



# *India-based Neutrino Observatory (INO)*

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**(On behalf of the INO collaboration)**

*<http://www.ino.tifr.res.in/ino/>*

# Introducing 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

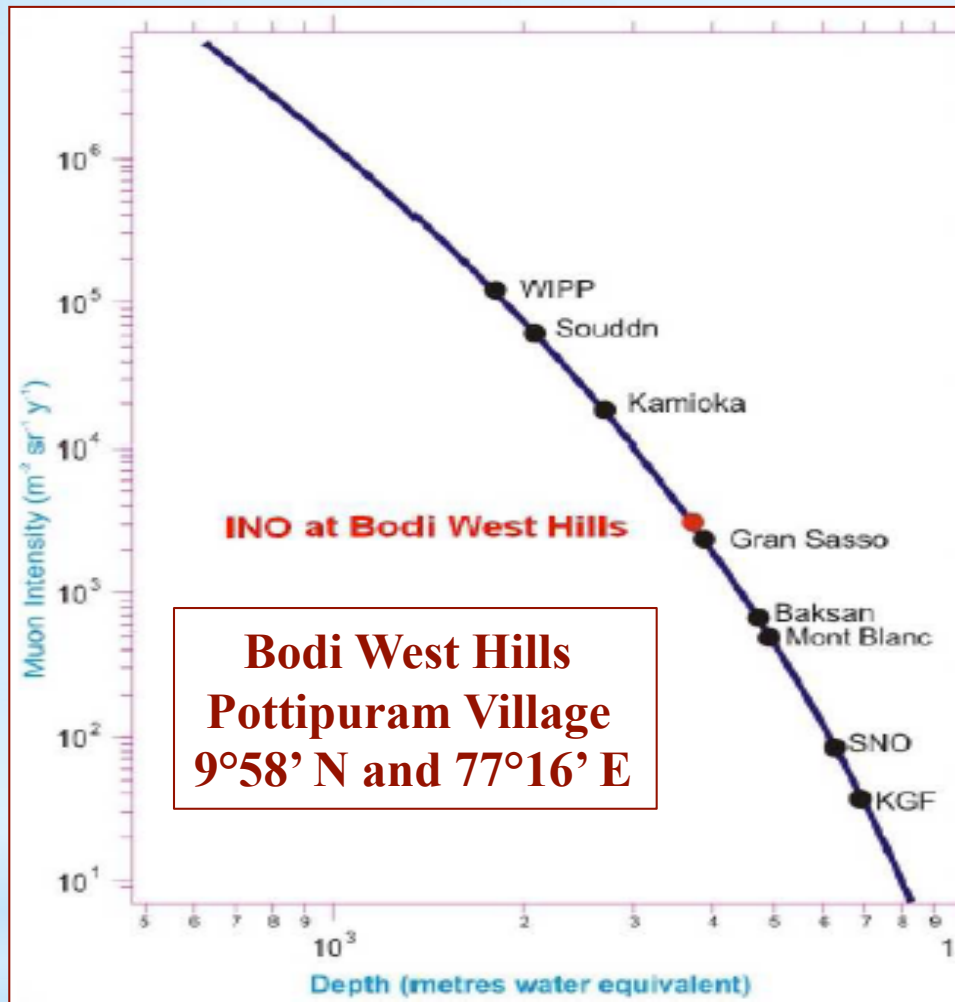
One of the largest basic science projects in India in terms of man power & cost as well

**We are growing day by day  
International Collaborators  
are most welcome**

# *India-Based Neutrino Observatory*

- *A multi-institutional attempt to build a world-class underground facility to study fundamental issues in science with special emphasis on neutrinos*
- *With ~1 km all-round rock cover accessed through a 2 km long tunnel.  
A large and several smaller caverns to pursue many experimental programs*
- *Complementary to ongoing efforts worldwide to explore neutrino properties*
- *A mega-science project (~250 M\$) in India, jointly funded (50:50) by the Department of Atomic Energy and the Department of Science and Technology*
- *INO project was discussed and approved by the Atomic Energy Commission*
- *Regarding Final approval: Clearance from the Cabinet expected soon*
- *International Community is welcome to participate in ICAL@INO activity.  
INO facility is also available to the entire community for setting up experiments like Neutrino-less Double Beta Decay, Direct Dark Matter searches*

# Coordinates of INO

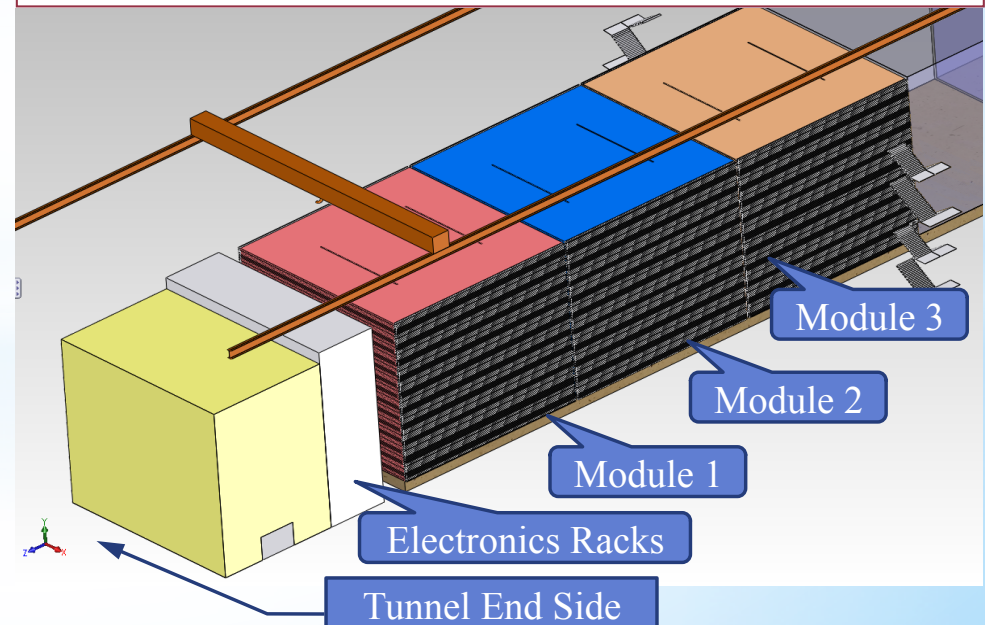
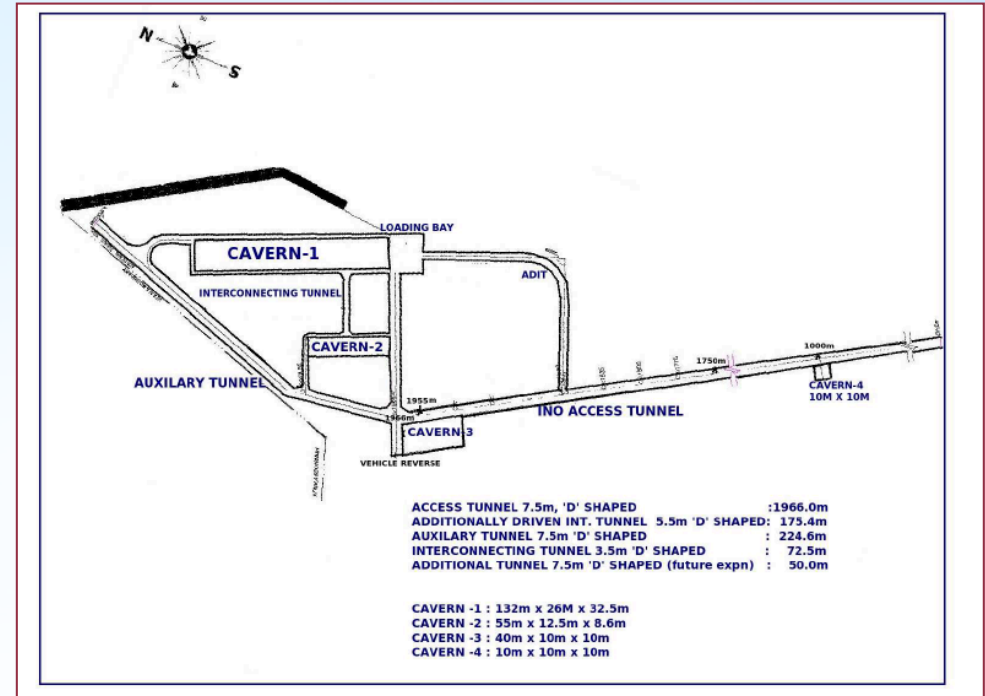


Located 115 km west of the Madurai city in the Theni district of Tamil Nadu

**Madurai has an International Airport**

# Approved projects under INO

- Come up with an underground lab & surface facilities near Pottipuram village in Theni district of Tamil Nadu
- Build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of neutrinos
- Construction of INO centre at Madurai: Inter-Institutional Centre for High Energy Physics (IICHEP)
- Human Resource Development (INO Graduate Training Program)
- Completely in-house Detector R&D with substantial INO-Industry interface
- Time Frame for 1<sup>st</sup> module: 2019



# *Physics Issues with ICAL-INO*

**Study Atmospheric neutrinos w/ a wide range of Baselines & Energies**

**Recent discovery of large  $\theta_{13}$  : A good news for ICAL-INO**

## *What do we want to achieve?*

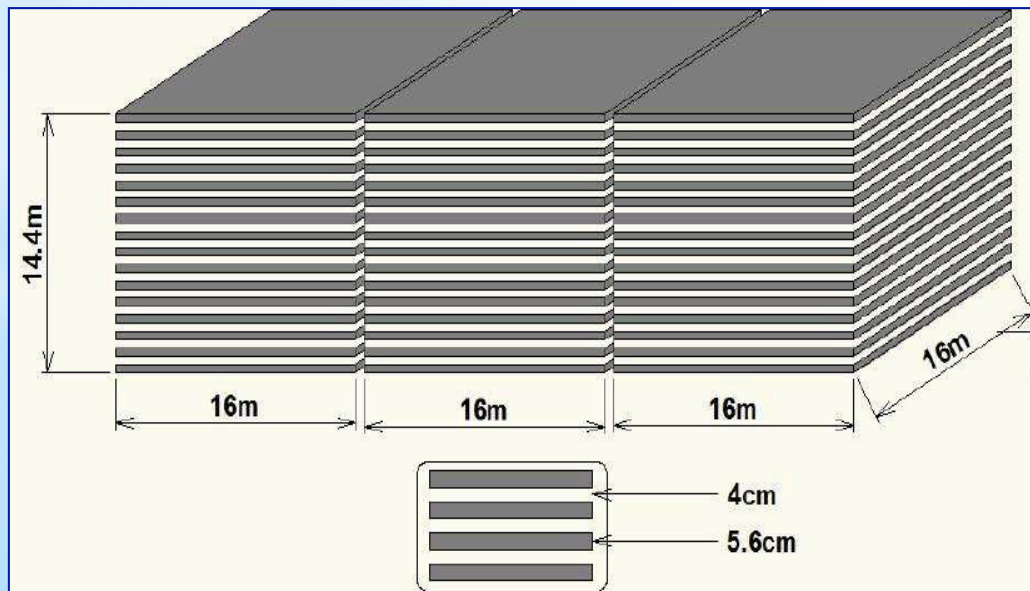
- ❖ *Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately*
- ❖ *Improved precision of atmospheric oscillation parameters*
- ❖ *Determine neutrino mass hierarchy using matter effects via charge discrimination*
- ❖ *Measure the deviation of 2-3 mixing angle from its maximal value and its octant*
- ❖ *Test bed for various new physics like NSI, CPT violation, long range forces*
- ❖ *Detect Ultra High Energy Neutrinos, Cosmic Muons, Indirect searches of DM*

# Detector Characteristics

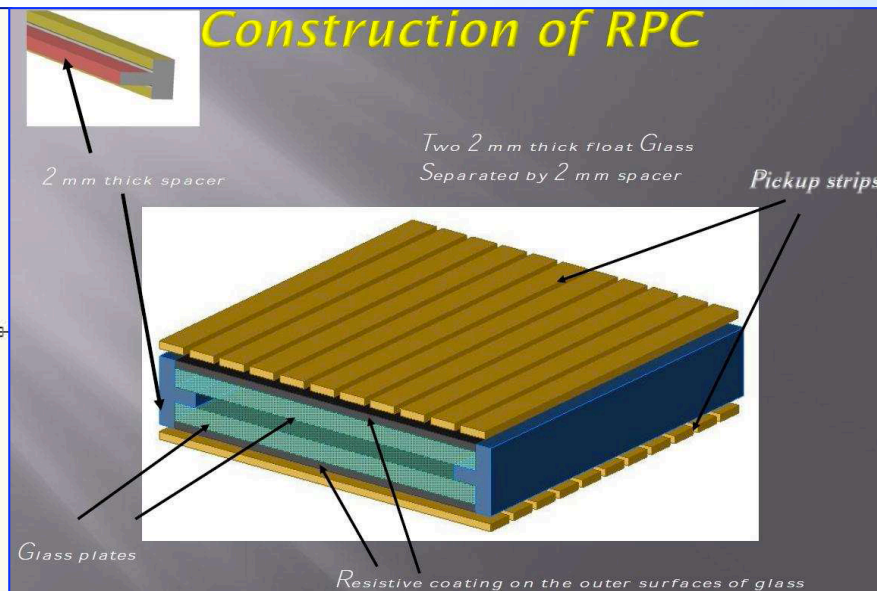
- *Should have large target mass (50 – 100 kt)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*
- *Complementary to the other existing and proposed detectors*

## Our choice

*Magnetized iron (target mass): ICAL*



*RPC (active detector element)*

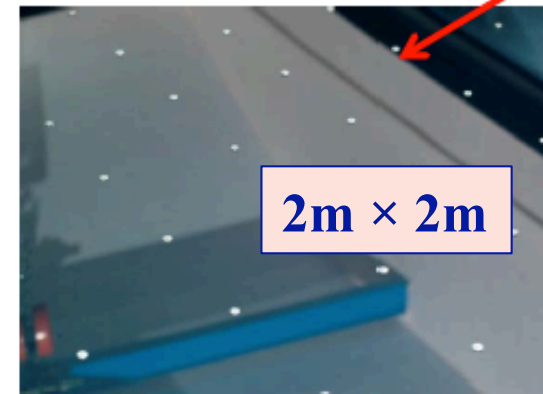
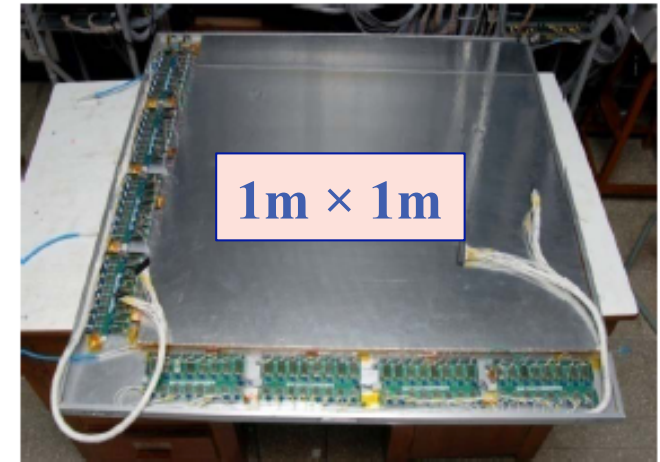
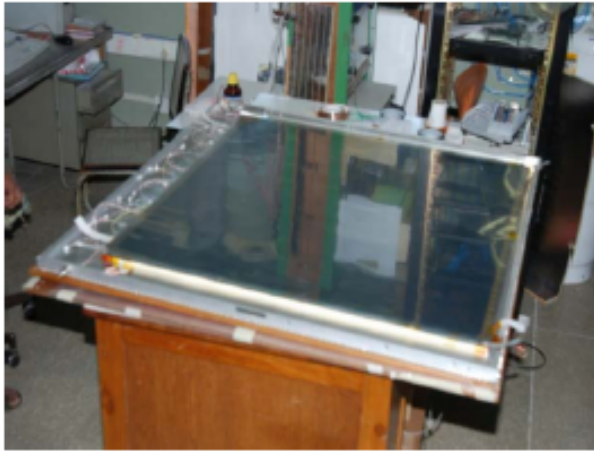


# *Specifications of the ICAL Detector*

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

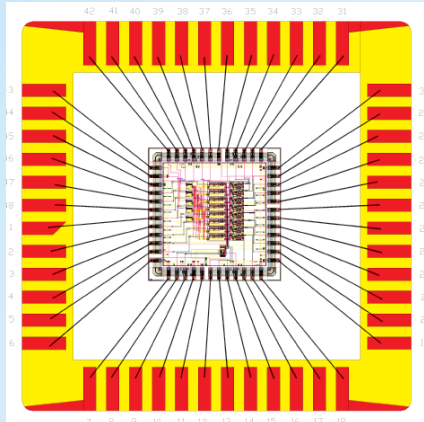


# *Fabricating Glass RPCs for ICAL*

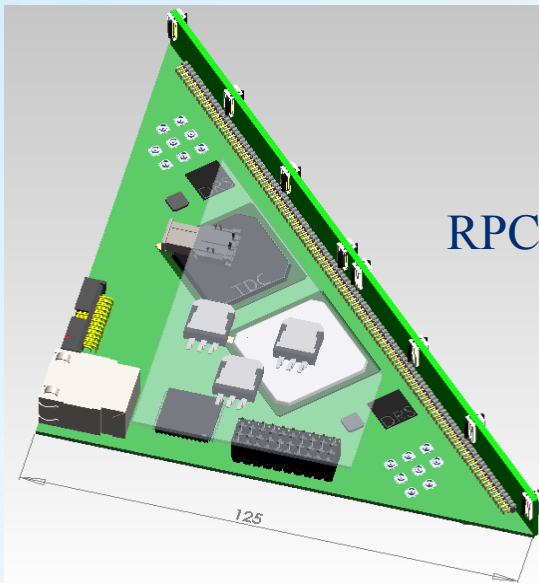


- *30 glass RPCs of 1m × 1m developed, tested for long in avalanche mode*
- *5 glass RPCs of 2m × 2m successfully assembled and tested*

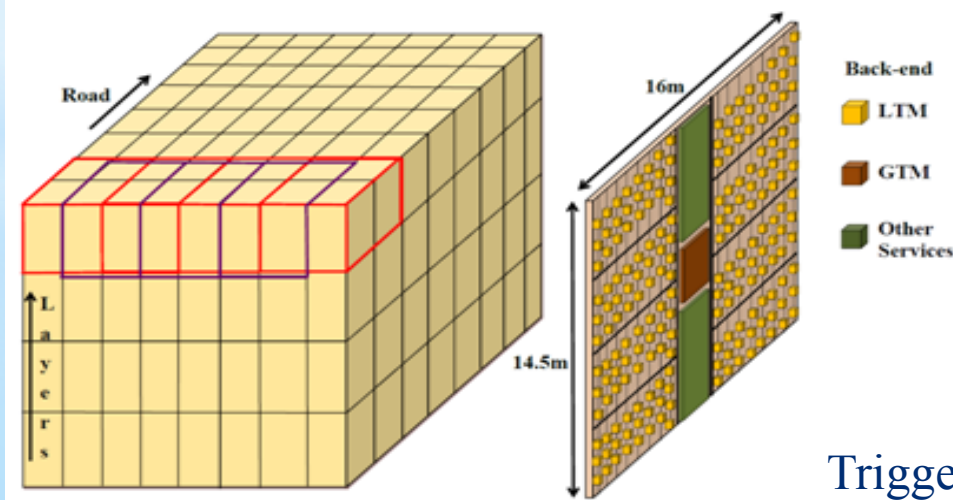
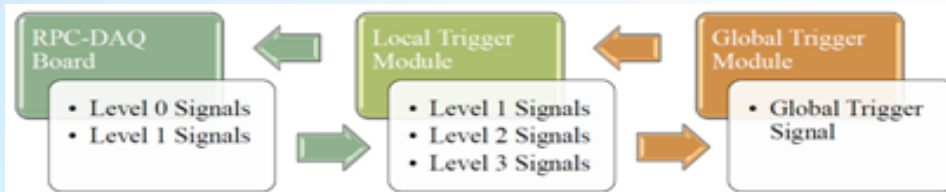
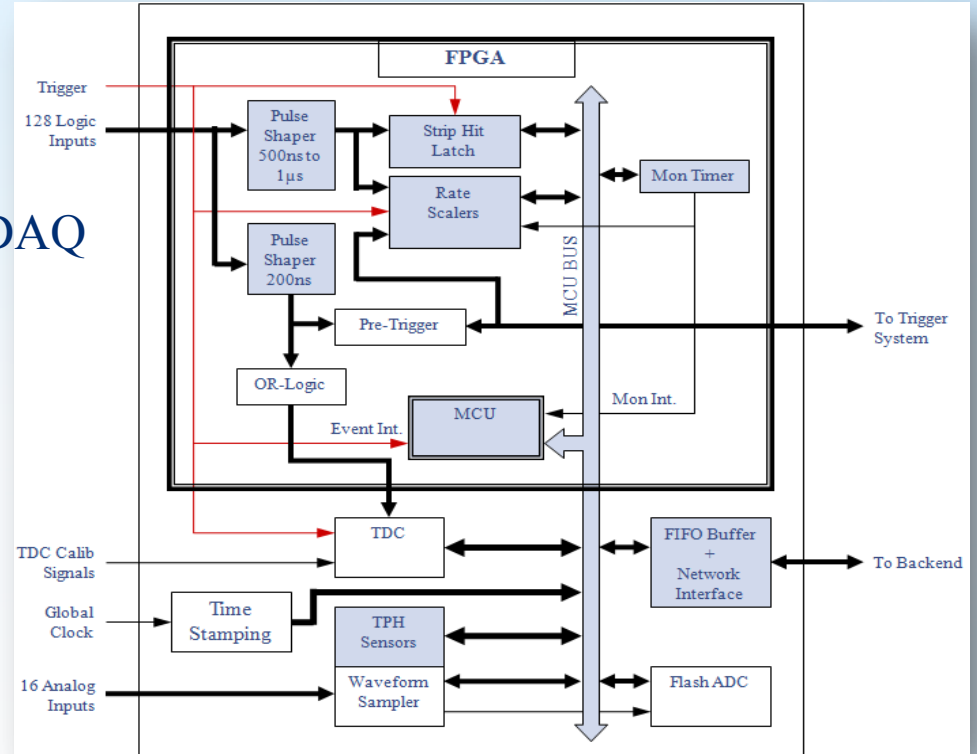
# Various Components of ICAL Electronics



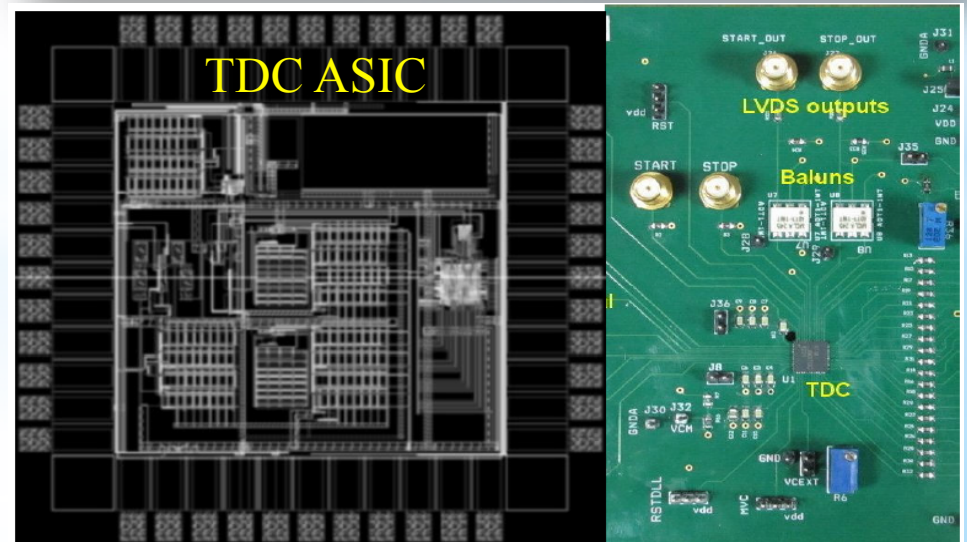
Front-end ASIC



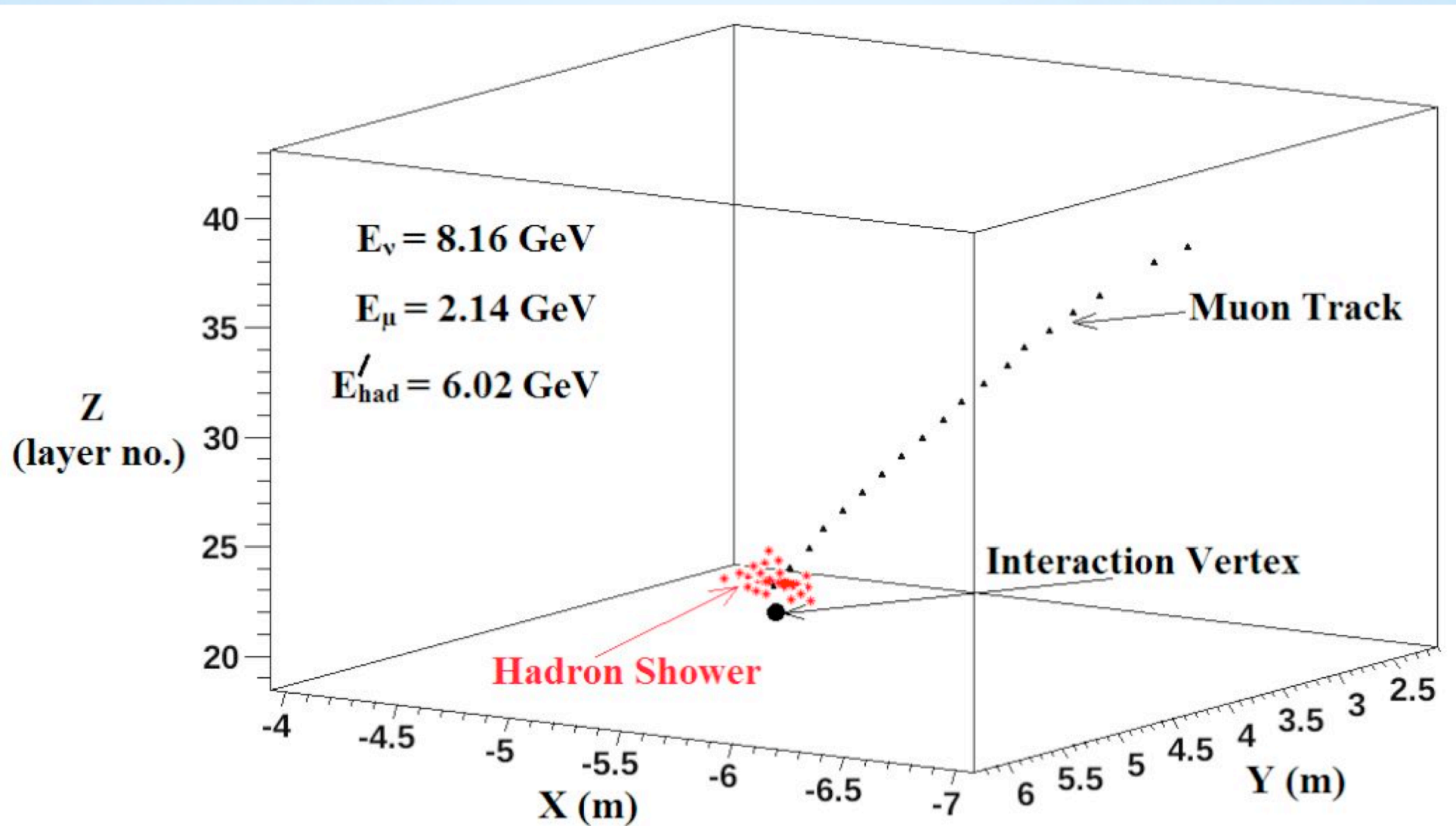
RPCDAQ



Trigger

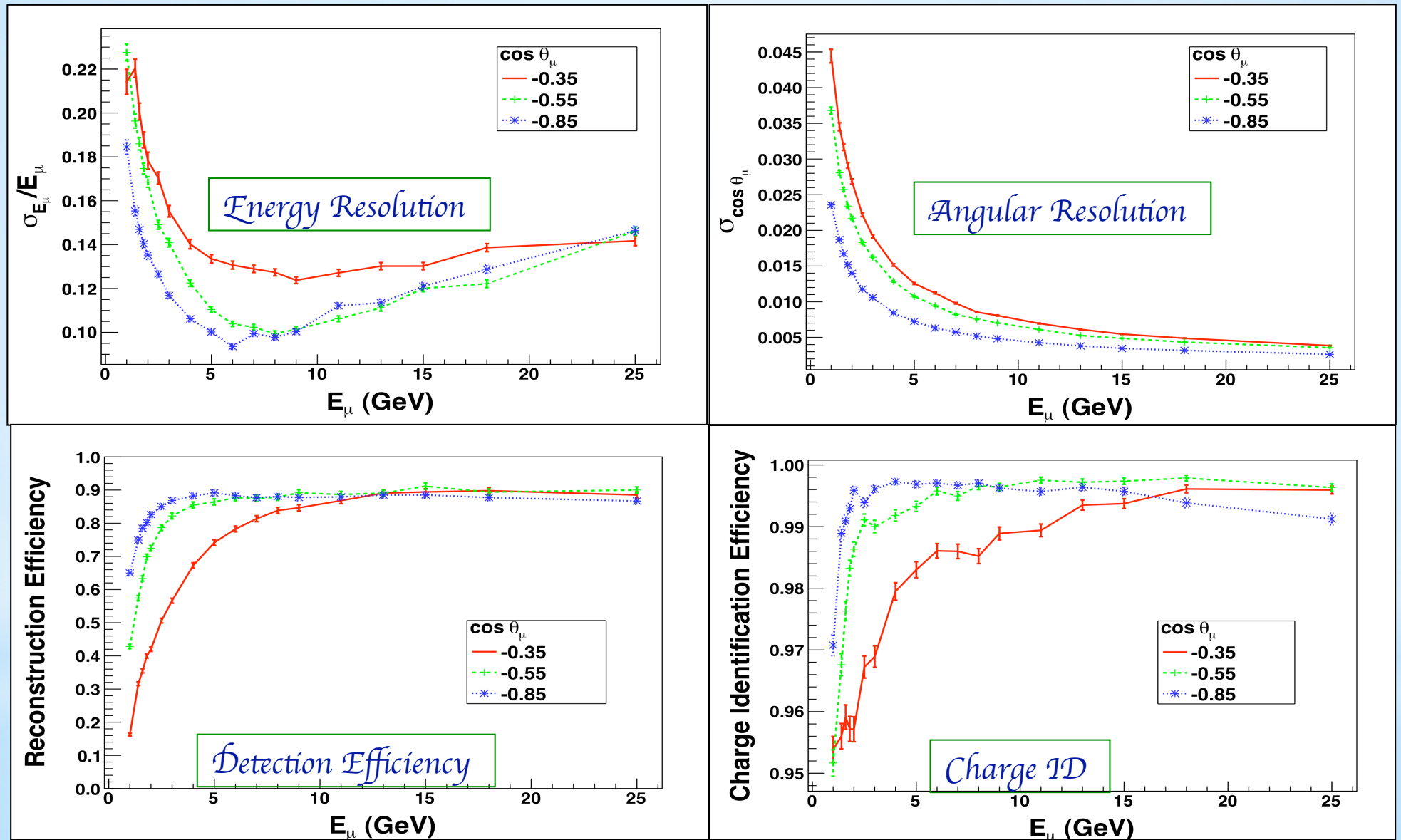


# Event Display Inside the ICAL Detector



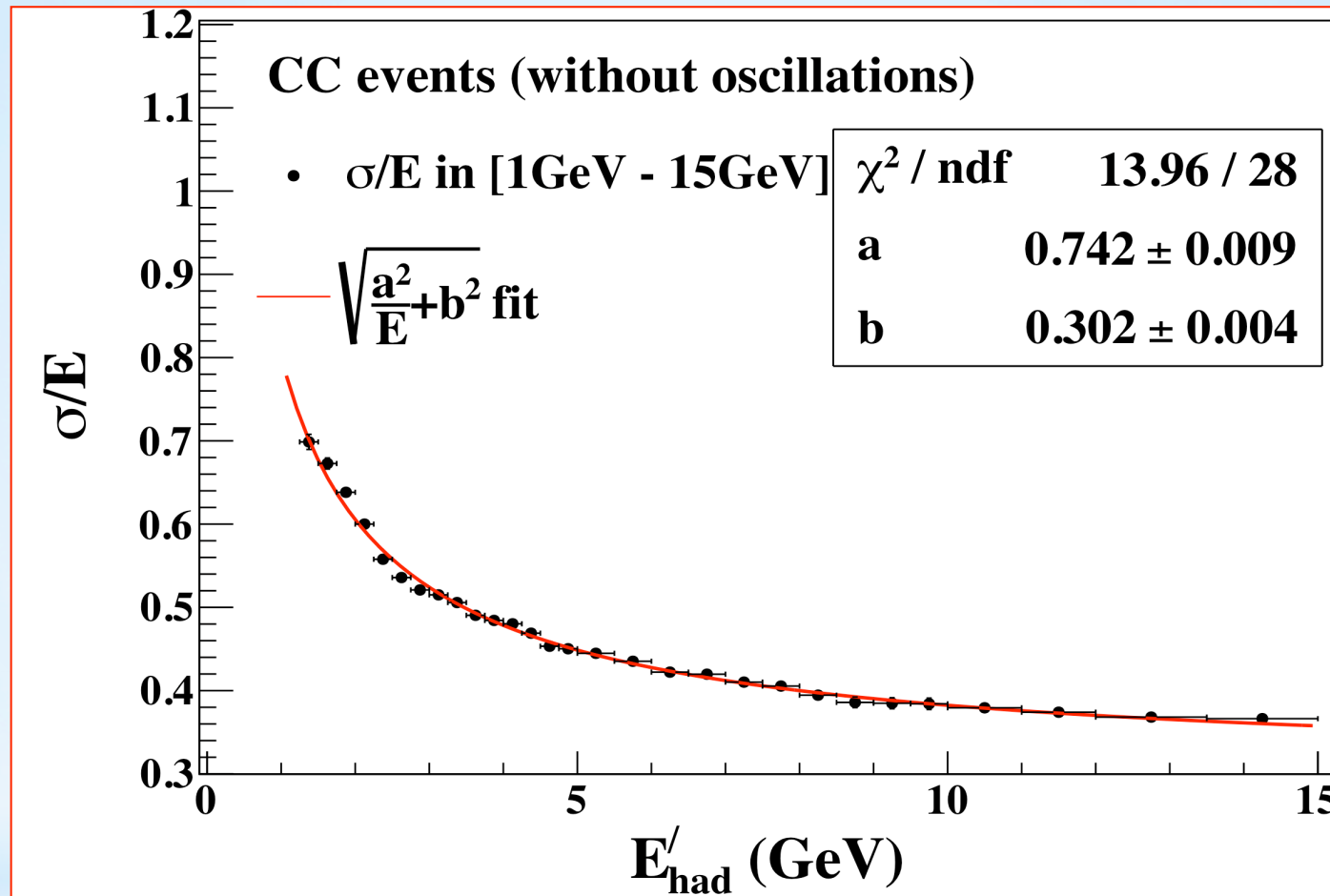
Using GEANT4 simulation

# Muon Efficiencies and Resolutions



Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore et al., arXiv:1405.7243 [physics.ins-det]

# Hadron Energy Response of ICAL



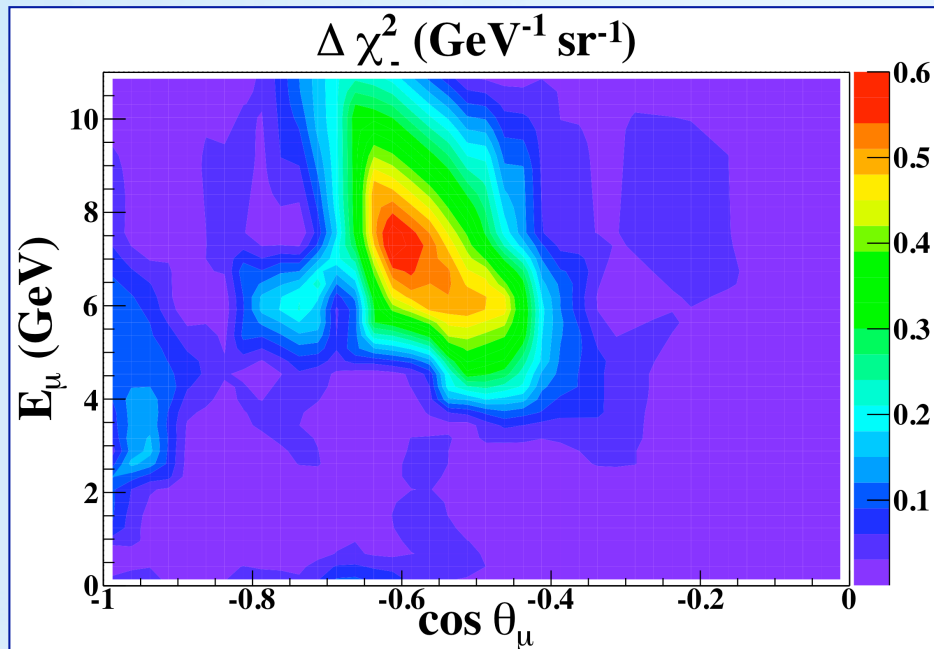
$$E'_h = E_\nu - E_\mu \text{ (from hadron hit calibration)}$$

**Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV**

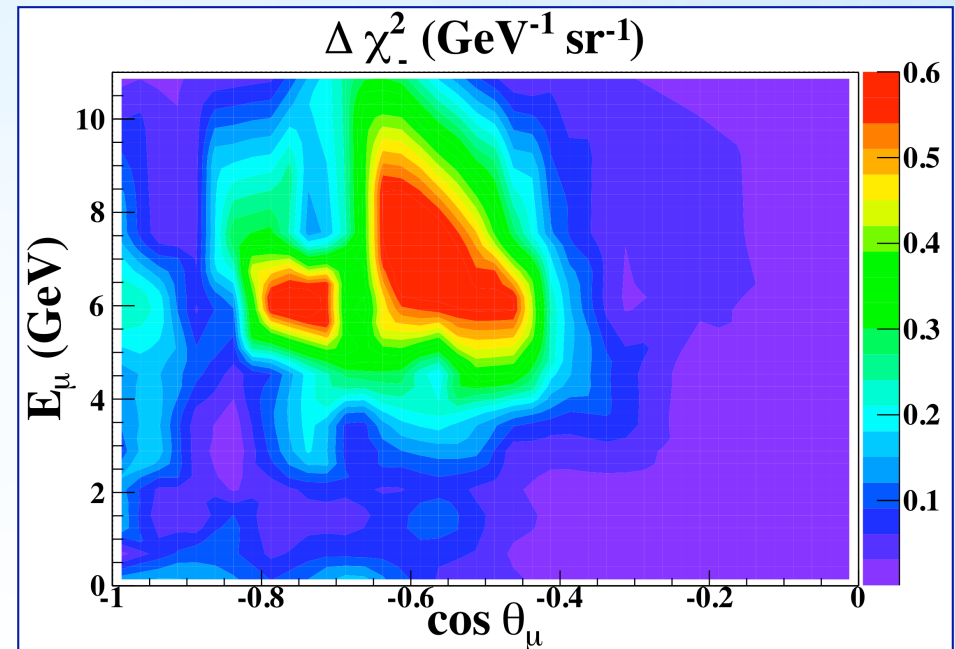
Moon Moon Devi, Anushree Ghosh, Daljeet Kaur, Lakshmi S. Mohan et al., JINST 8 (2013) P11003

# Neutrino Mass Hierarchy Discrimination

Distribution of  $\Delta\chi^2$  [ $\chi^2$  (IH) -  $\chi^2$  (NH)] for mass hierarchy discrimination considering  $\mu^-$  events



Hadron energy information not used

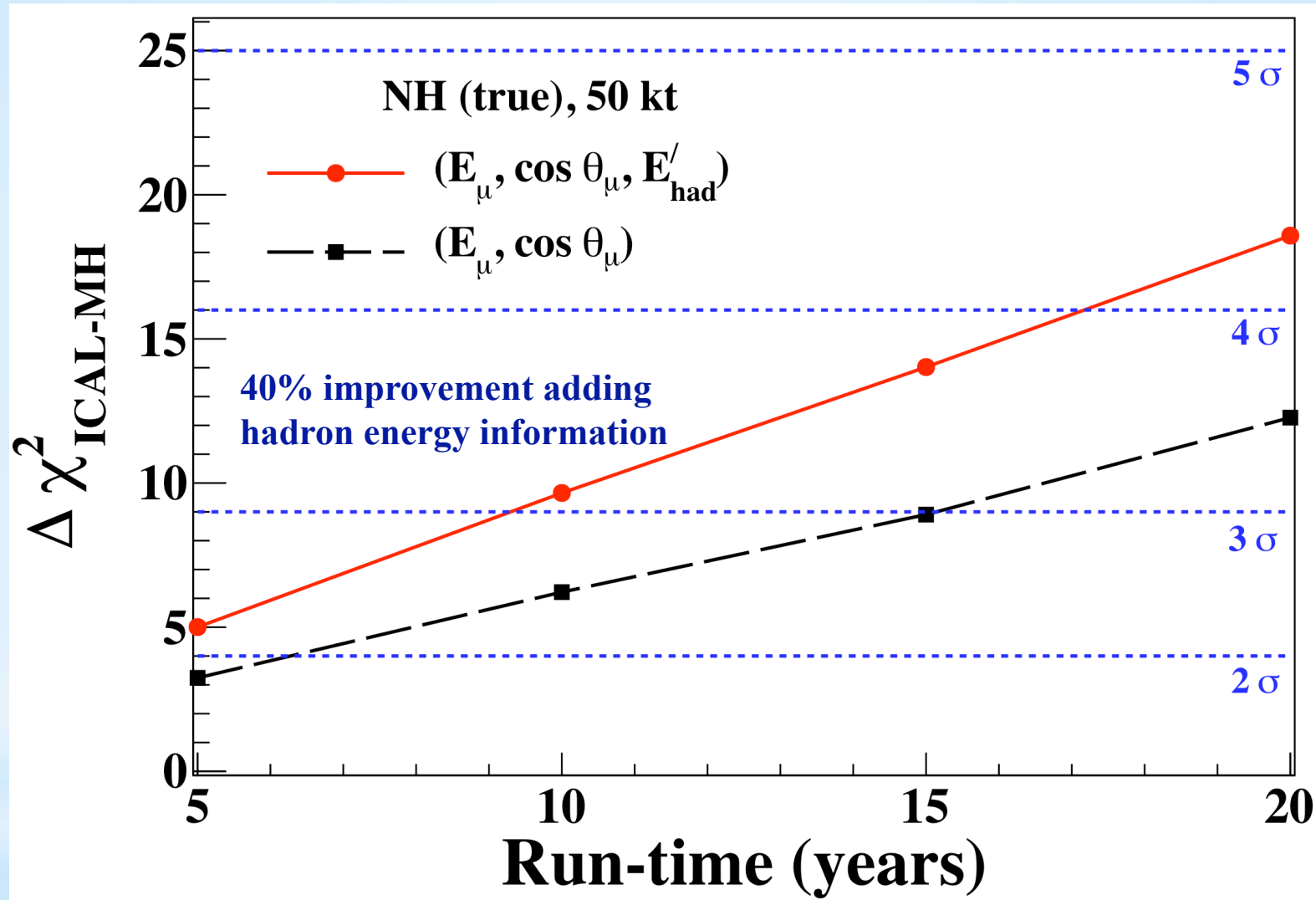


Hadron energy information used

Observable	Range	Bin width	Total bins
$E_\mu$ (GeV)	[1, 4)	0.5	6
	[4, 7)	1	3
	[7, 11)	4	1
$\cos \theta_\mu$	[-1.0, -0.4)	0.05	12
	[-0.4, 0.0)	0.1	4
	[0.0, 1.0]	0.2	5
$E'_{\text{had}}$ (GeV)	[0, 2)	1	2
	[2, 4)	2	1
	[4, 15)	11	1

- ⊙ Further subdivide the events into four hadron energy bins
- ⊙ Hadron energy carries crucial information
- ⊙ Correlation between hadron energy and muon momentum is very important

# Identifying Neutrino Mass Hierarchy with ICAL

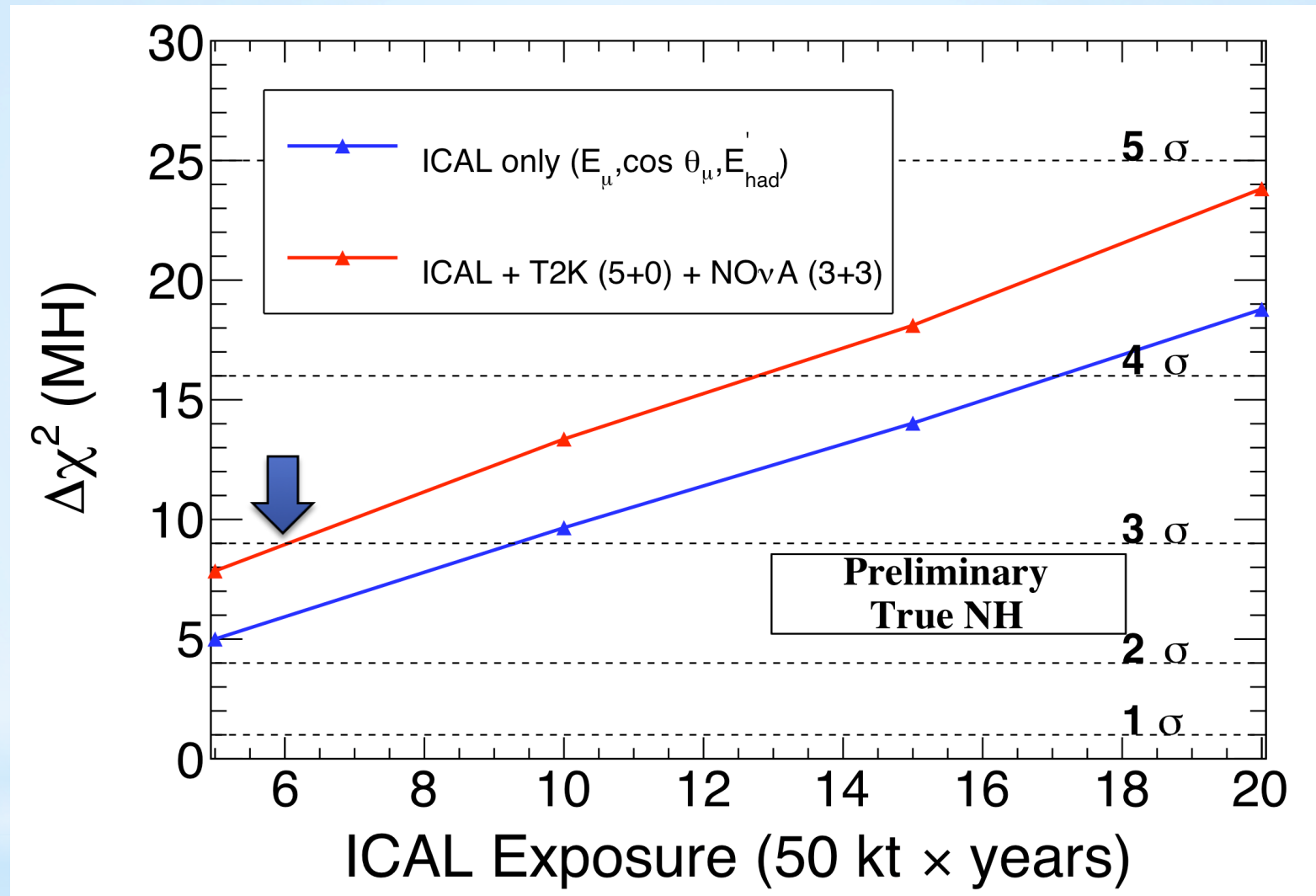


Median Sensitivity

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

50 kt ICAL can rule out the wrong hierarchy with  $\Delta\chi^2 \approx 9.5$  in 10 years

# MH Discovery with ICAL+T2K+NOvA

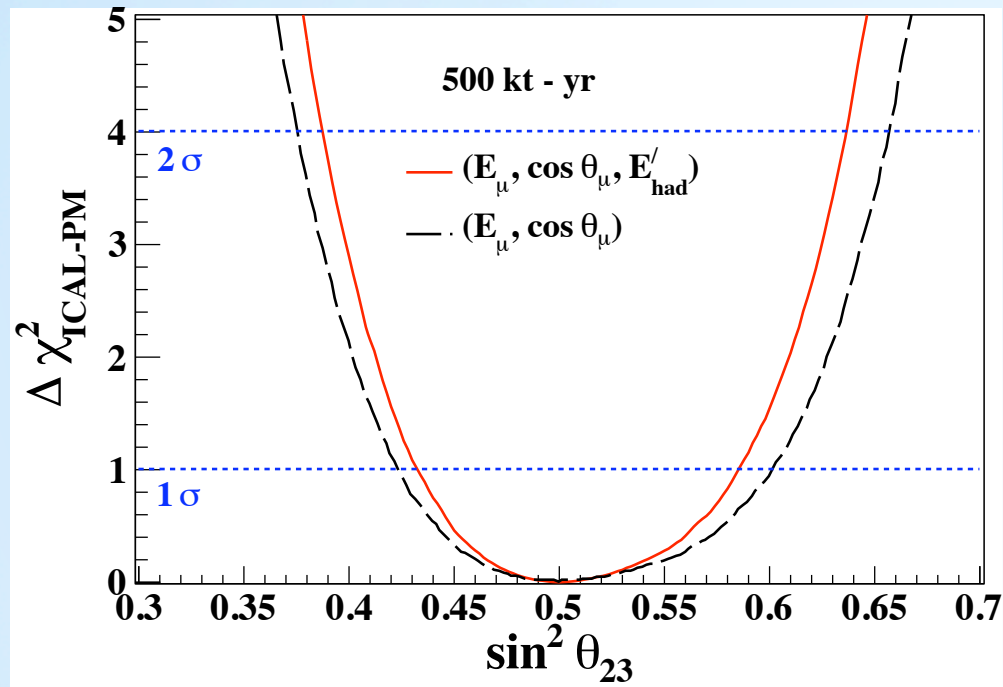


Devi, Thakore, Agarwalla, Dighe, work in progress (INO Collaboration)

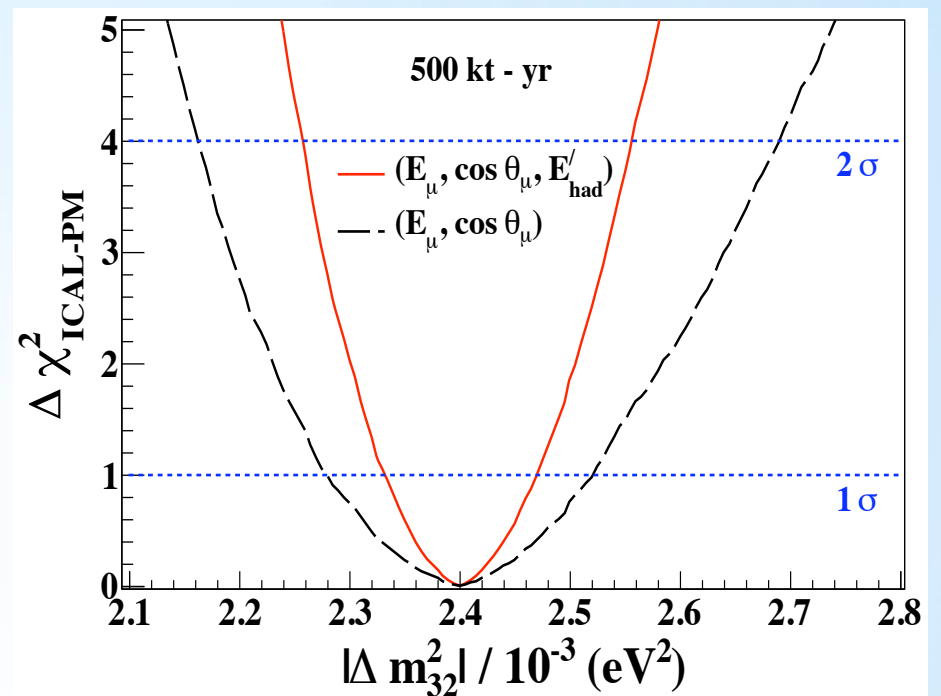
**$3\sigma$  median sensitivity can be achieved in 6 years**



# Precision of Atmospheric Oscillation Parameters



Relative 1σ precision: 12%



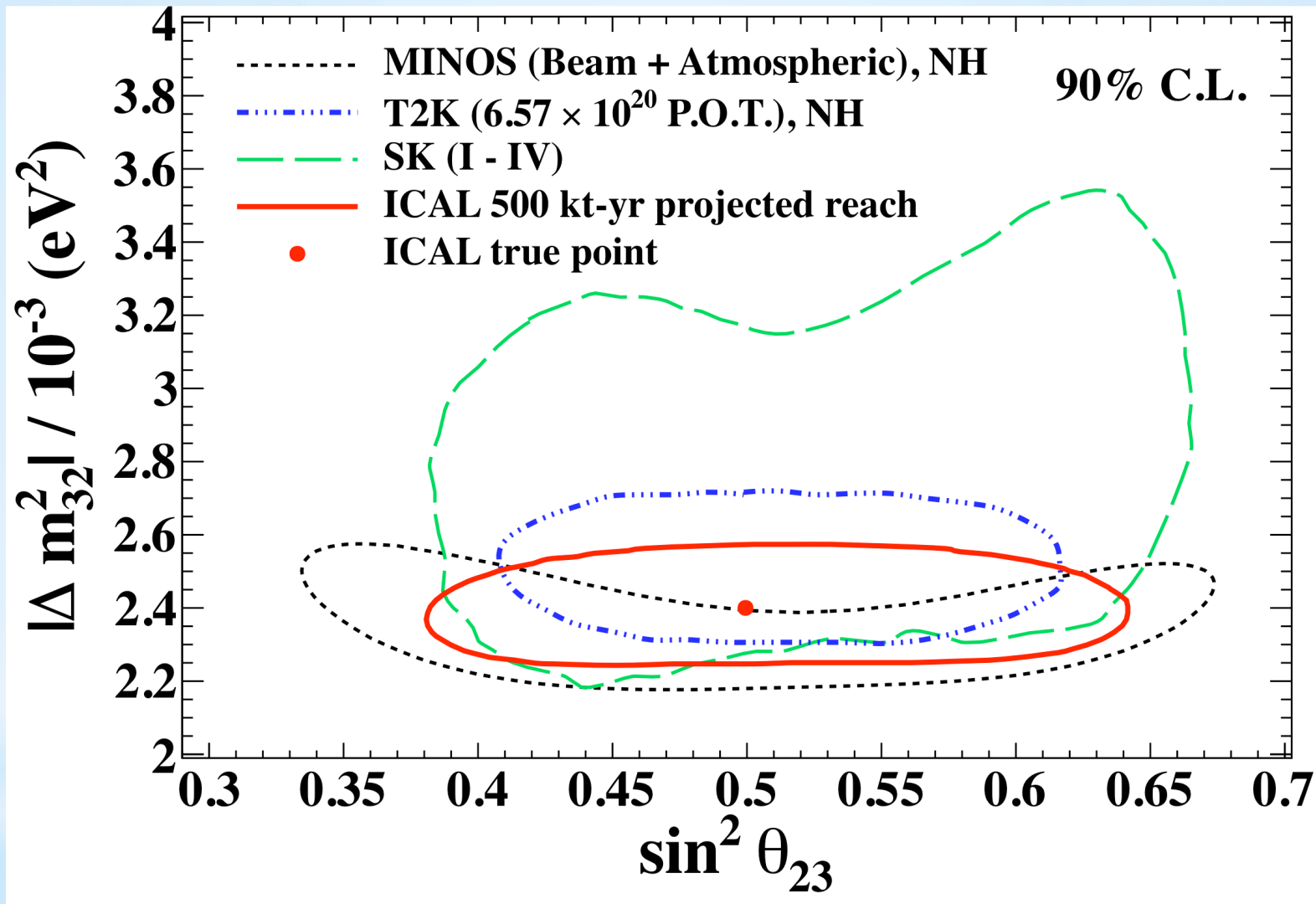
Relative 1σ precision: 2.9%

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

See the poster by Daljeet Kaur (INO Collaboration): Track no. 173

See the poster by Sanjib Kumar Agarwalla (INO Collaboration): Track no. 181

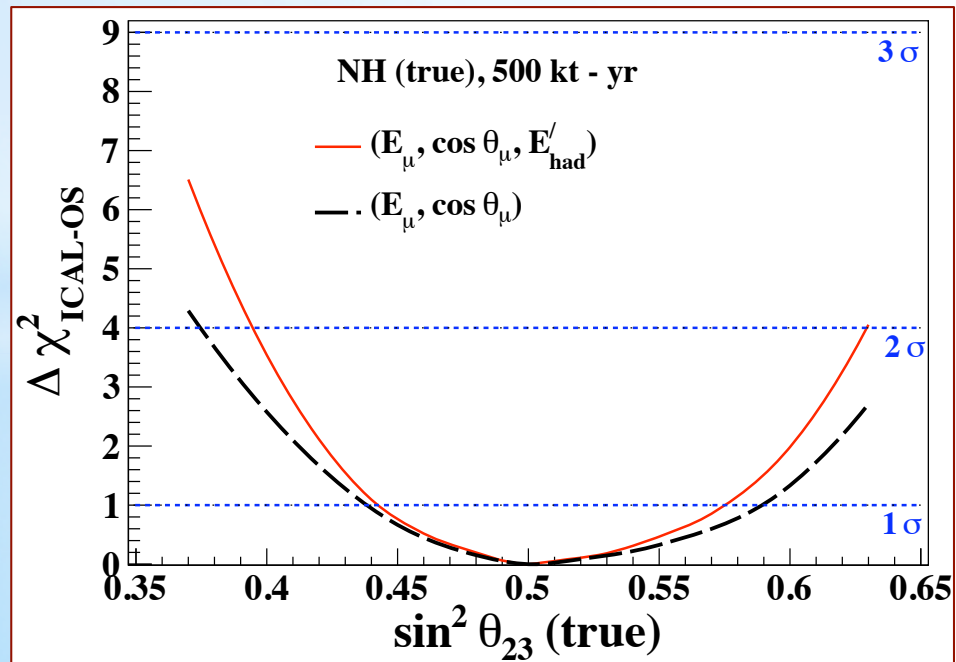
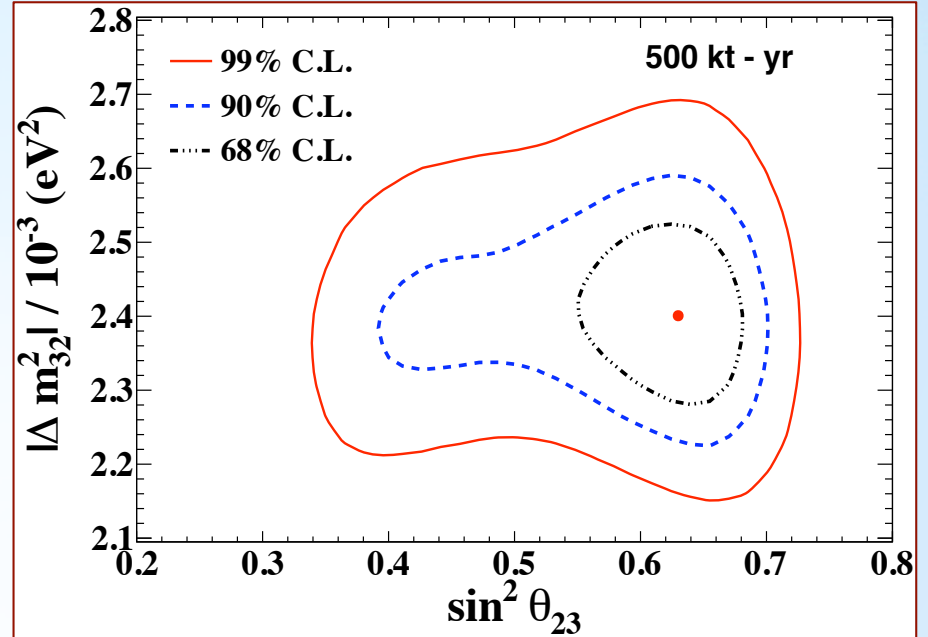
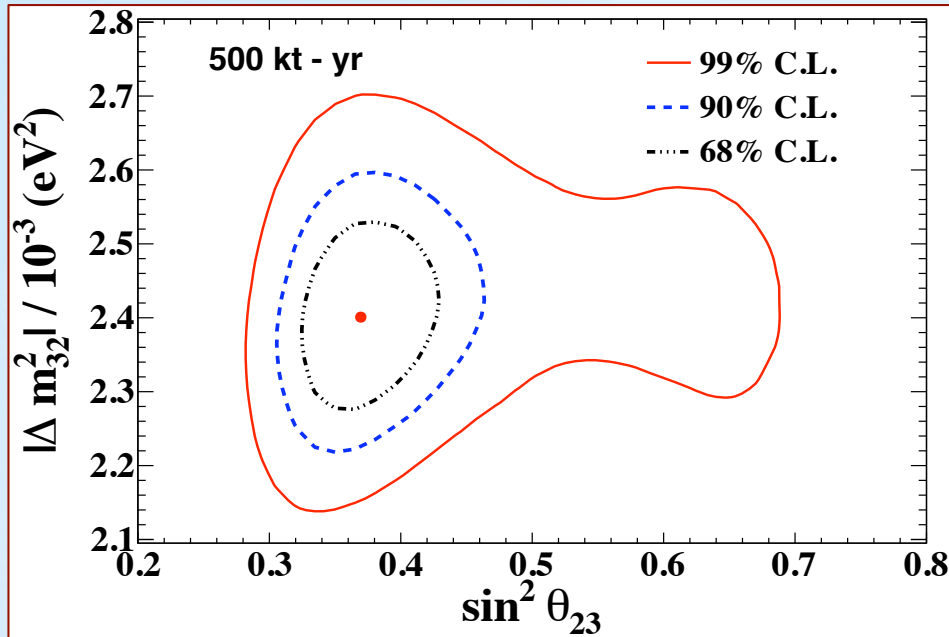
# Precision Measurement of Atmospheric Parameters



Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

ICAL's expected precision on atmospheric mass splitting is far superior than SK

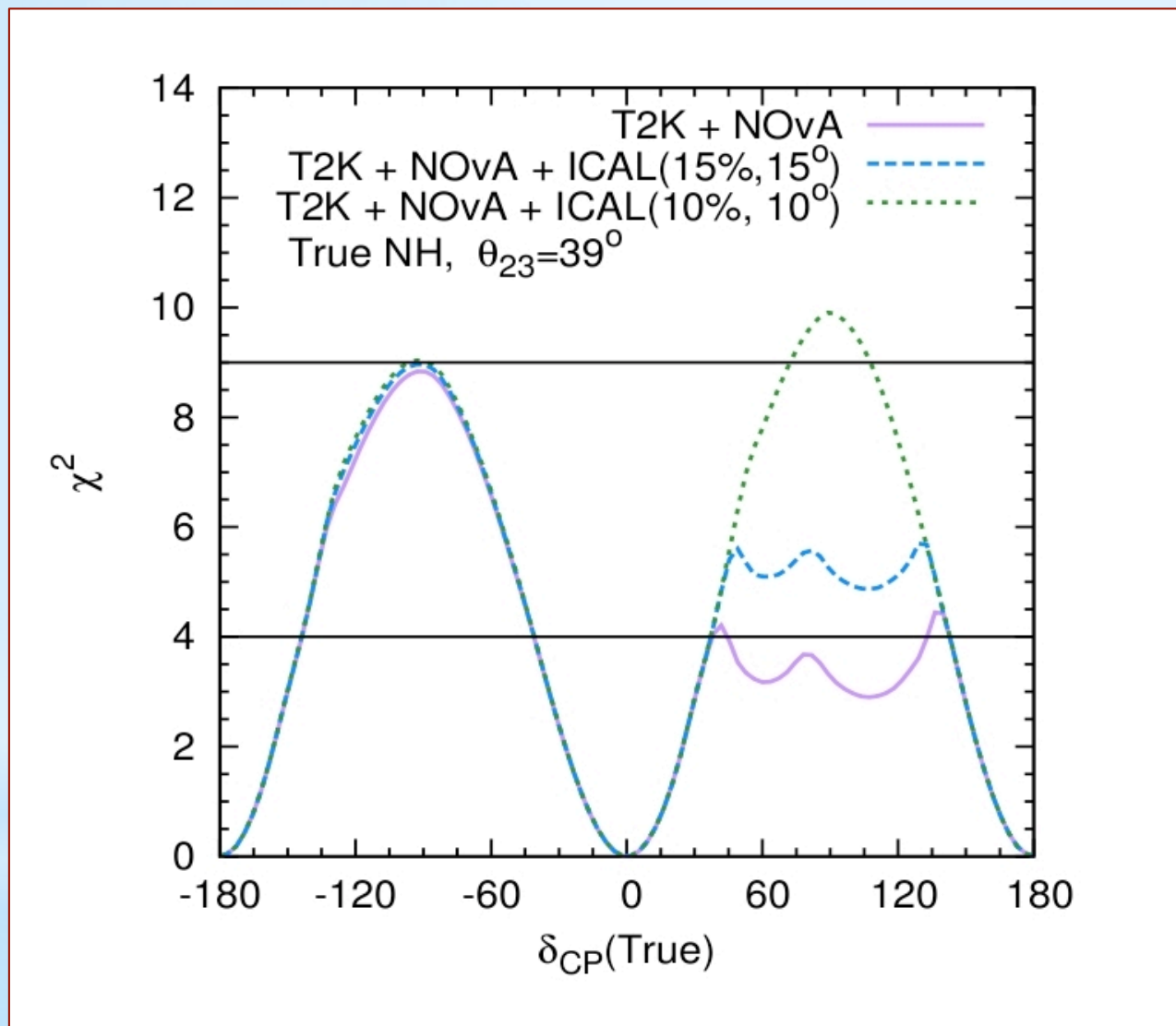
# Octant of $\theta_{23}$ with ICAL-INO



**Median  $2\sigma$  discovery of  $\theta_{23}$  octant is possible if  $\theta_{23}$  is sufficiently away from maximal value**

Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689 (INO Collaboration)

# Synergy with T2K and NOvA: CPV



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

*Monojit Ghosh, Pomita Ghoshal, Srubabati Goswami, Sushant Raut arXiv: 1306.2500 [hep-ph]*

## *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 (ICHEP)**
- **Construction of an 1/8<sup>th</sup> size engineering prototype module**
  
- **Detector R&D is now over**
  
- **DPR for Detector and 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 approval from Prime Minister's cabinet committee to start construction**

## *Concluding Remarks*



Collaboration meeting at VECC, Kolkata, 3<sup>rd</sup> to 5<sup>th</sup> April, 2014

Satisfactory progress  
in all fronts in last  
2 to 3 years

Strong support from  
The community &  
Funding agencies

All set to move ahead  
with this mega-science  
project

For more updates visit: <http://www.ino.tifr.res.in/ino/>

You can join us at: <https://www.facebook.com/ino.neutrino>

*International collaboration most welcome*

**!! Looking Forward for Exciting Discoveries at INO !!**

**Thank You**

# *Backup Slides*

# *Bakelite RPC R&D at VECC & SINP (Kolkata)*

- *Bakelite RPCs being developed, operating in streamer mode, inner surface coated with PDMS (silicone) for smooth surface, efficiency plateau over 96% with reduced noise rate and long term stability*
- *ICAL@INO being modular in size, can use both glass as well as bakelite RPCs*

*13 layers of soft iron*

*Each Iron Plate: 2.48m x 2.17m x 0.05m*

*12 layers of 1m × 1m RPCs*

*8 glass RPCs and 4 Bakelite RPCs*

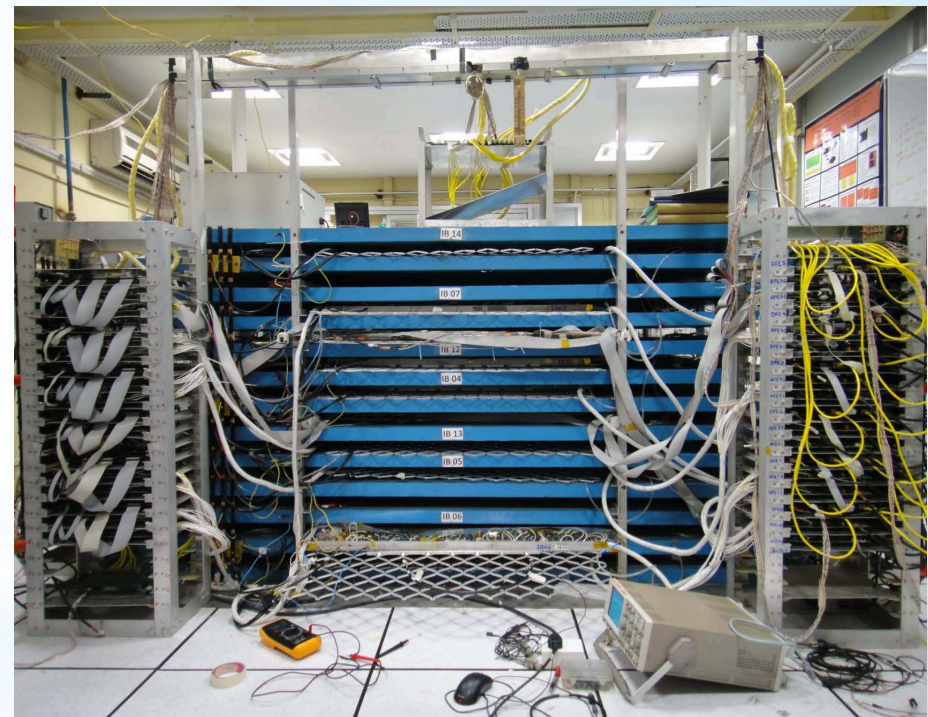
*Total of 4 coils, each having 5 turns*

*perpendicular to the plane of the Fe (1.6 Tesla)*

*512 channels of preamp for 8 glass RPCs*

*timing discriminators for avalanche RPCs*

*Designed to study the working behavior of RPCs together with the front end electronics in presence of magnetic field*



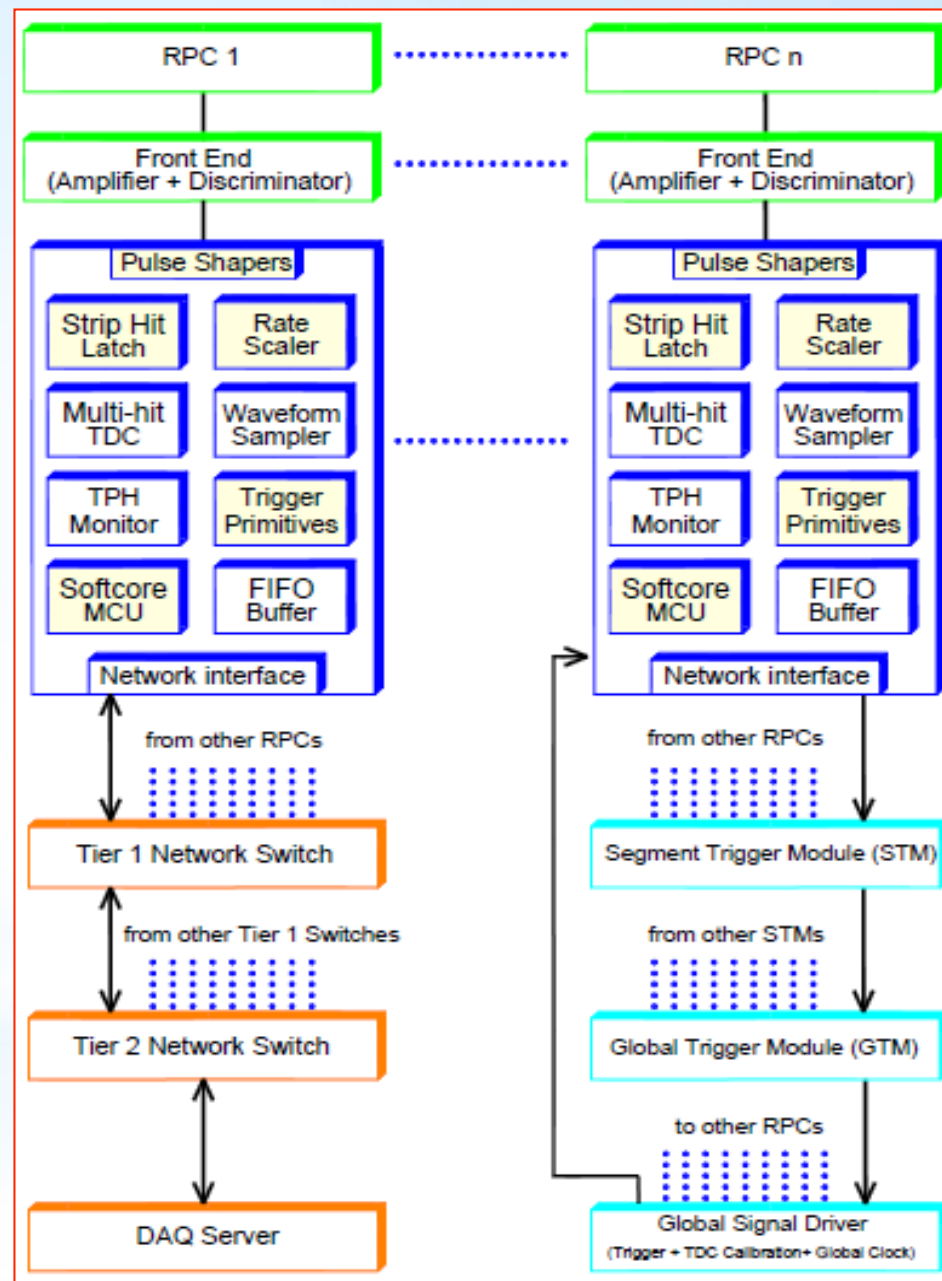
*ICAL@INO Prototype Detector ~ 50 tons  
Total Height 1.302 m*



# Overall Scheme of ICAL Electronics

## ❖ Major elements

- Front-end board
- RPCDAQ board
- Segment Trigger Module
- Global Trigger Module
- Global Trigger Driver
- Tier1 Network Switch
- Tier2 Network Switch
- DAQ Server



# *Human Resource Development and Training*



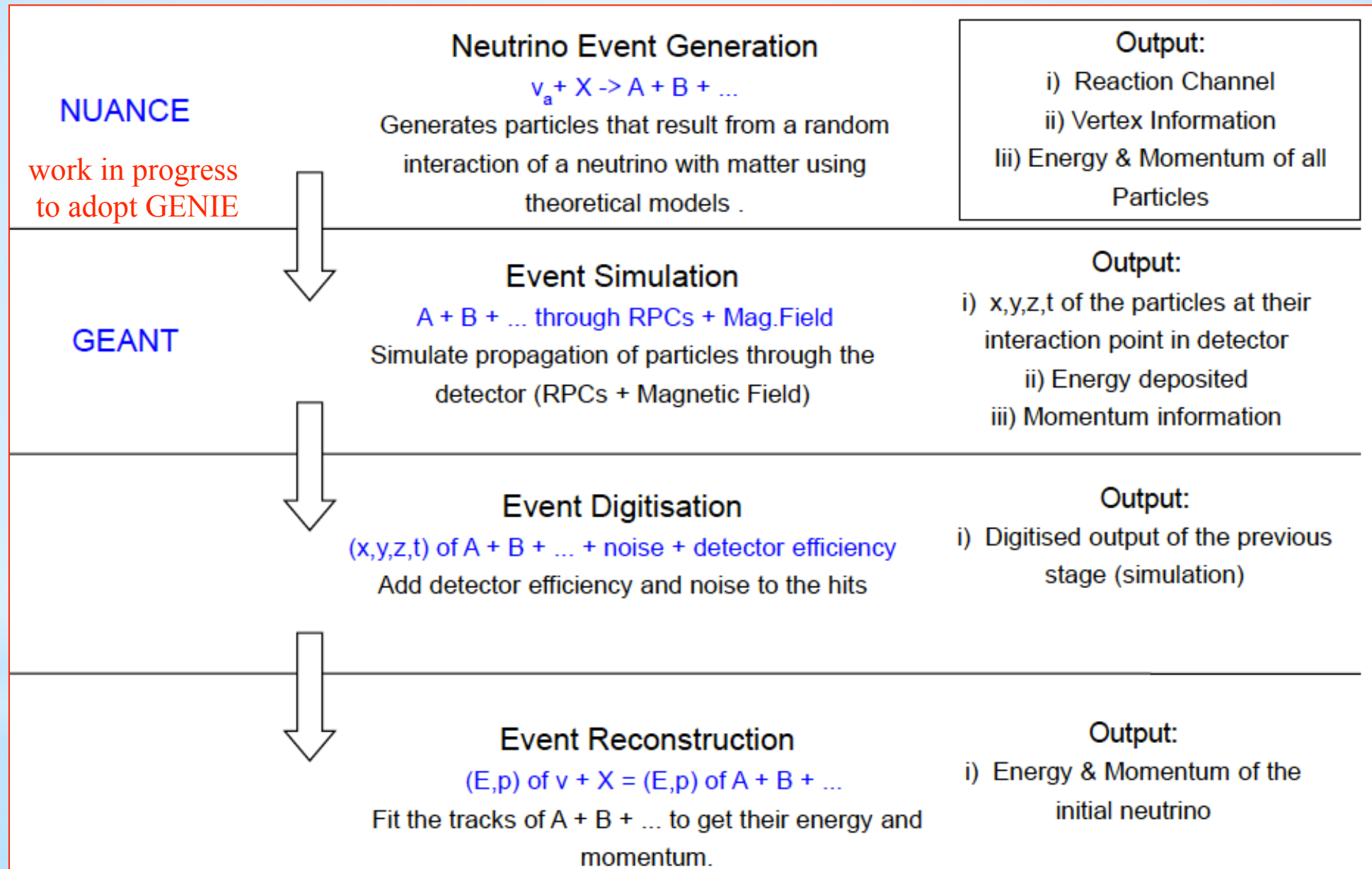
- **INO Graduate Training Program started in August 2008, students are affiliated to HBNI**
- **At present students being trained for 1 year at TIFR in both experimental techniques & theory**
- **After completion of coursework, attached to Ph.D. guides at various collaborating institutions**
- **Many short/long term visits to RPC labs (Mumbai & Kolkata) of students & faculties from Universities in last several years**
- **Several students from 1<sup>st</sup> batch (2008) are at the final stage of writing their theses. Few of them have already received good post-doctoral offers from various experiments**
- **6<sup>th</sup> batch of 7 students have started their course work at TIFR in 2013**

## *Short term goals and Future Roadmap*

- *ICAL-INO Physics White paper w/ detailed Detector Simulation under progress*
- *Building a large 8m X 8m - 20 layer detector with final specifications at Madurai*
- *Magnet & coil design & fabrication, Industrial production of RPCs*
- *Finalize Electronics and DAQ, Pre-project activities at site*

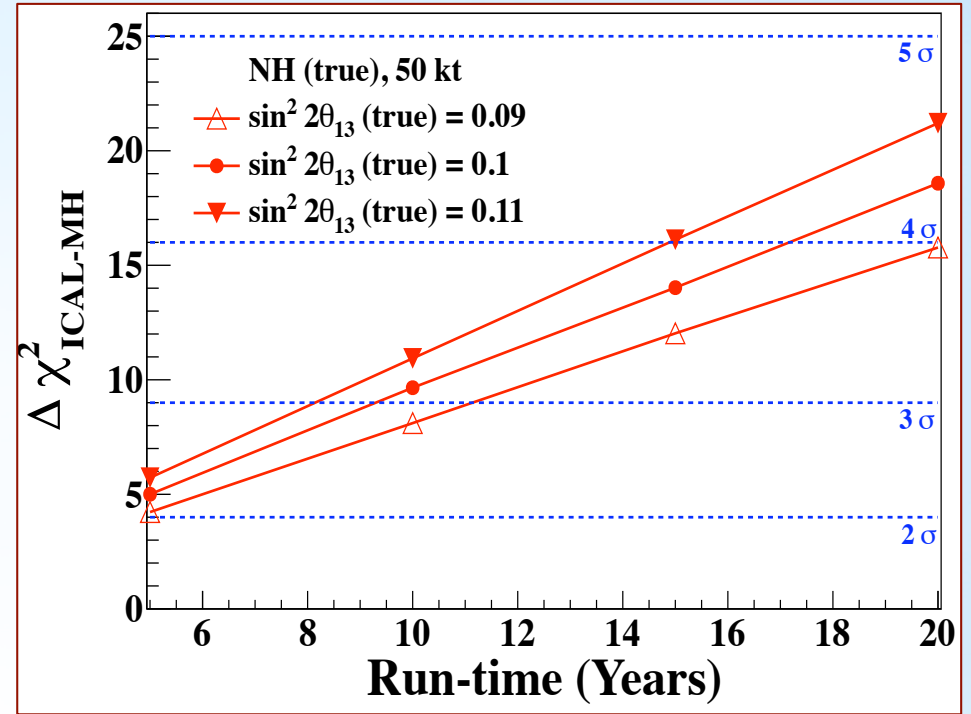
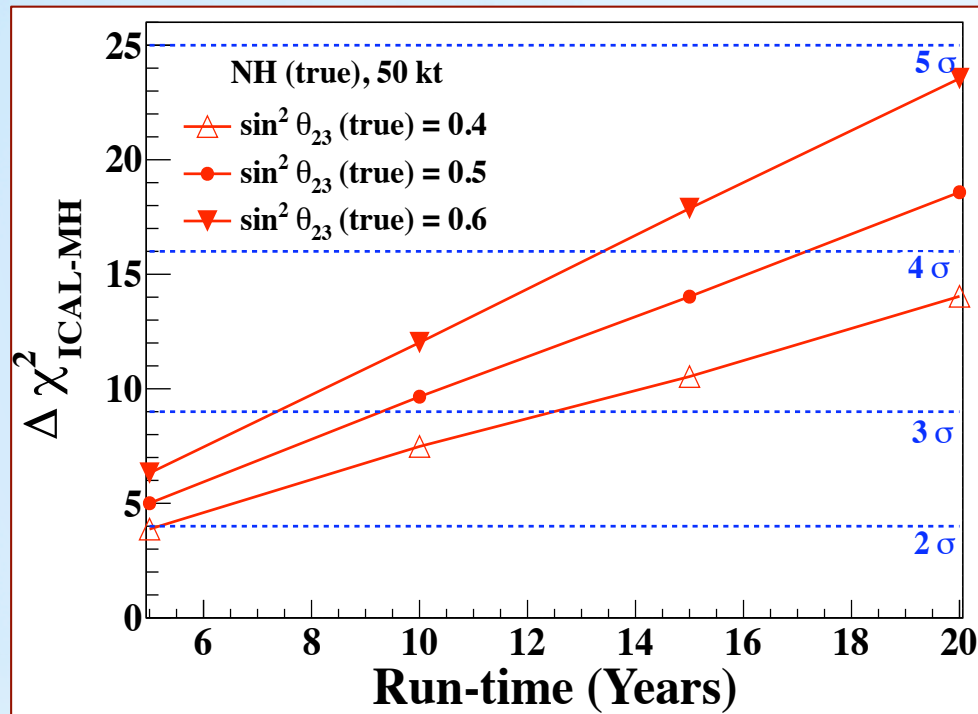
		2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
<b>Civil work at Pottipuram</b>								
1	Architectural and Engineering Consultancy	←→						
2	Tendering and award of contracts		←→					
3	Mining of access portal			←→				
4	Excavation of Tunnel			←→				
5	Excavation of caverns				←→			
6	Installation of Services, Cranes, Lifts etc					←→		
7	Surface facilities			←→				
<b>Magnet</b>								
8	Engineering Prototype	←→						
9	Procurement of steel plates		←→					
10	Machining and Transportation				←→			
11	Copper Coils					←→		
12	Assembly/Erection						←→	
<b>Detector/Electronics</b>								
13	Finalization of design details and tendering	←→						
14	Procurement of components		←→					
15	Fabrication and tests of 30000 RPCs			←→				
16	Electronics, Daq, gas handling	←→						
17	Installation and commissioning						←→	

# Overview of Simulation Framework



**Simulation work is under progress in full swing!**

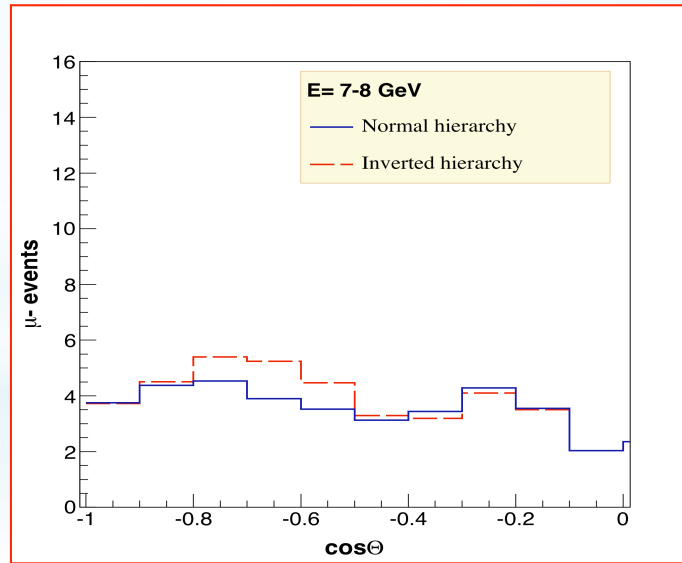
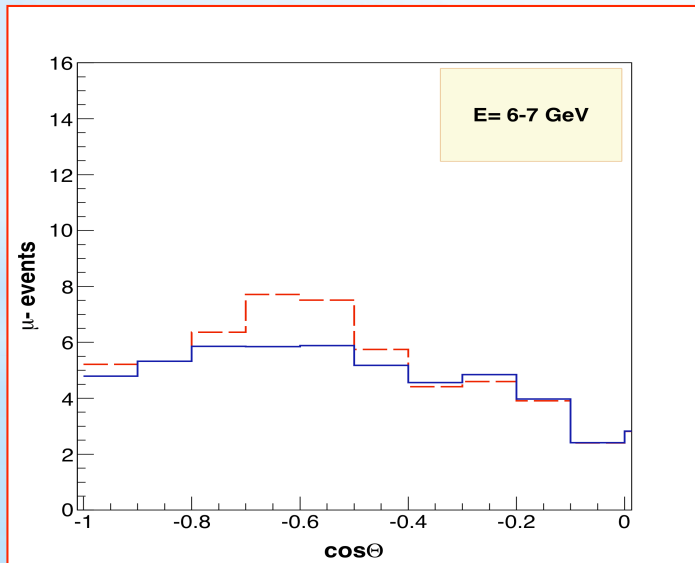
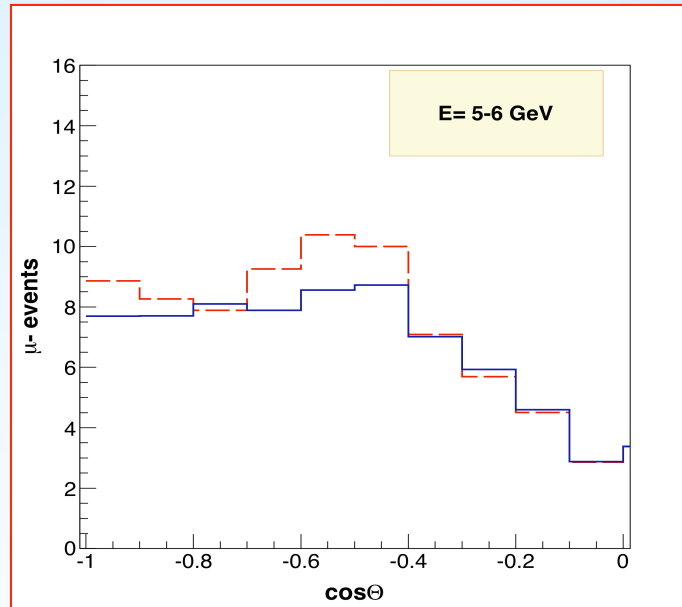
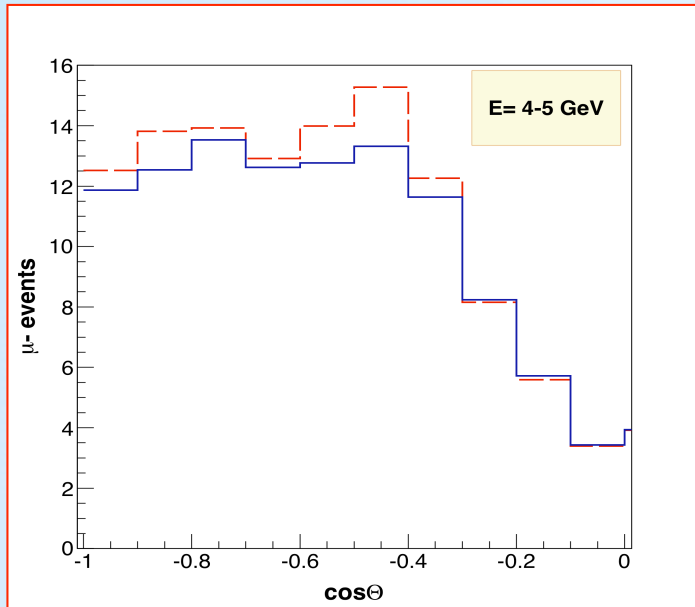
# Impact of $\theta_{23}$ and $\theta_{13}$ on Mass Hierarchy



Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

50 kt ICAL can rule out the wrong hierarchy with median  $\Delta\chi^2 \approx 7$  to 12 depending on the true values of  $\theta_{23}$  and  $\theta_{13}$  in 10 years

# Event Spectrum in ICAL-INO



$\mu^-$  event spectrum  
for 10 years exposure

Comparison between  
Normal and Inverted  
hierarchy

Ghosh, Thakore, Choubey, JHEP 1304 (2013) 009 (INO Collaboration)

Sanjib Kumar Agarwalla, ICHEP 2014, Valencia, Spain, 4<sup>th</sup> July, 2014