Status of
India-based Neutrino Observatory

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For and on behalf of

INO Collaboration

NNN'16 **3-5 November, 2016, IHEP, Beijing, China**

Rabindranath Tagore (1861-1941)

Cheena Bhavan @ Santiniketan

Tan Yun-Shan (1898-1983)

- Sino-Indian Cultural Society, Nanking, China,1933.
- Sino-Indian Studies, Cheena Bhavana, Santiniketan ,1937.

January, 2013

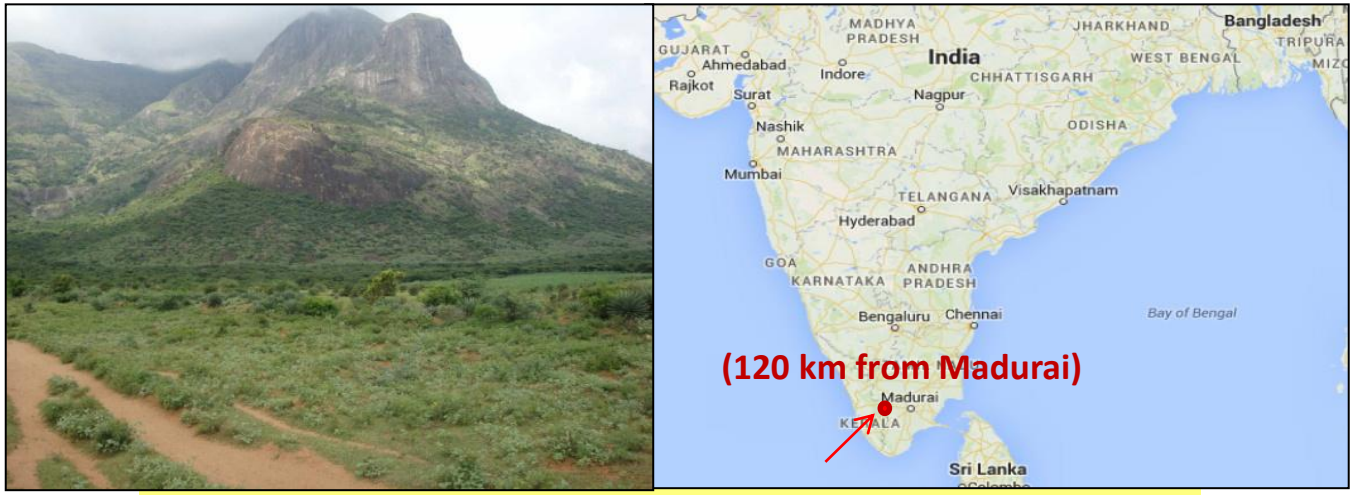
September, 2015

September, 2016

Photo courtesy: www.visvabharati.ac.in

India-based Neutrino Observatory

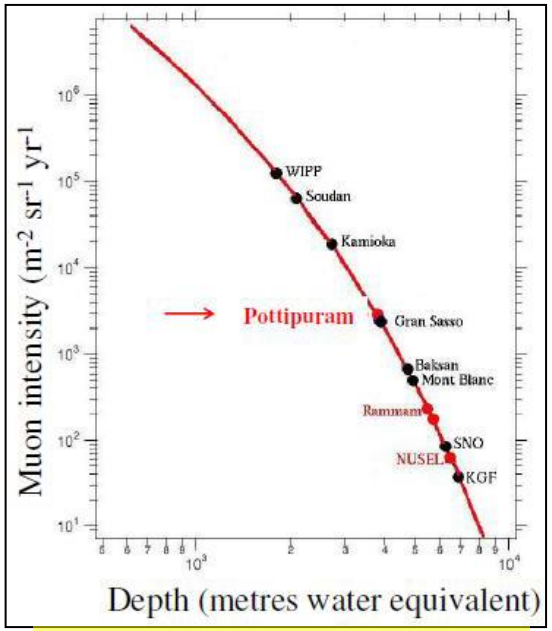
- INO is one of the endeavors across the world that strive together towards the new horizon beyond the realm of Standard Model.
- It is one of the largest basic science project on the land of India aspiring to contribute in the modern era of particle physics research past the discovery of finite mass and flavor oscillation of neutrino.
- It offers an underground site suitable for building an observatory to explore the rich and diverse world of atmospheric neutrinos and other experiments with special requirement of low-background.



INO site at Bodi West Hills, Pottipuram, Tamil Nadu

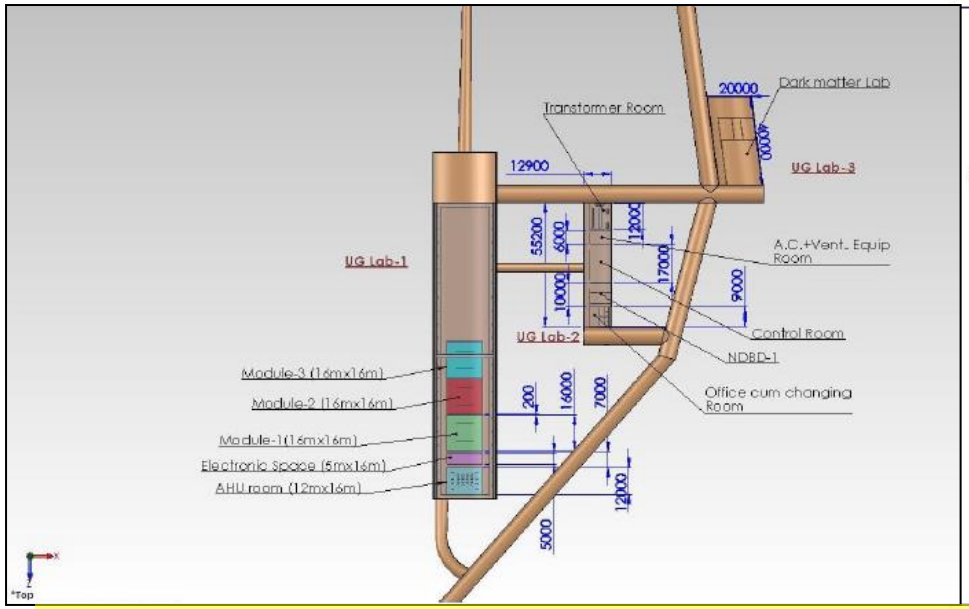
Choice of Site

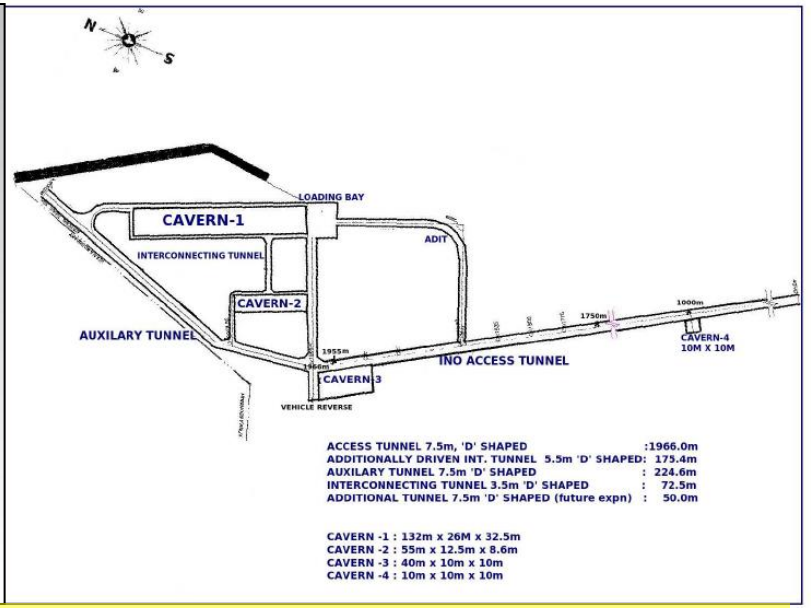
- Cavern set in good quality massive Charnockite rock under 1589m high peak with vertical cover of 1289m and 1000m all around *(reduction in cosmic ray background comparable to Gran Sasso lab).*
- Flat terrain with good access to major roads.
- Warm, low rainfall area *(low humidity condition throughout the year desirable for experimental setups).*
- Portal set outside the reserve forest boundary *(no environmental issues).*



Cosmic ray muon flux as a function of depth

Underground INO Laboratory

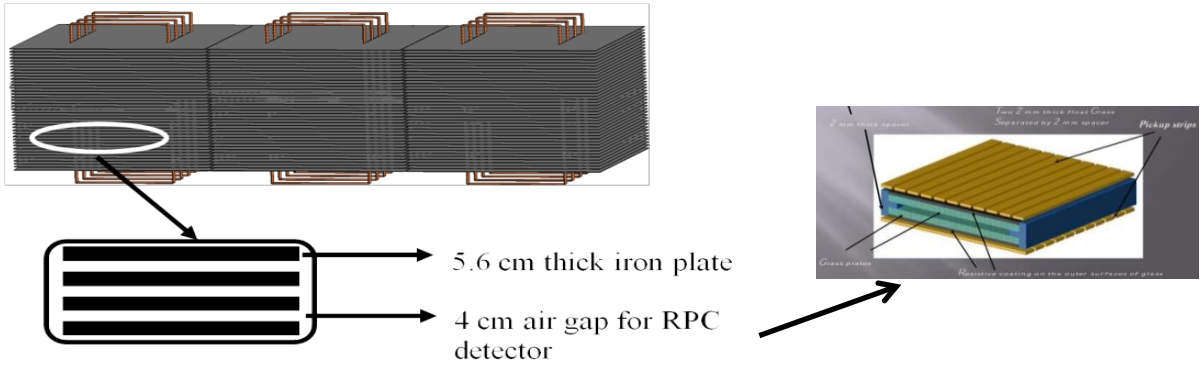




Laboratory layout with footprints of proposed experiments and other components

- Cavern access through 2km long adit (almost horizontal tunnel).
- One large cavern for proposed Iron Calorimeter (ICAL) experiment and two small caverns for Neutrino-less double beta decay and dark matter search.
- A small cavern on the tunnel-way to accommodate rock mechanics, geology, biology experiments etc.

Iron Calorimeter (ICAL)



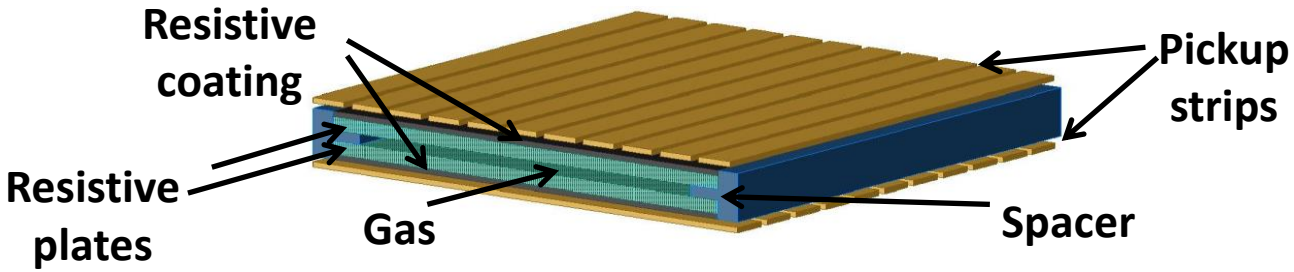
Magnetized Iron Calorimeter (ICAL) with RPC as detection element

Main detector : magnetised Iron CALorimeter (ICAL) of mass 50 kTon to detect atmospheric muon neutrinos through CC interaction with matter.

- Optimised to be sensitive in 1-10 GeV energy range.
- 5.6 cm thick iron plates in 151 layers to act as the target mass.
- Resistive Plate Chambers (RPCs) in 4 cm inter-plate air gap to act as the active detector elements for tracking muons and hadrons.
- Uniform magnetic field of 1.5 T applied across the calorimeter for charge separation and momentum measurement of muons.

Resistive Plate Chamber (RPC)

- Providing position and timing information of charged particles passing through it (position resolution ~mm, time resolution~1ns, efficiency > 95%)
- Two resistive plates (float glass/bakelite) of thickness 2mm separated by 2mm thick gas volume.
- Thin layer of resistive graphite coating applied on the plates for supplying high voltages.
- Two planes of pickup strips of 3cm width laid outside in orthogonal direction for providing position information.
- Avalanche mode operation with gas mixture of Freon (R-134A) 95% + Isobutane 4.5% + SF_6 0.5%.

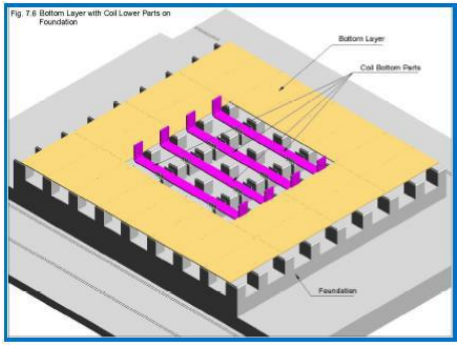


Schematic layout of RPC

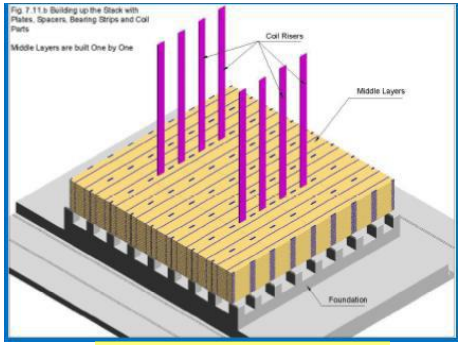
ICAL Specifications

ICAL Specification	
ICAL dimension	48.4m x16m x14.4m
No. of modules	3
Module dimension	16m x16mx14.4m
No. of layers	151
Iron plate thickness	56mm
Gap for RPC trays	40mm
Magnetic field	1.4 Tesla

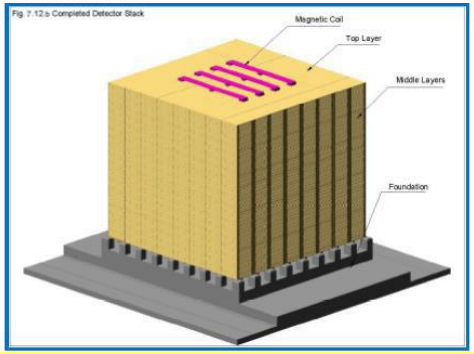
RPC Specification	
RPC dimension	195cmx184cmx2.4cm
Readout strip width	3cm
No. of RPC/layer	192
Total no. of RPC	28800
No. of electronic channel	3.7×10^6



Bottom layer



Middle layer



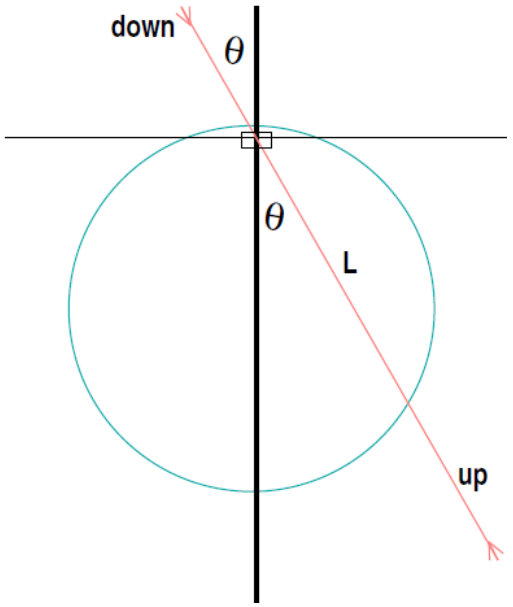
Completed ICAL module

Advantages of ICAL

- Large target mass to achieve statistically significant number of neutrino interactions in a reasonable time-frame (say 5 years) for the confirmation of atmospheric neutrino oscillation.

- Almost complete coverage to incoming neutrinos except those traveling almost horizontally. Thus providing sensitivity to a large range of path length (L) for the neutrinos travelling through the Earth.

- Measurement of L/E of incoming neutrino with wide variation possible due to variations in energy spectrum (E) of atmospheric neutrinos along with the path length (L). Good possibility of observation of oscillation pattern in L/E spectrum.

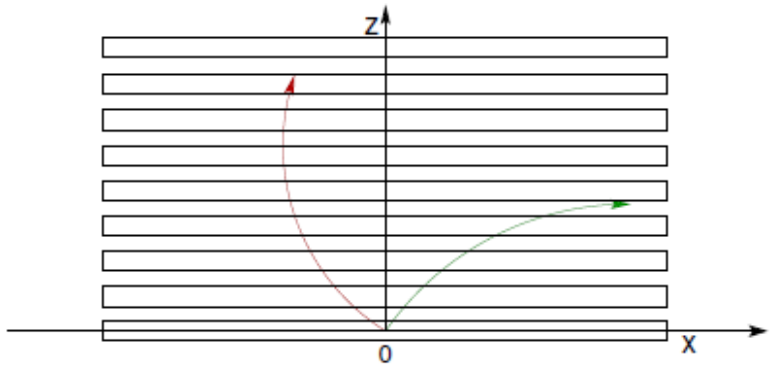


Measurement Capabilities

- Determination of neutrino flight direction using TOF technique effective due to fast timing response of RPC (to estimate the distance (L) traversed by neutrino).
- Discrimination between two charge states of muons with applied magnetic field and tracking capability of RPC (to study matter effects for different charge states) and thus allowing sensitivity to the neutrino mass hierarchy,
- Momentum measurement of muons from the extent of bending of tracks in local magnetic field using tracking capability of RPC (to estimate energy (E)).

Key contributors:

- **RPC time resolution ~ ns**
- **RPC space resolution ~ mm**
- **RPC efficiency > 95%**
- **Magnetic field ~ 1.5 Tesla**



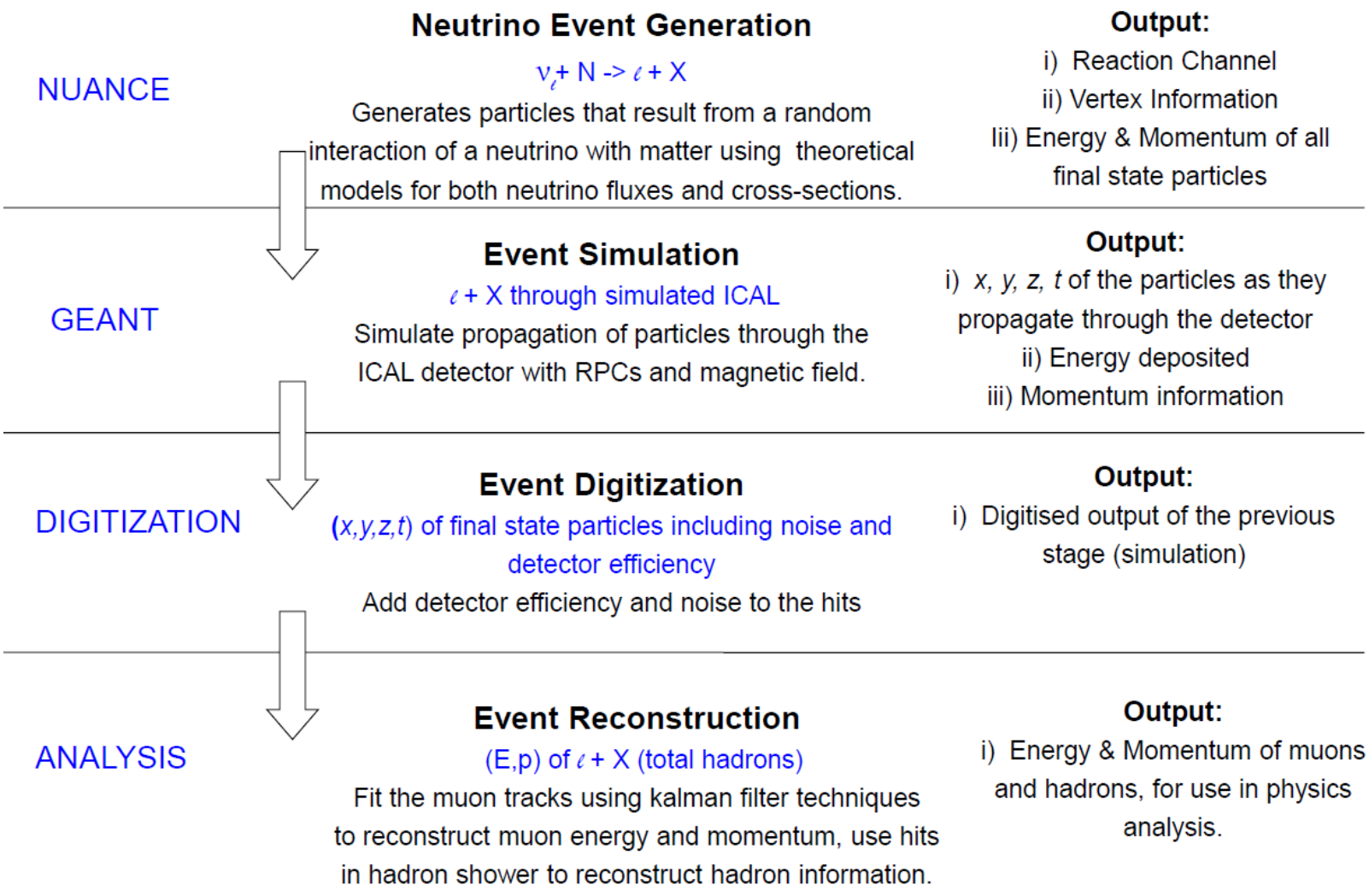
Physics Reach of ICAL

The good tracking ability and energy resolution of ICAL for muons make it very well suited for the study of atmospheric neutrino oscillation physics. ICAL is also sensitive to the energy deposited by hadrons in multi-GeV range that enables a significant improvement in the physics reach of ICAL.

- **To determine the neutrino mass hierarchy (sign of $|\Delta m^2_{32}|$, same as that of $|\Delta m^2_{31}|$) using matter effects independent of CP phase at ICAL.**

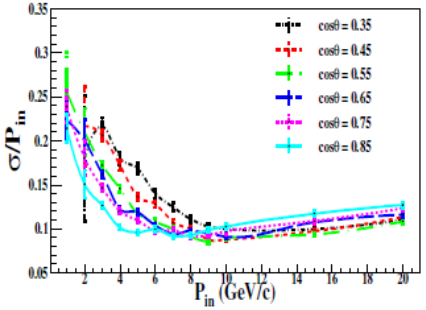
- To deliver improved precision of oscillation parameters ($|\Delta m^2_{32}|, \sin^2 2\theta_{23}$).
- To measure the deviation of 2-3 mixing angle (θ_{23}) from its maximal value and determine its correct octant.
- To offer test grounds for various new physics like NSI, CPT violation, long range forces, ultra-high energy neutrinos, indirect searches of dark matter.

Simulation Framework

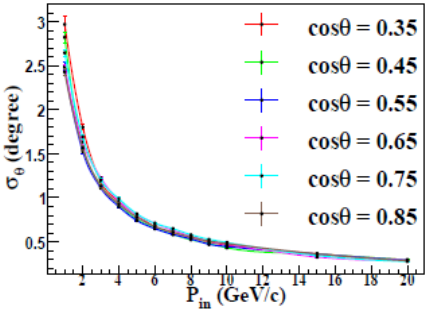


ICAL Muon Responses

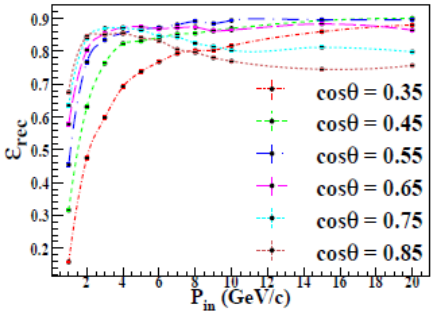
- ICAL optimised for detecting muons produced in CC interactions of neutrinos.
- The momentum resolution ~ 20% (10%) for energies of 2 GeV (10 GeV)
- The direction resolution better than a degree for all angles for Eμ > 4 GeV.
- The reconstruction efficiency ~ 80% for Eμ > 2 GeV.
- The relative charge identification efficiency ~ 98% for all energies.



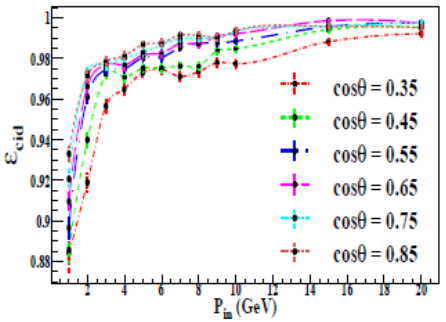
Momentum resolution



Zenith angle resolution



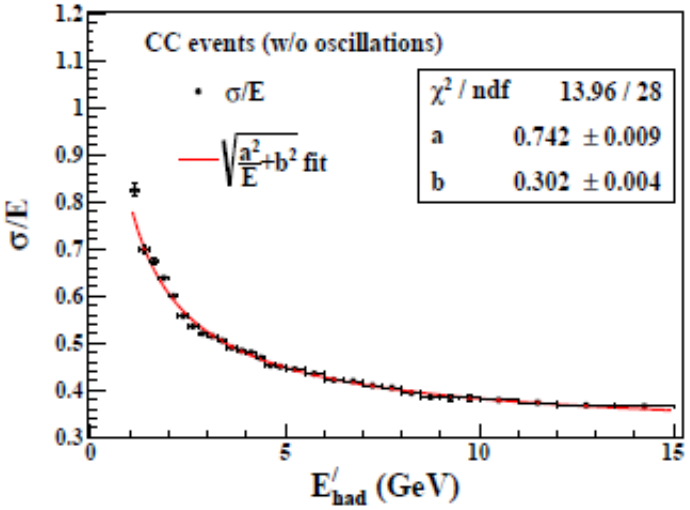
Reconstruction efficiency



Relative charge identification efficiency

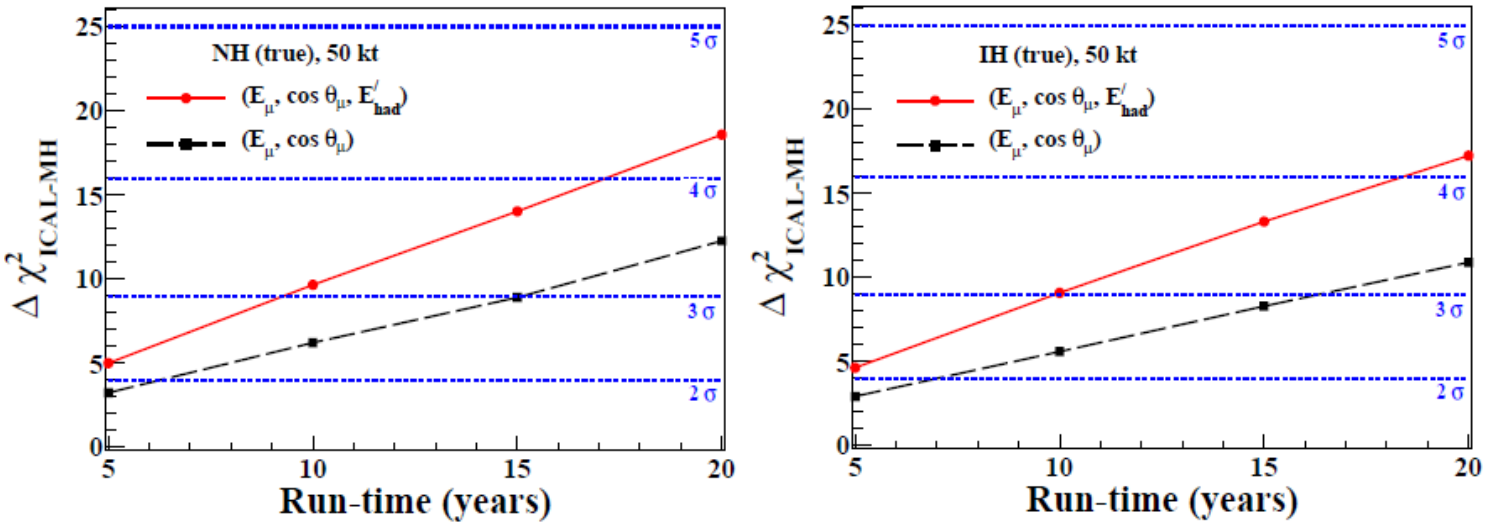
Hadron Response

- ICAL sensitive to hadrons over a wide energy range.
- Hadron energy resolution of ICAL required to perform physics analysis as the correlated information of muon and hadron in a CC event helpful to enhance the capabilities of the ICAL.
- The simulated hadron energy resolution ranging from 85% (at 1 GeV) to 36% (at 15 GeV).



Hadron energy resolution

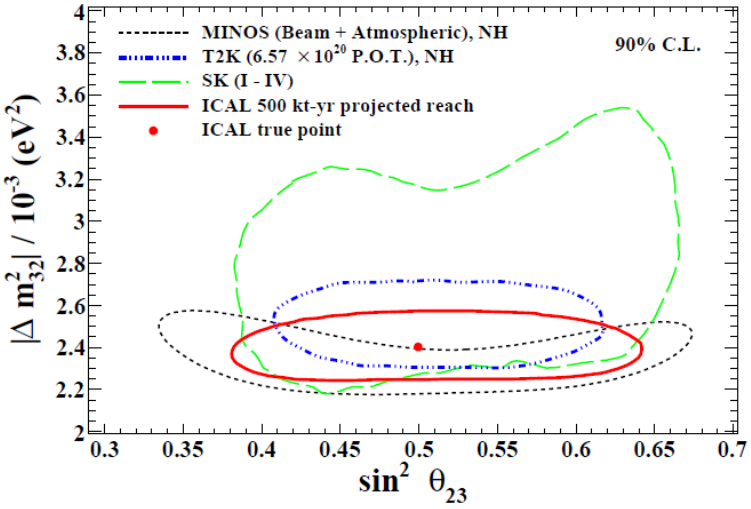
Physics Capabilities



Mass hierarchy sensitivity of ICAL as a function of the experiment run-time
[for $sin^2 2\theta_{13}(true) = 0.1$ and $sin^2 2\theta_{23}(true) = 0.5$]

- Statistical significance to rule out the wrong hierarchy quantified by $\Delta\chi^2{}_{ICAL-MH} = \chi^2{}_{ICAL}(false\ MH) - \chi^2{}_{ICAL}(true\ MH)$
- 10 years of running of the 50 k Ton ICAL can rule out the wrong hierarchy with $\Delta\chi^2{}_{ICAL-MH} \approx 9.7$ (for true NH) and $\Delta\chi^2{}_{ICAL-MH} \approx 9.1$ (for true IH).
- Increase of 40% in $\Delta\chi^2{}_{ICAL-MH}$ compared to muon-only value due to addition of correlated hadron energy information.

Physics Capabilities



Comparison of the projected 90% C.L. precision reach of ICAL with other experiments

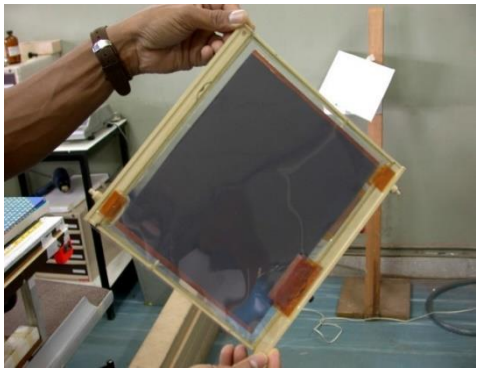
- Precision in the measurements of a parameter λ ($sin^2\theta_{23}$ or $|\Delta m^2_{32}|$) quantified as $\Delta\chi^2{}_{ICAL-PM} = \chi^2{}_{ICAL}(\lambda) - \chi^2{}_0$ where $\chi^2{}_0$ is the minimum of $\chi^2{}_{ICAL}$ in the allowed parameter range.
- ICAL able to achieve a $sin^2\theta_{23}$ precision comparable to the current precision for SK or T2K using hadron energy information.
- ICAL $|\Delta m^2_{32}|$ precision comparable to the MINOS reach.
- True choices of the parameters marked with a dot.

Physics Capabilities Highlights

- ICAL is extremely suitable for determining the neutrino mass hierarchy, due to its capabilities of measurements of muon and hadron energies, and identification of the muon charge.
- The cleanest and the simplest analysis of the ICAL data uses the information on muons only. However the reach of the detector improves tremendously if the information on hadron energy is also used in addition.
- Analysis indicates that in 10 years, a 50kTon ICAL can, by itself, distinguish between the normal and the inverted hierarchy with a significance of more than 3σ.
- Mass hierarchy measurement of ICAL is independent of the actual value of CP phase.
- This feature may be exploited by combining the ICAL information with that from other CP-sensitive experiments, to improve the mass hierarchy discrimination.

Orchestra of Neutrino Physics

RPC Research & Development

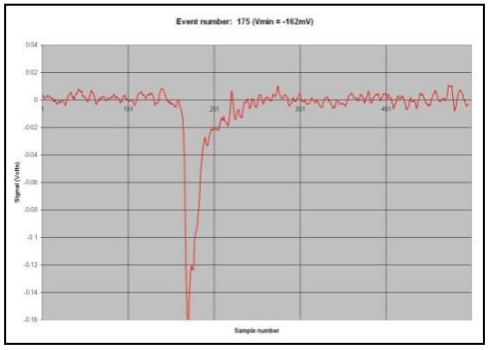


30cmx30cm

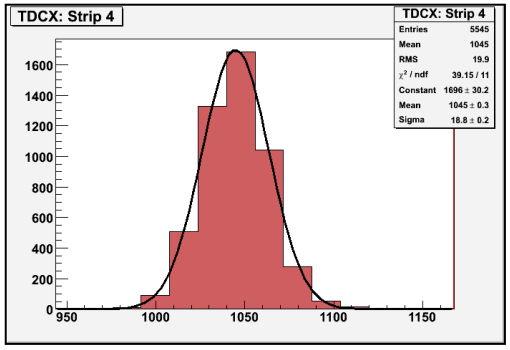
1mx1m

2mx2m

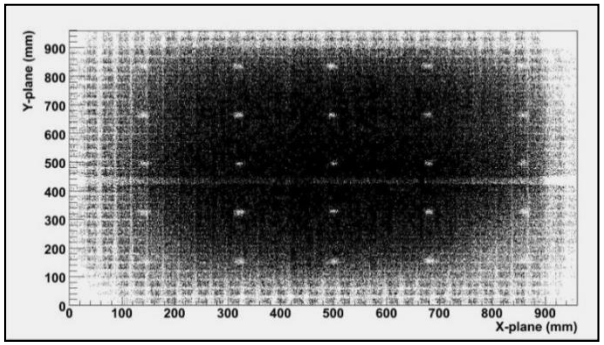
Evolution of glass RPC prototypes



Muon pulse in RPC



RPC timing response



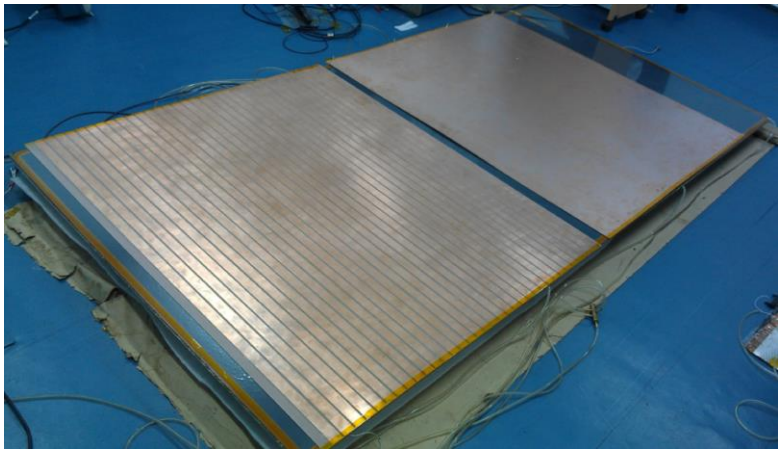
RPC image using muons

RPC responses

RPC Research & Development

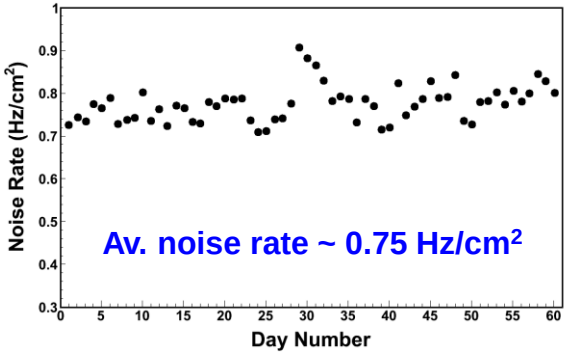
30cmx30cm

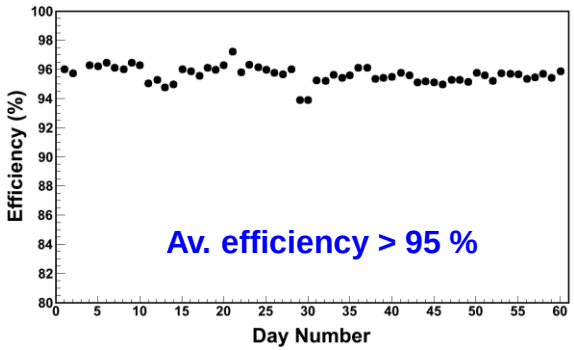
1.2mx2.4m

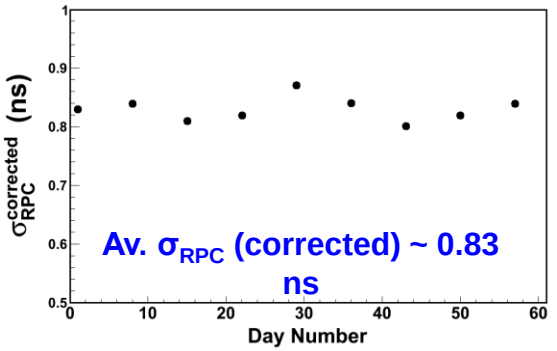


1.07mx1.22m pickup panel

Evolution of bakelite RPC prototypes



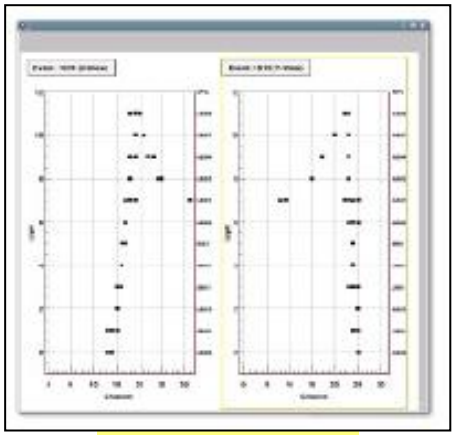




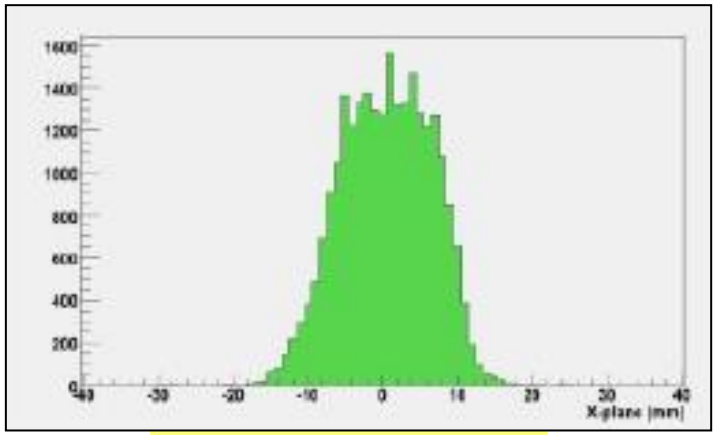
Long-term performances

Cosmic Ray Test

Stack of 12 RPCs of 1mx1m

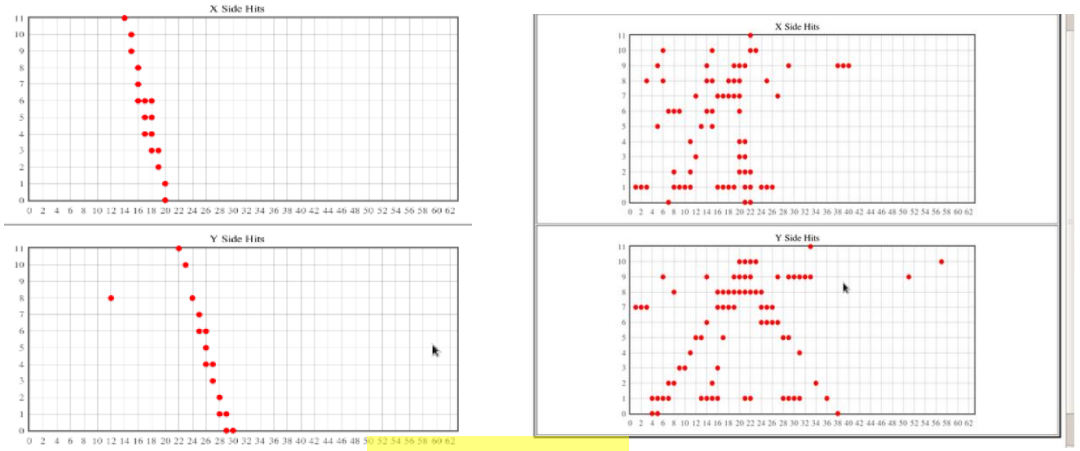


Muon tracks



Track residue in mm

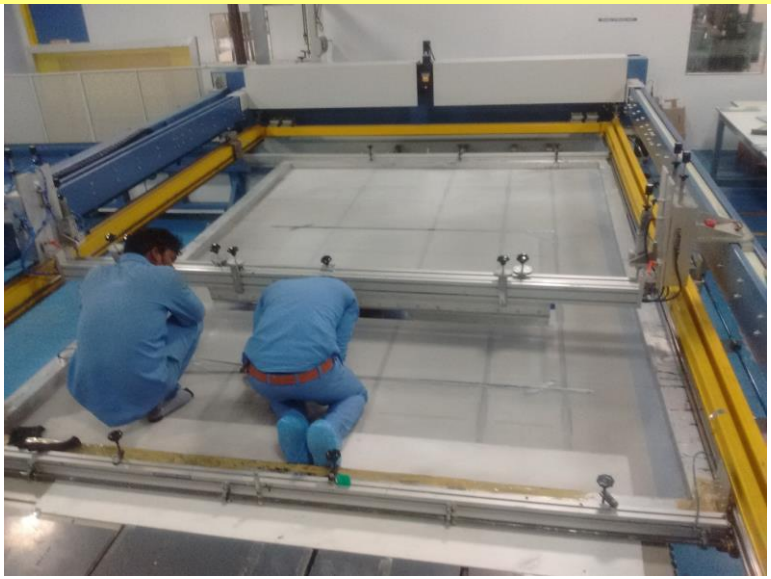
Stack of 12 RPCs of 2mx2m



Muon tracks

Production

Production of 2mx2m glass RPC gap at Saint Gobain industry

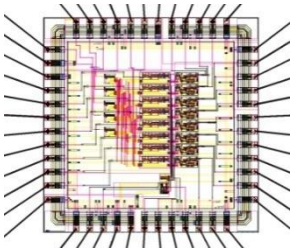


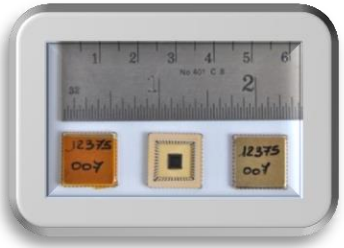
RPC Handling & Storage

Procurement and storage of RPC gaps

ICAL Electronics

- ICAL FEE ASIC chip ANUSPARSH-III based on 0.35µ mixed CMOS technology ready.
- 4 prototype FEE boards operational.
- Small volume production of ANUSPARSH-III planned to be started shortly.
- Automated test setup for ASIC IC and pre-assembly testing of ASIC chipset developed and tested.





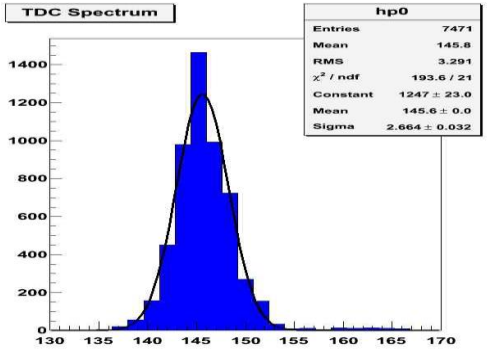
Specification of ANUSPARSH	
Channel gain	~ 4 mv/µA
I/p dynamic range	1- 80 µA
I/p impedance (upto 500MHz)	< 45 Ohm
Propagation delay	< 1 ns
Power Consumption/Channel	~ 45 mW
LVDS output current	+/- 4 mA

Automated IC testing

ICAL Data Acquisition

- High performance FPGA (featuring a μC softcore), TDC and waveform sampler based 64 channel RPC-DAQ board prototyped and operational.

DAQ with TDC ASIC



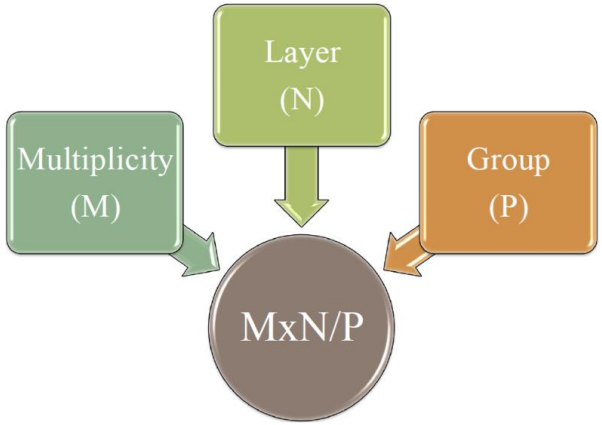
TDC measurement of RPC

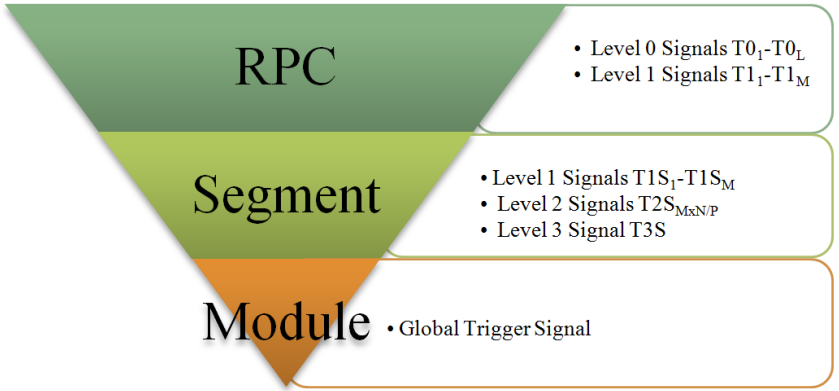
- 20 RPC-DAQ-v1s produced with same HW specs and received (Dexcel, Bangalore).
- RPC-DAQ-v1 integrated with one of the 2m x 2m RPC.
- RPC-DAQ-v3 under development addressing integration issues.

RPC-DAQ-v3 corner module

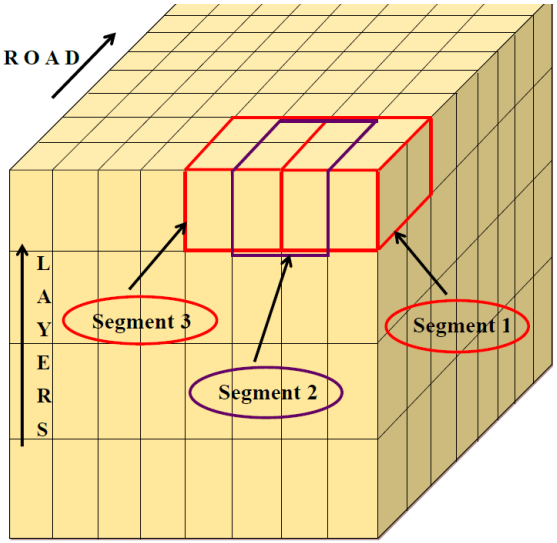
ICAL Trigger Scheme

- 1st version of ICAL trigger scheme in place.
- Many implementation aspects tested, integration issues being addressed.

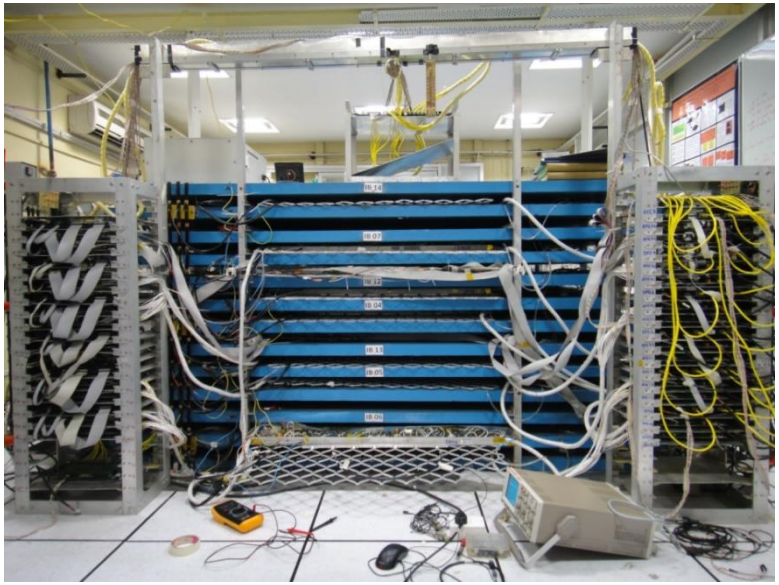




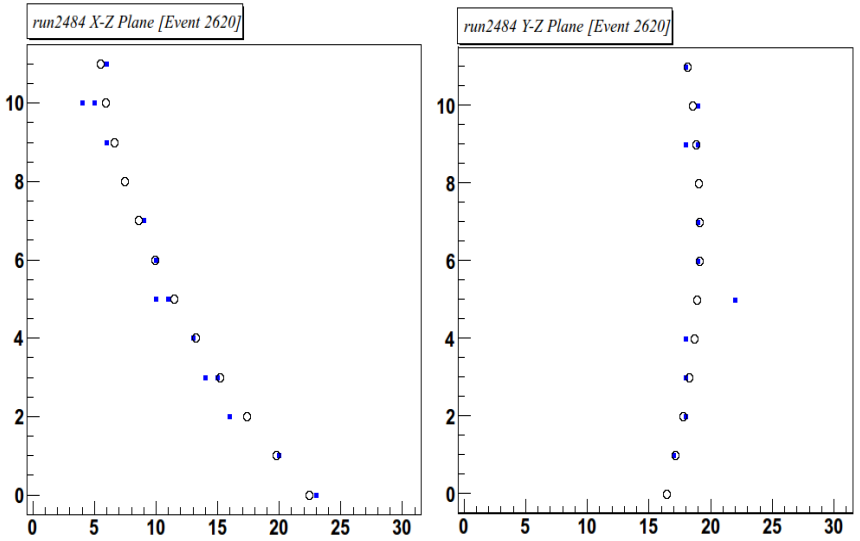
- Trigger criteria based on event topology alone.
- Distributed and hierarchical architecture.
- Detector module segmented to generate local trigger.
- Combination of local triggers produces global trigger.
- Global trigger latches event data.



ICAL Prototype



35 Ton ICAL prototype



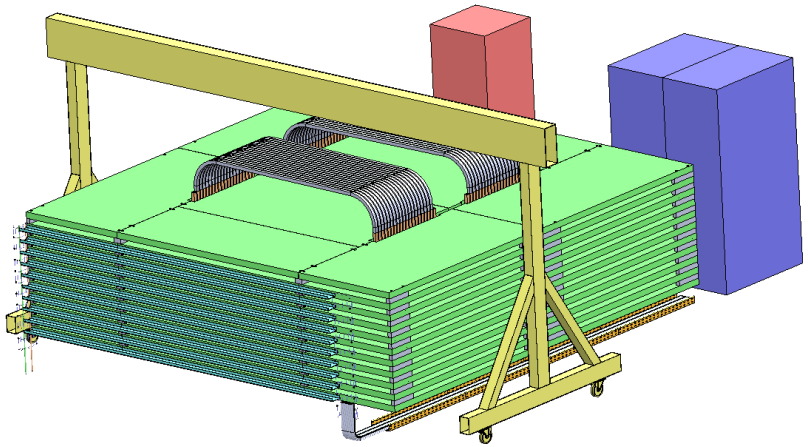
Muon tracks

- Built 35 Ton prototype with 12 gaps.
- Housed 1mX1m RPCs of both glass and bakelite-type.
- Long term operational experience of RPCs achieved.
- Stability and suitability of LV and HV electronics tested.
- Muon track reconstruction done with and without magnetic field.

Next Milestone

Mini-ICAL by the end of March, 2017

(to be followed by Engineering Prototype in near future)



Iron plate machining at ESSAR industry

- Planned to set up at Madurai, IICHEP transit camp.
- 4m x 4m x 11 plate layers Mini-ICAL Model.
- 2 RPCs in each of 10 layers.
- Test ground of latest FEE, DAQ, Trigger, analysis etc.

Current Status of ICAL & INO

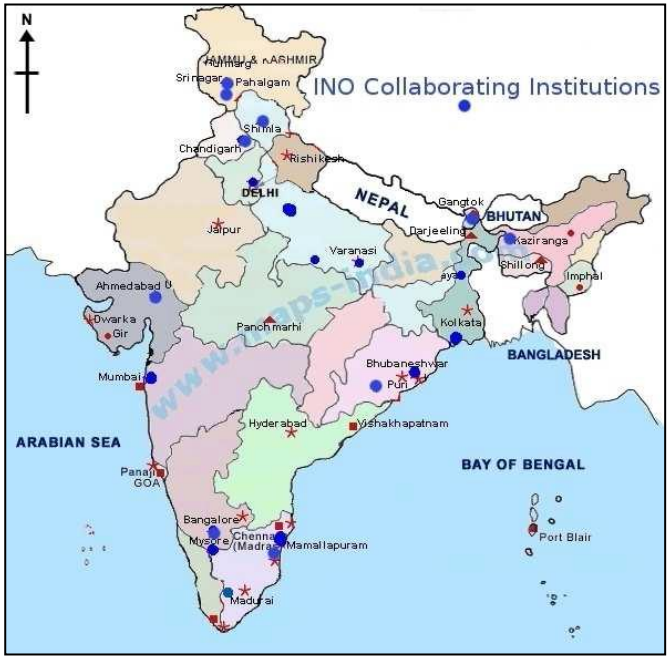
ICAL Status

- Detector R&D over for glass RPC.
- Industrial production of glass RPC started.
- Foundry-level production of Front-End Electronics to start shortly.
- Mini-ICAL development by March, 2017.

INO Status

- Full project approved by PM's cabinet committee to start construction.
- INO site infrastructural plan complete. Construction work presently on hold due to oppositions from some quarters.
- Plan of Inter-Institutional Centre for High Energy Physics (IICHEP) at Madurai city (110 km from the underground site) ready. Awaiting clearance from the land department of the state government.

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

- One of the largest basic science projects in India in terms of man power and cost as well.
- Nearly 100 scientists from 23 research institutes and universities of India.
- Graduate students inducted every year through national level selection test since 2008.

INO Collaboration meeting, 24-25 October, 2016, Mumbai

Thank you all on behalf of INO Collaboration!!

Back-up

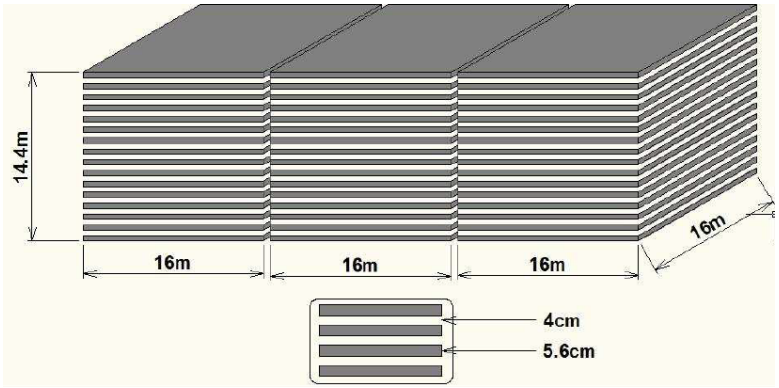
Site Activities (Preliminary)

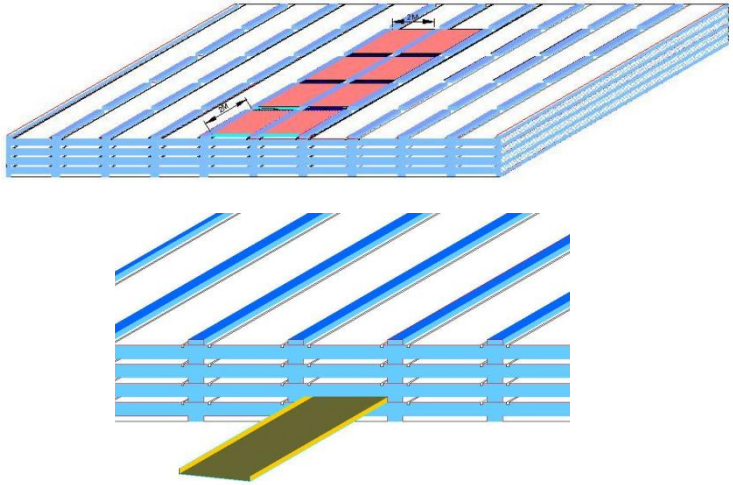
IICHEP construction activities

INO site construction activities

Choice of Design

- Technological capabilities available within the country.
- Modularity and possibility of phasing.
- Compactness and ease of construction.
- Low cost material budget.
- Material availability within the country.
- Design of other neutrino detectors around the world.





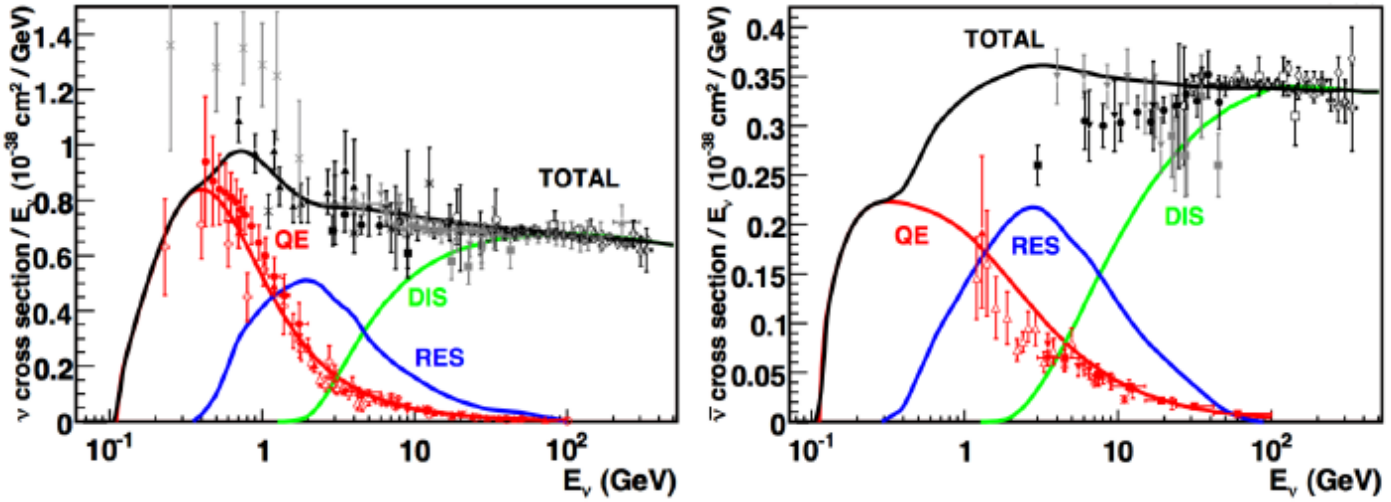
Schematic arrangement layout of ICAL

Future Projection

Parameter	ICAL	e-ICAL	m-ICAL
No. of modules	3	1	1
Module dimensions	16.2m×16m×14.5m	8m×8m×2m	4m×4m×1m
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	1,950mm×1,910mm×24 mm	1,950mm×1,910mm×24 mm	1,950mm×1,910mm×24mm
Readout strip pitch	30mm	30mm	30mm
No. of RPCs/Road/Layer	8	4	2
No. of Roads/Layer/Module	8	4	1
No. of RPC units/Layer	192	16	2
No. of RPC units	28,800 (107,266m^2)	320 (1,192m^2)	20 (74.5m^2)
No. of readout strips	3,686,400	40,960	2,560

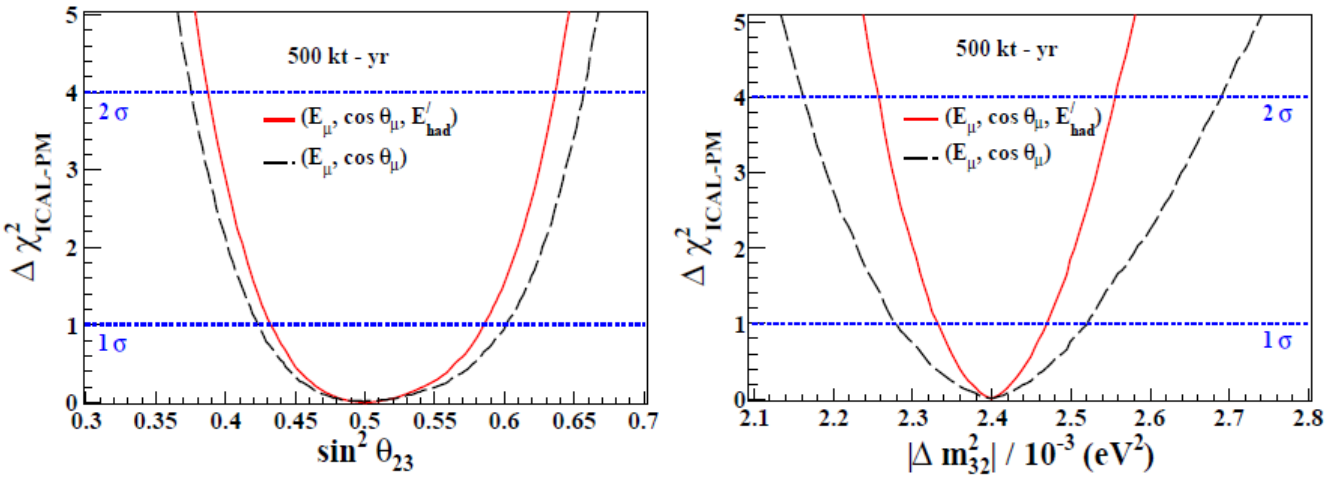
Event Generation

- Neutrino events generated through NUANCE3.5 event generator.
- Presently HONDA fluxes generated at Kamioka site used.
- Several interaction processes relevant at this energy modelled in NUANCE (cross-sections shown below)
- Simple ICAL geometry with iron and glass components considered.
- Only unoscillated neutrino events generated and oscillation applied later externally.



Typical CC process cross-sections for ν_μ and $\bar{\nu}_\mu$

Physics Capabilities



Precision measurement of atmospheric parameters of ICAL assuming NH as true hierarchy

- Precision in the measurements of a parameter λ ($sin^2\theta_{23}$ or $|\Delta m^2_{32}|$) quantified as $\Delta\chi^2{}_{ICAL-PM} = \chi^2{}_{ICAL}(\lambda) - \chi^2{}_0$ where $\chi^2{}_0$ is the minimum of $\chi^2{}_{ICAL}$ in the allowed parameter range.
- With the inclusion of hadron energy information, 500 kT-yr of ICAL exposure able to measure $sin^2\theta_{23}$ to a 1σ precision of 12% and $|\Delta m^2_{32}|$ to a 1σ precision of 2.9%.
- Muon-only precisions 13.7% and 5.4%, respectively.