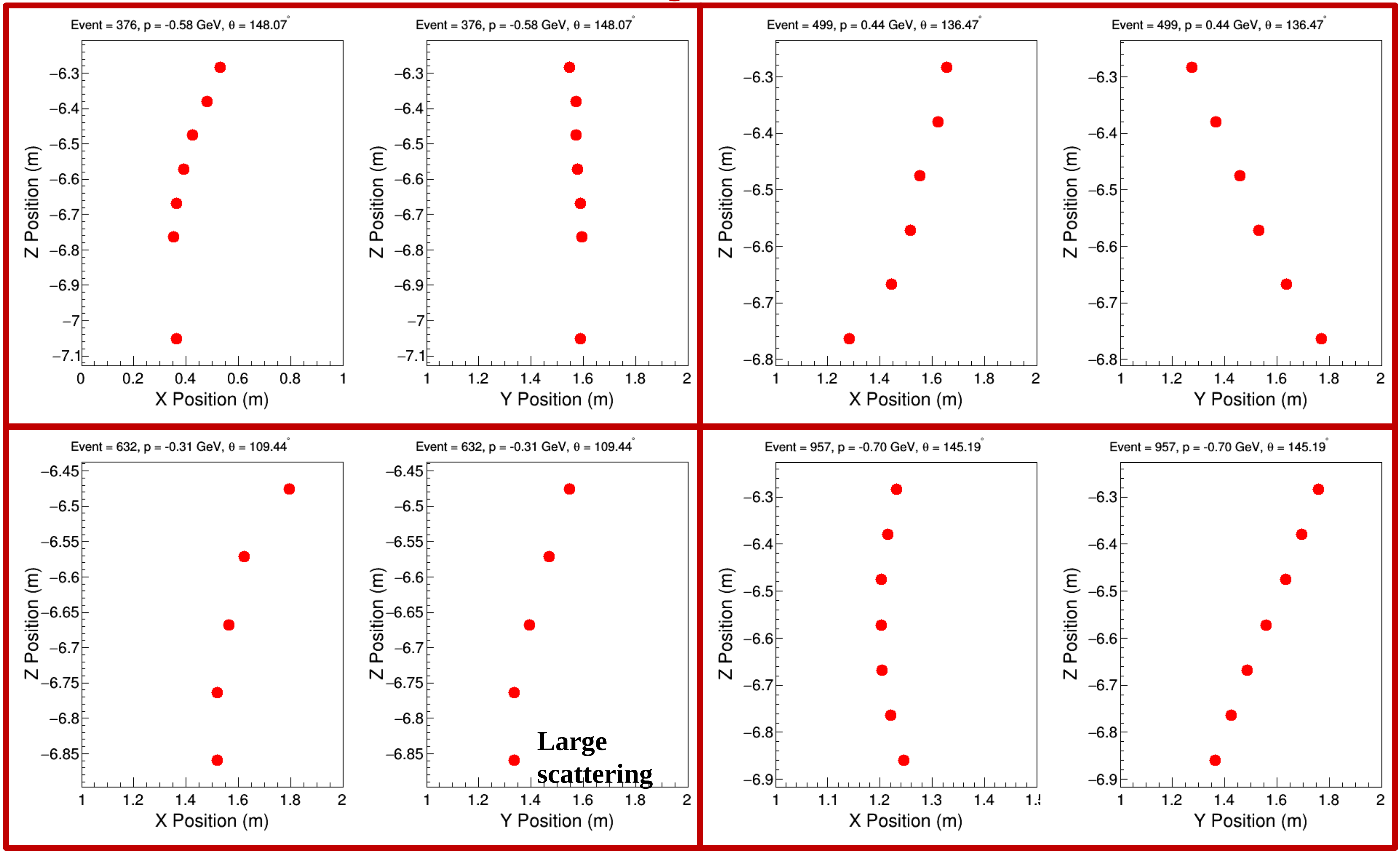
2m×2m RPC stack inside 4m × 4m magnetised iron at IICHEP, Madurai

Close loop gas recirculation and purification system



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

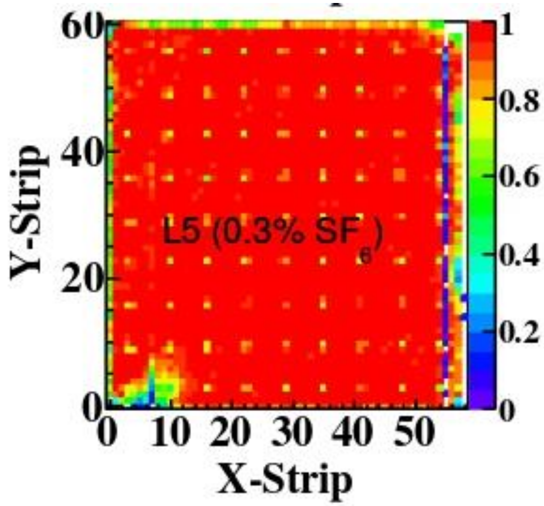
Few clean muon trajectories in miniICAL



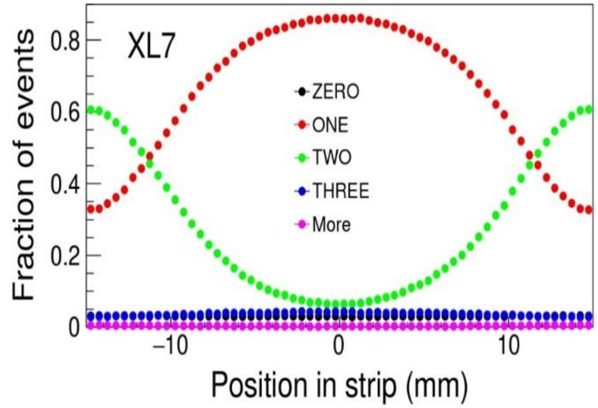
- **Bending in X-side due to magnetic field in Y-direction.**

Running Prototype RPC Stack at TIFR/IICHEP

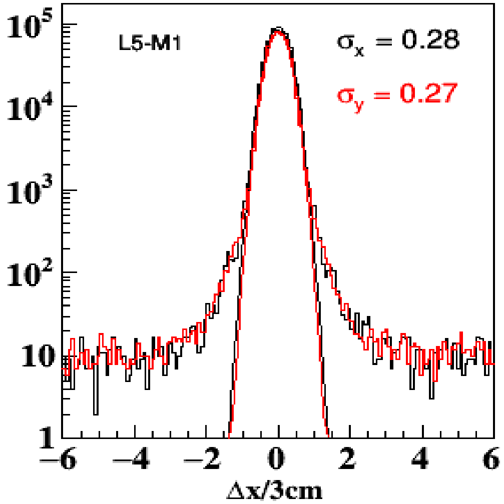
Inefficiency due to button, dead strip, but edge effect also present



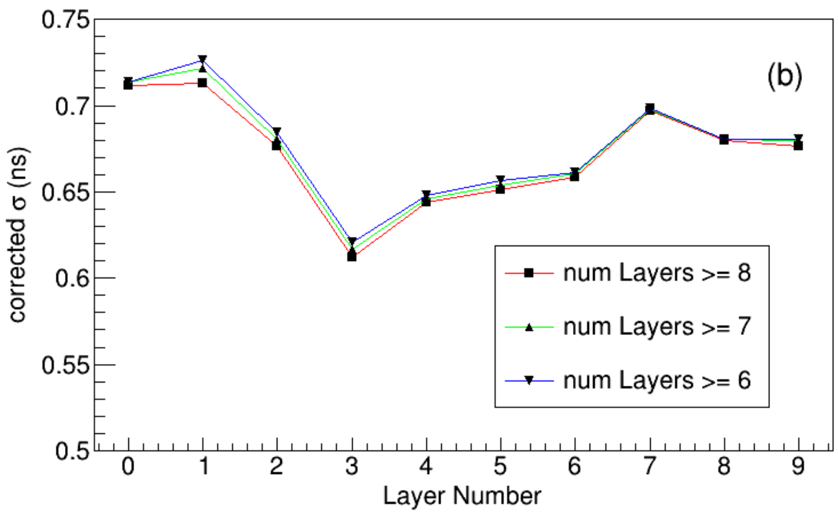
Multiplicity and position



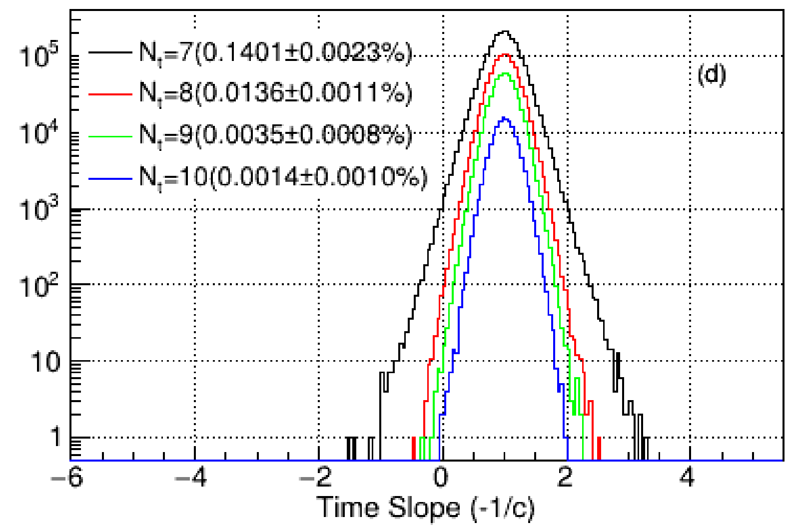
Position resolution ~7mm, better than strip width/$\sqrt{12}$



Time resolution of RPC layers



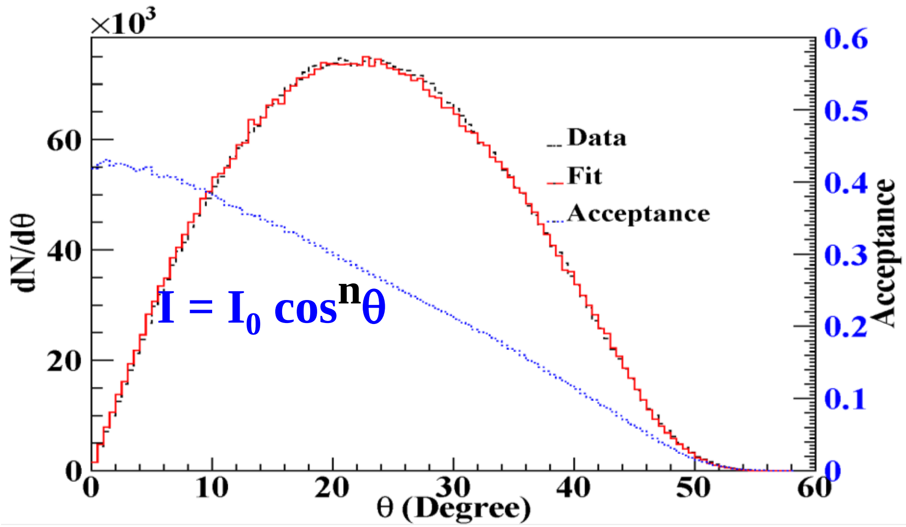
Distinction of up/down Muon

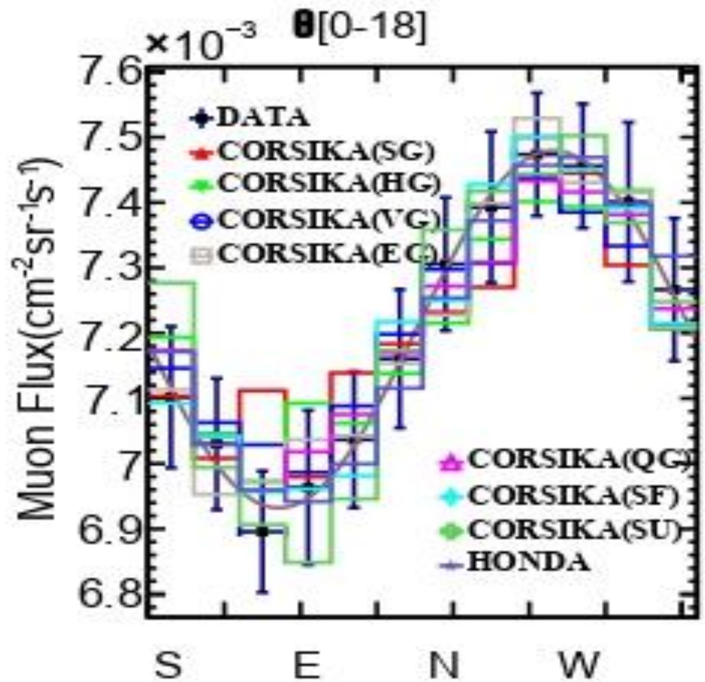


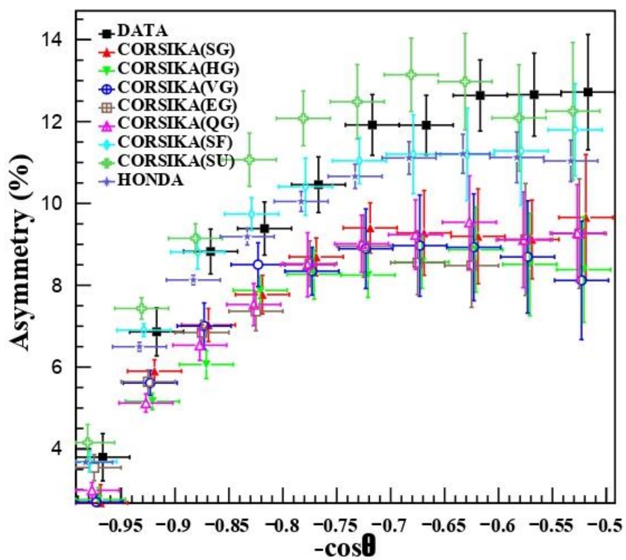
Input to detector simulation and digitisation

Cosmic muon spectrum

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







There is a mismatch of momentum spectrum of muon estimated from COSRSIKA simulation as well as HONDA flux

- **Expected ratio of # of μ^+ and μ^-, though measurement has large uncertainty**

INO-ICAL e-ICAL & m-ICAL Detector

Parameter	ICAL	e-ICAL	m-ICAL
No. of modules	3	1	1
Module dimensions	16.2m×16m×14.5m	8m×8mx2m (90:1)	4m×4mx1m (720:1)
Detector dimensions	49m×16m×14.5m	8m×8m×2m	4m×4m×1m
No. of layers	150	20	10
Iron plate thickness	56mm	56mm	56mm
Gap for RPC trays	40mm	40mm	45mm
Magnetic field	1.3Tesla	1.3Tesla	1.3Tesla
RPC dimensions	1.950m×1.91m×24mm	1.95m×1.91m×24mm	1.95m×1.91m×24m
Readout strip pitch	30mm	30mm	30mm
RPCs/Road/Layer	8	4	2
Roads/Layer/Module	8	4	1
RPC units/Layer	192	16	2
No. of RPC units	28,800 (107,266m^2)	320 (1,192m^2) (90:1)	20 (74.5m^2) (1440:1)
No. of readout strips	3,686,400	40,960 (90:1)	2,560 (1440:1)

INO-ICAL e-ICAL & m-ICAL Detector

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RPCs/Road/Layer			
Roads/Layer/Module			
RPC units/Layer			
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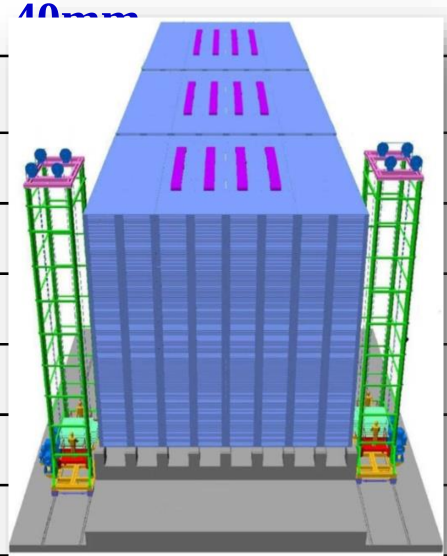
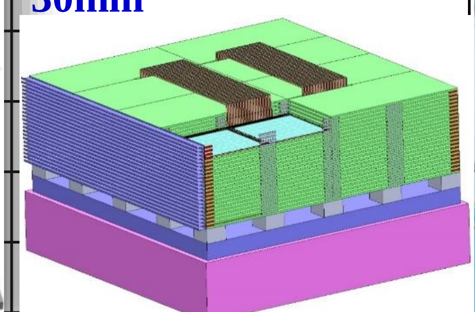




Detector simulation and event reconstruction

GENIE : modified
3D neutrino flux,
Weighted evt

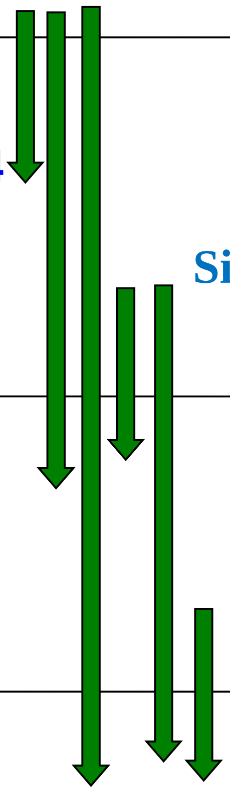
Neutrino Event Generation

$\nu_a + X \rightarrow A + B + \ldots$

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

Geant4



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/Madurai

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

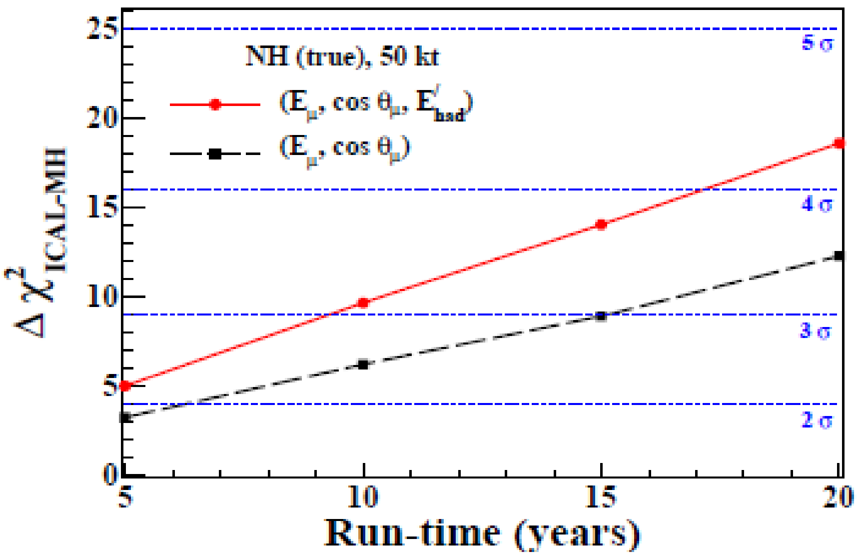
Event Reconstruction

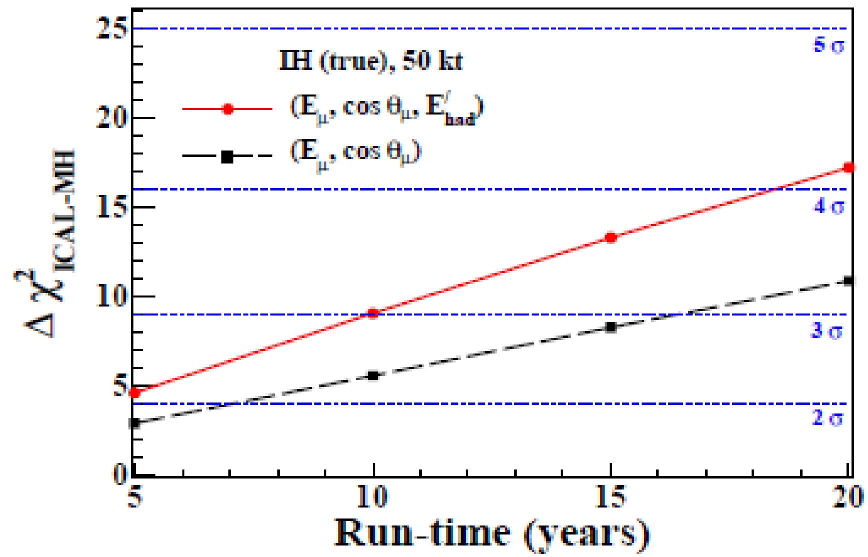
(E,p) of ν + X = (E,p) of A + B + ...

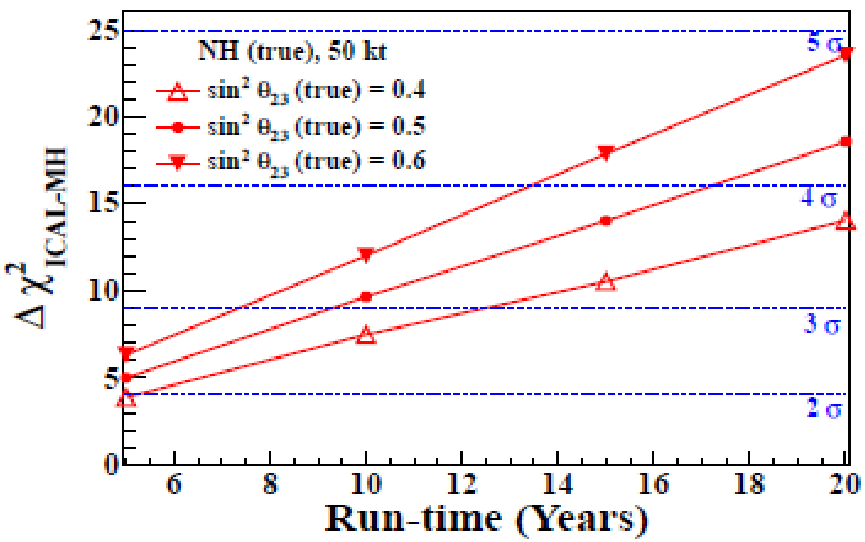
Fit the tracks of A + B + ... to get their energy and momentum.

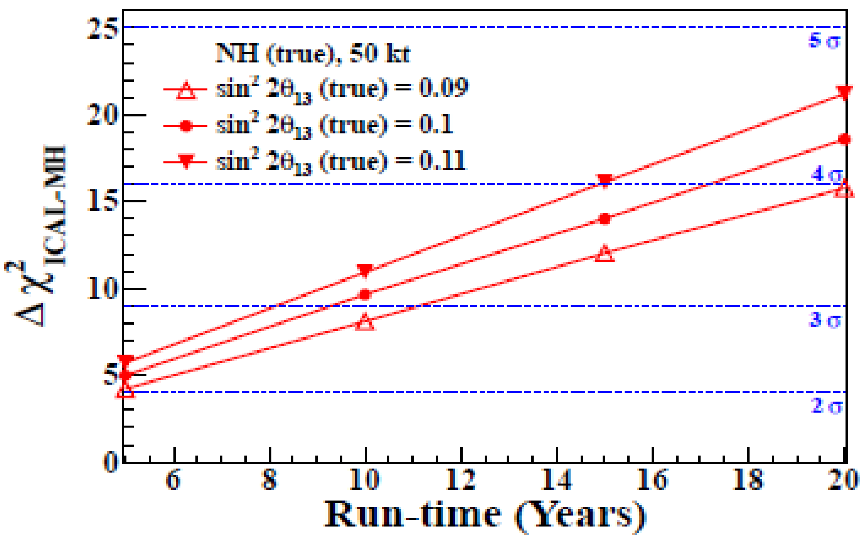
Output:
Energy & Momentum of the initial neutrino

Determination of neutrino mass hierarchy



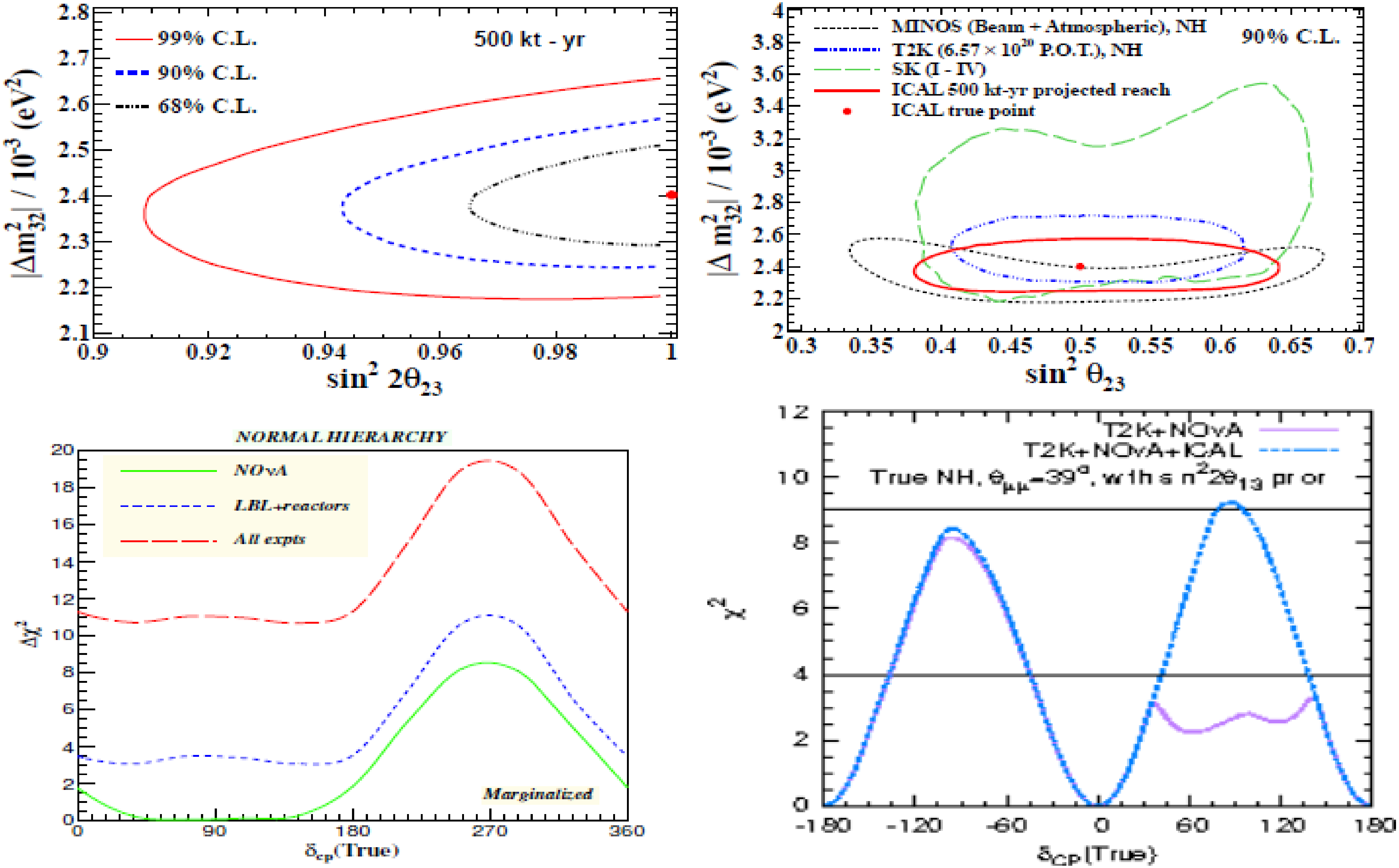






- **Larger value of $\sin^2\theta_{13}$, more confidence level/less year to have same CL**

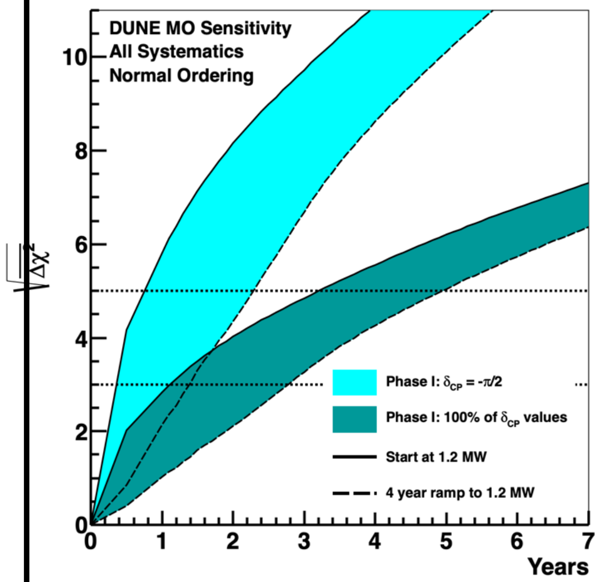
Precision of neutrino mass matrix

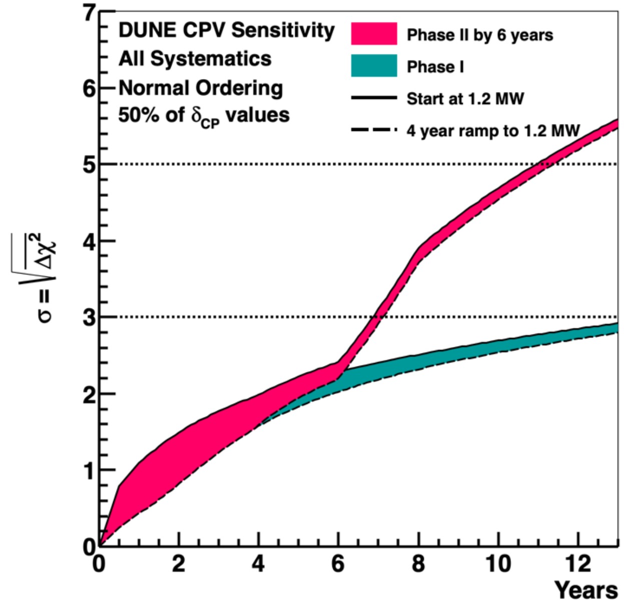


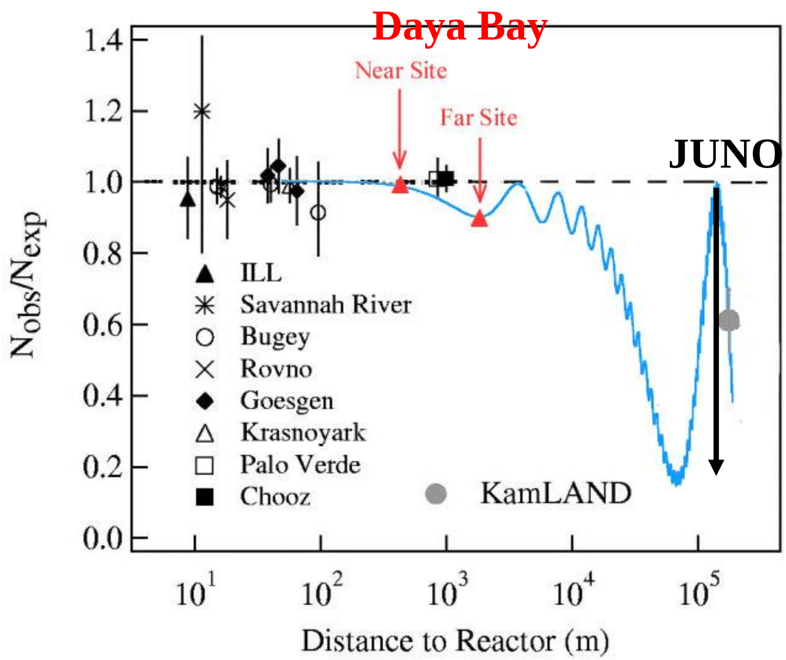
ICAL will play an important role to determine these parameter more precisely

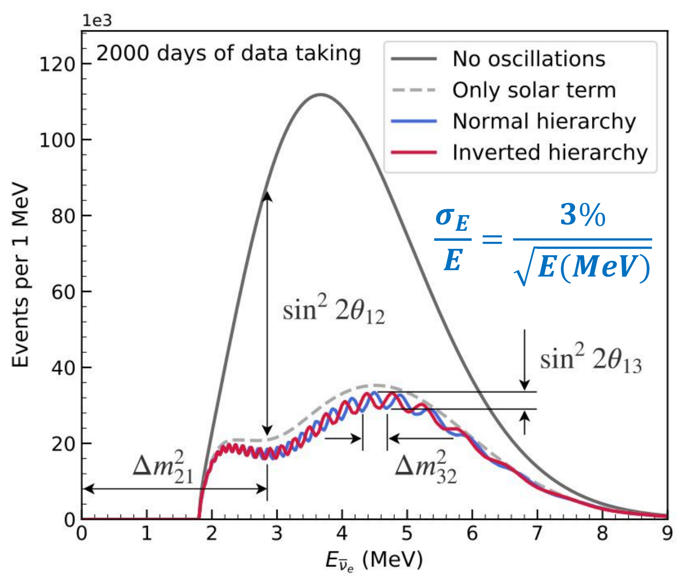
Challenge from other experiments on mass hierarchy measurement

- **DUNE : start 2032 : Two year for 5σ discovery of mass hierarchy**
- **JUNO : Start 2023 : 3σ around 2031 (with 3%/√E resolution), for 4%, it will take 12 years**
- **ICAL : 10 year for 3σ (but 6 year for 3σ with input from NOvA & T2K)**





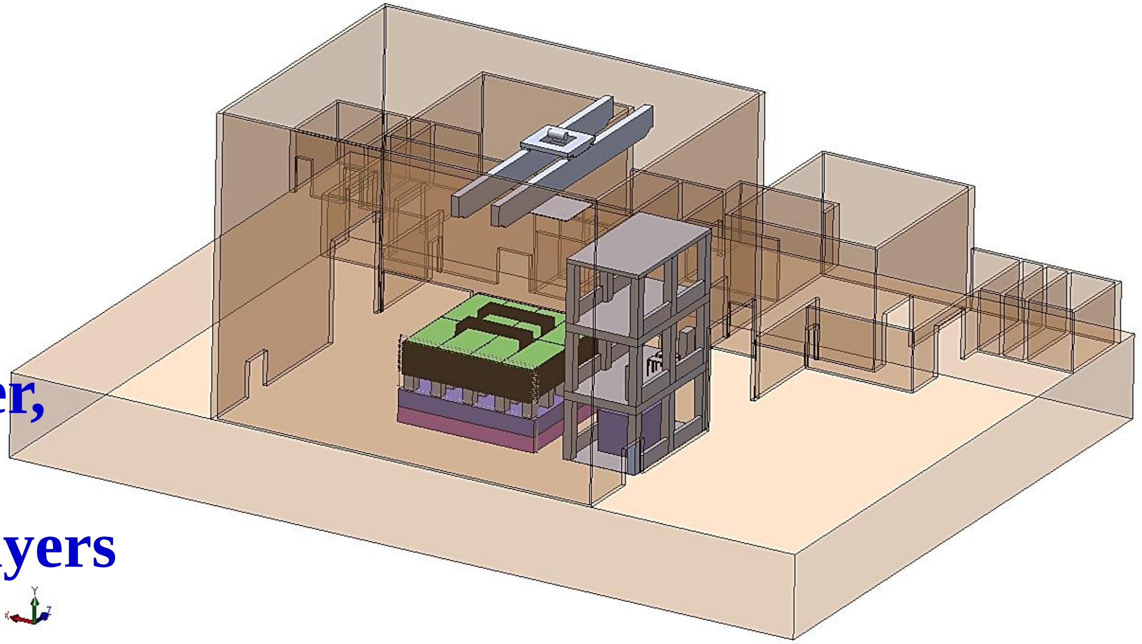




Immediate plan

- A new site for setup the Engineering Module (EM)
  - Most of the iron plates and copper coil are in hand
  - Electronics are prototyped
  - RPC Tray and pickup panels are being fabricated at factories
  - New vendor for RPC production

- EM : Only 20 layers of RPC, but Iron in 23 layer, but height is able to accommodate upto 70 layers



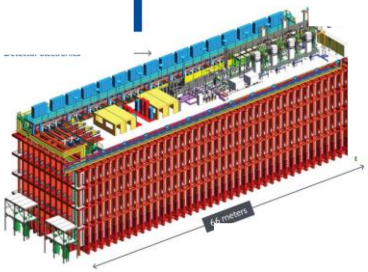
Ultimate goal

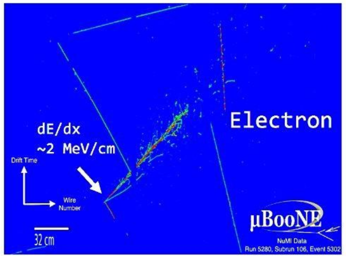
- **Choose an alternate site for the INO project**
  - **Site selection committee is formed to search and identify an alternate site**

Backup

One-slide DUNE

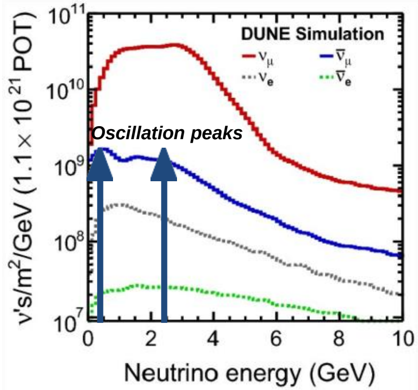
1500m underground



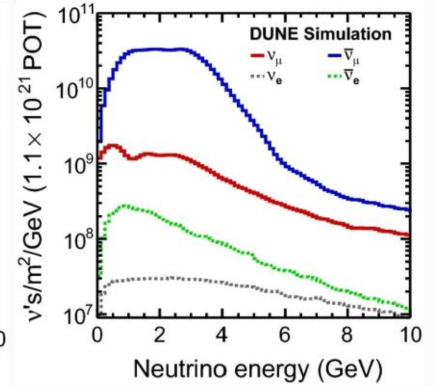


Broad band neutrino and antineutrino beam

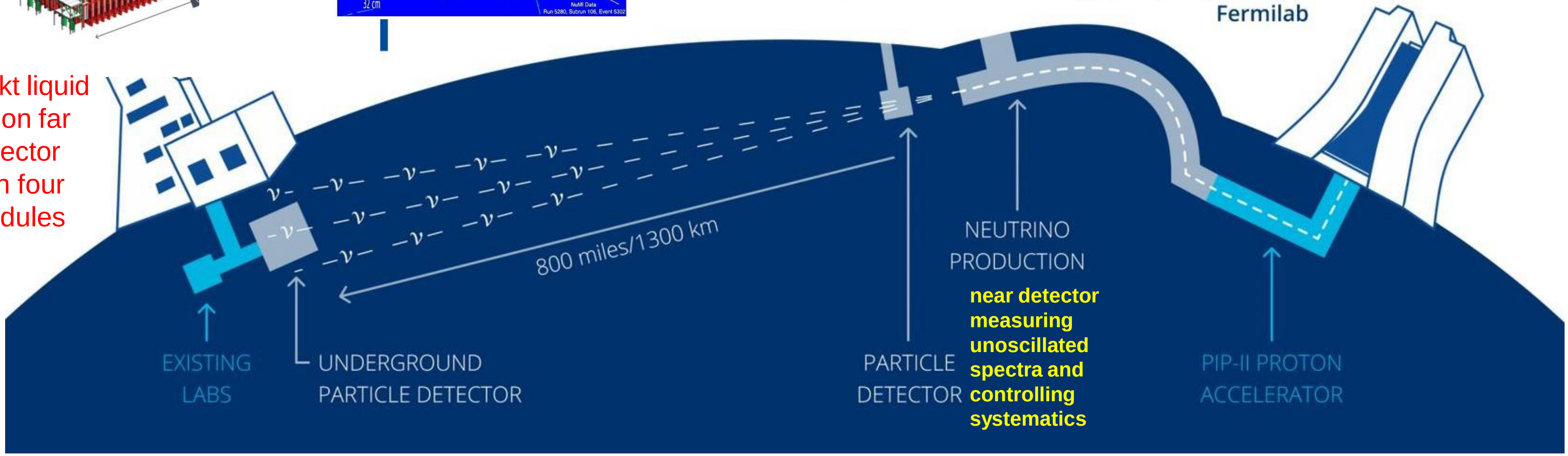
Neutrino mode

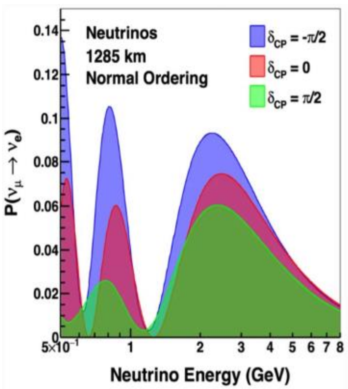


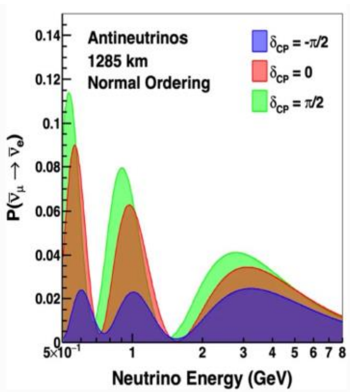
Antineutrino mode

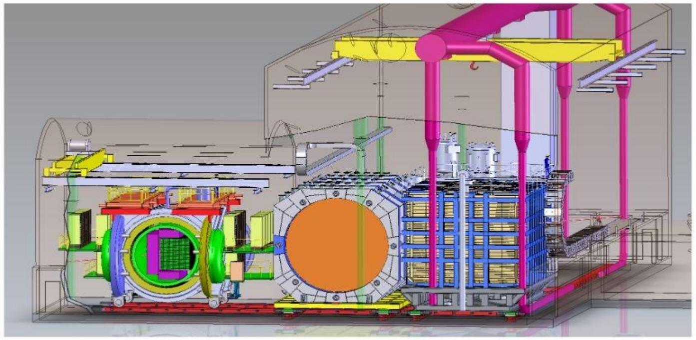


70 kt liquid argon far detector with four modules



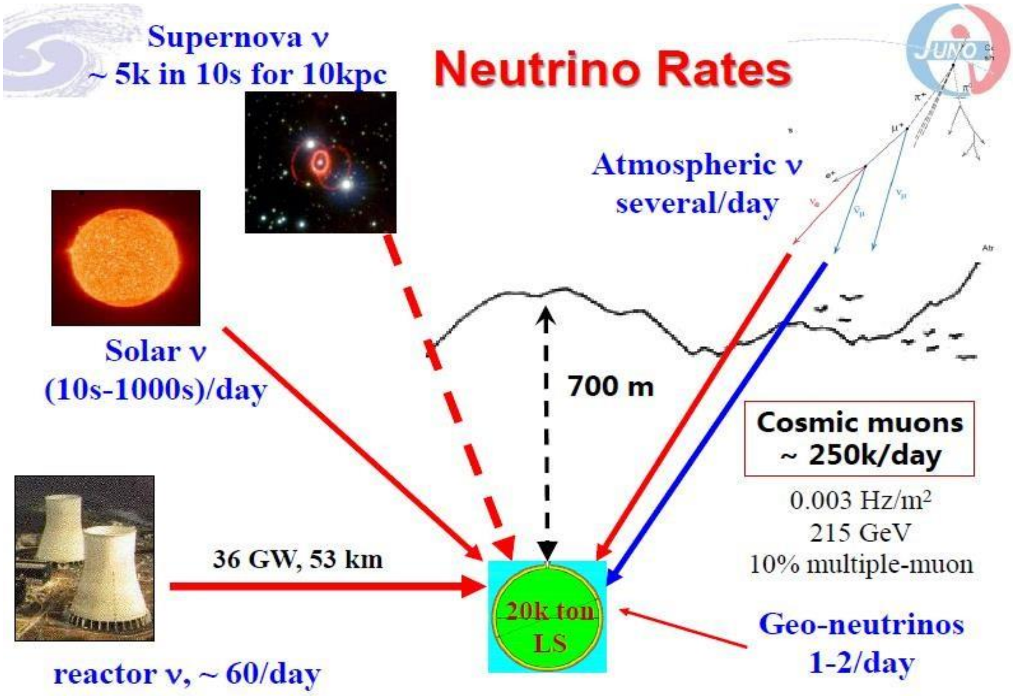




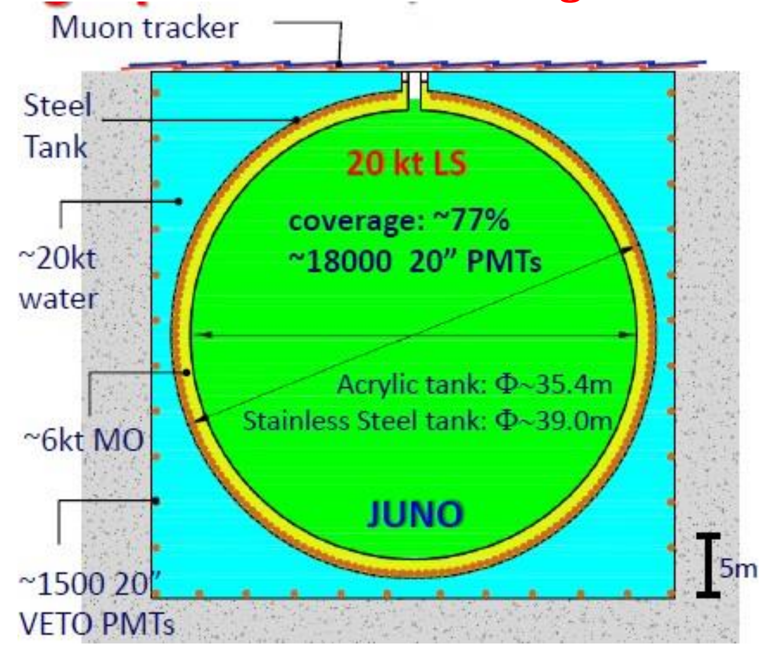


Jiangmen Underground Neutrino Observatory

The JUNO experiment



700m underground

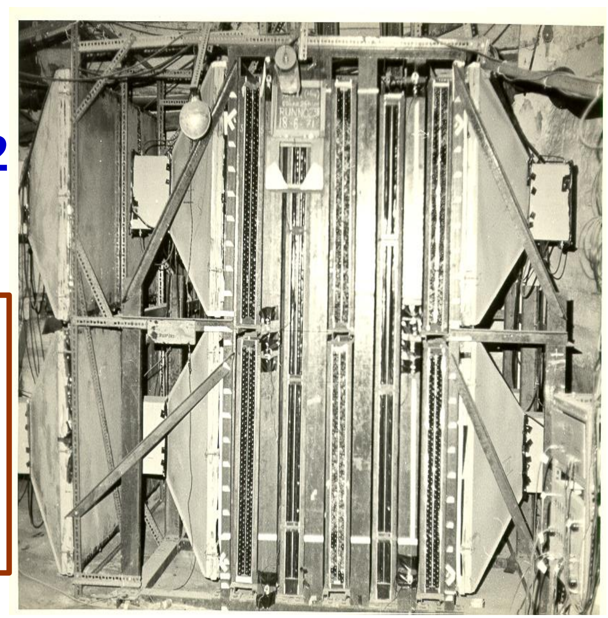


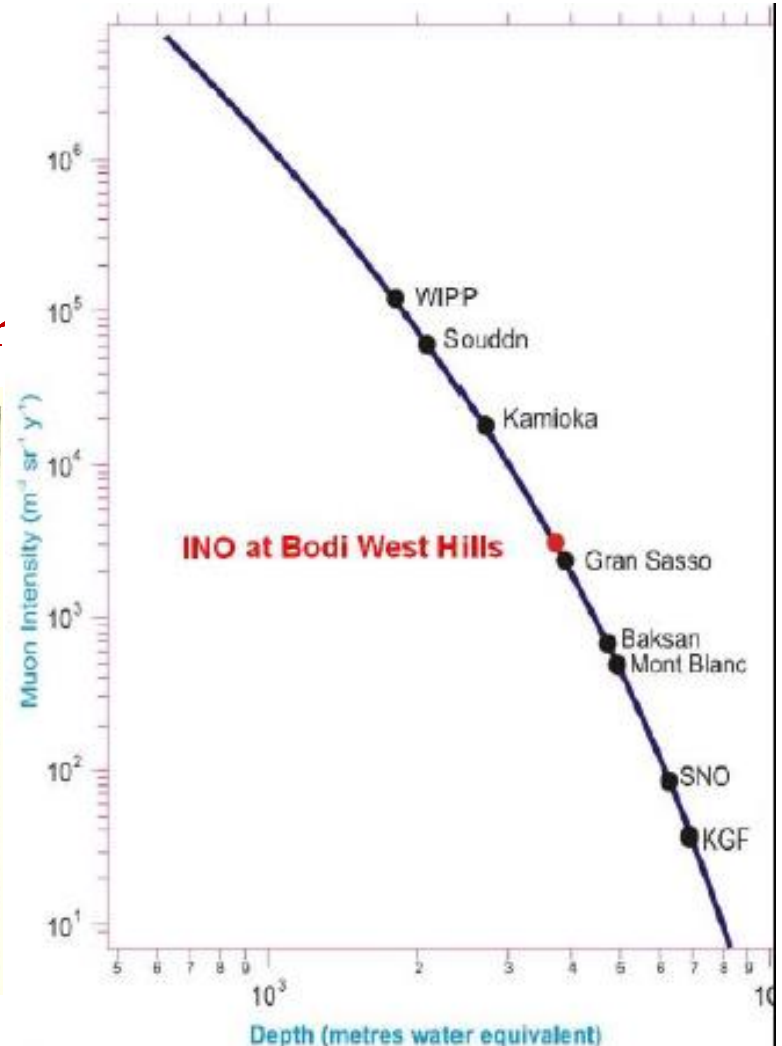
Estimated numbers of neutrino events in JUNO **(Supernova)**

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

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.

- TIFR 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/m²/sr at KGF, increased by a factor of ~100 at INO

Building blocks of detector and electronics