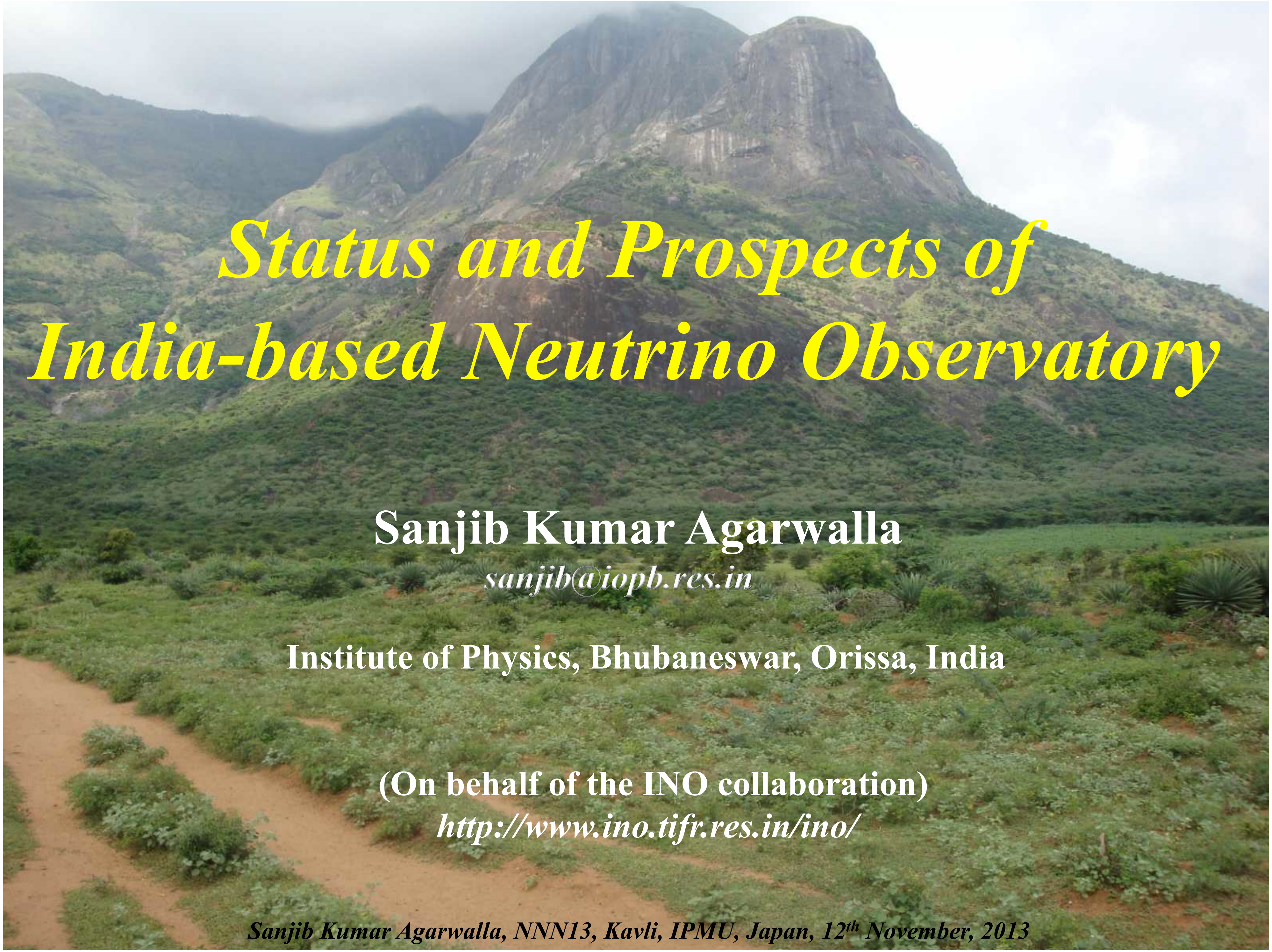

Status and Prospects of India-based Neutrino Observatory

Sanjib Kumar Agarwalla

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Institute of Physics, Bhubaneswar, Orissa, India

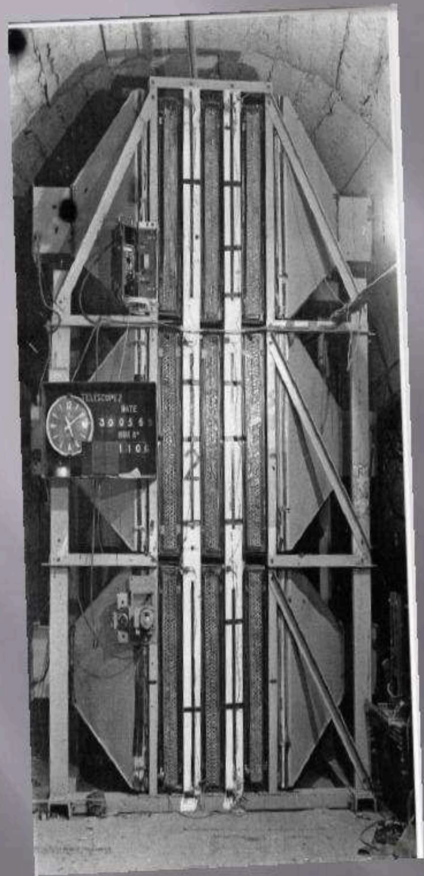
(On behalf of the INO collaboration)

http://www.ino.tifr.res.in/ino/

An Old Saga of Underground Laboratory in India

- *KGF: Deepest underground lab in world till 1992 > 6500 MWE*
- *In 1965, at KGF at a depth of 2.3km, first atmospheric neutrino was observed by the TIFR-Osaka-Durham group*
- *During early 80s dedicated detectors were setup at KGF by TIFR-Osaka collaboration to look for proton decay*

Atmospheric neutrino detection in 1965



Atmospheric neutrino detector at Kolar Gold Field -1965

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

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

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

PRL 15, (1965), 429, dated 30th Aug. 1965

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 !

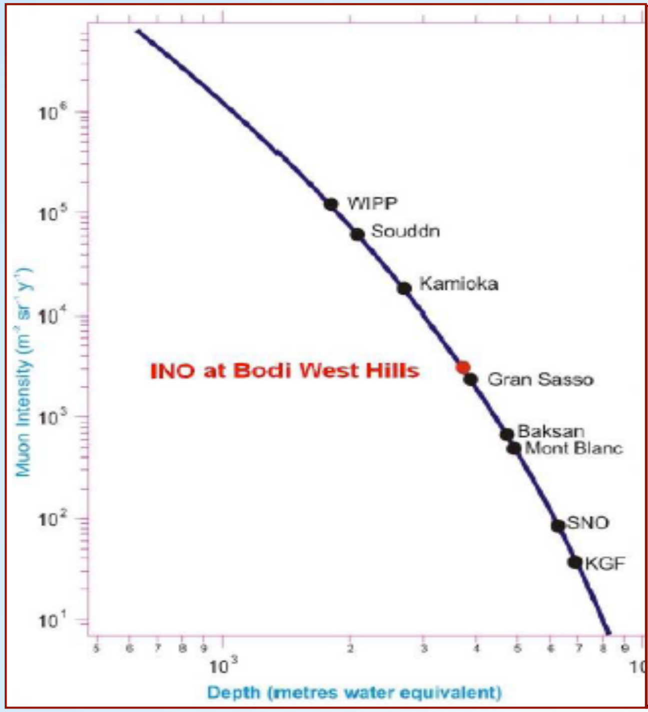
We are growing day by day!

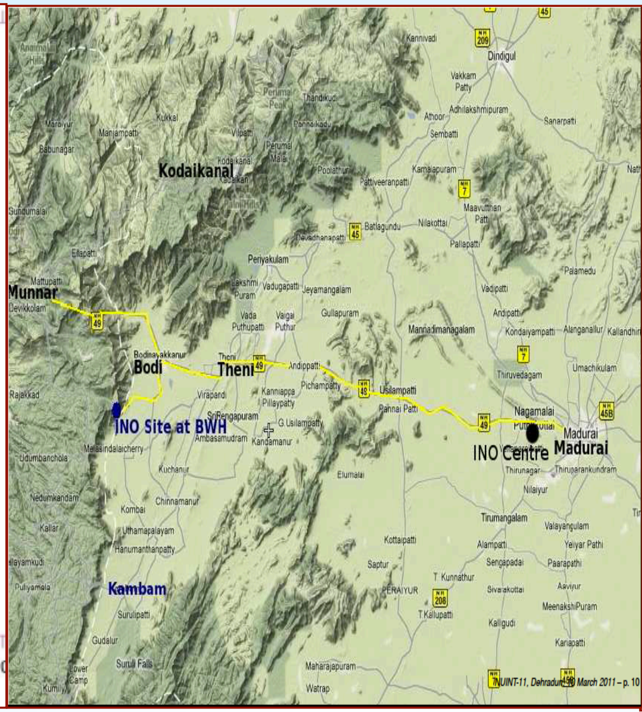
Collaborators are most welcome!

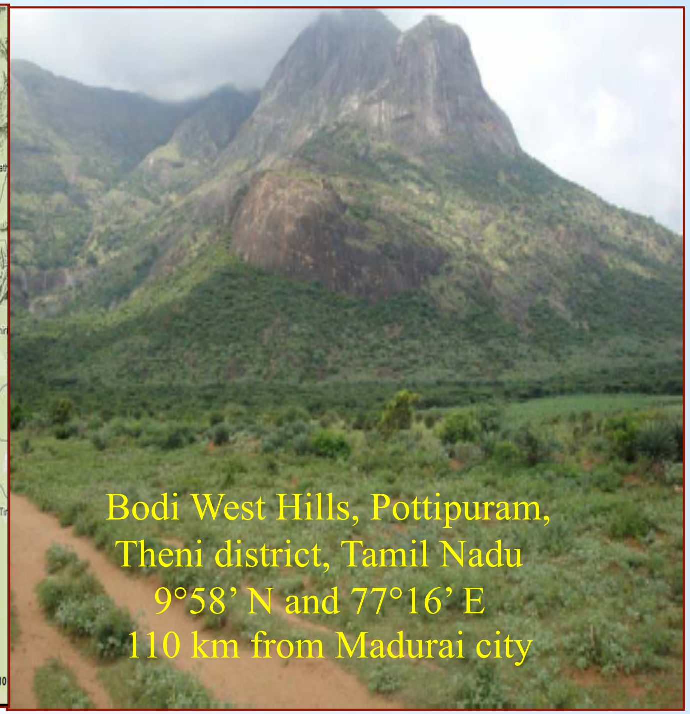
India-Based Neutrino Observatory

- *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 on 17th August, 2013 at New Delhi***
- *Regarding Final approval: Clearance from the Cabinet expected soon*
- *International Community is welcome to participate in ICAL@INO as well as the INO facility is available to the entire community for setting up experiments like Neutrino-less Double Beta Decay, Direct Dark Matter searches*

Location of INO & Unique Features



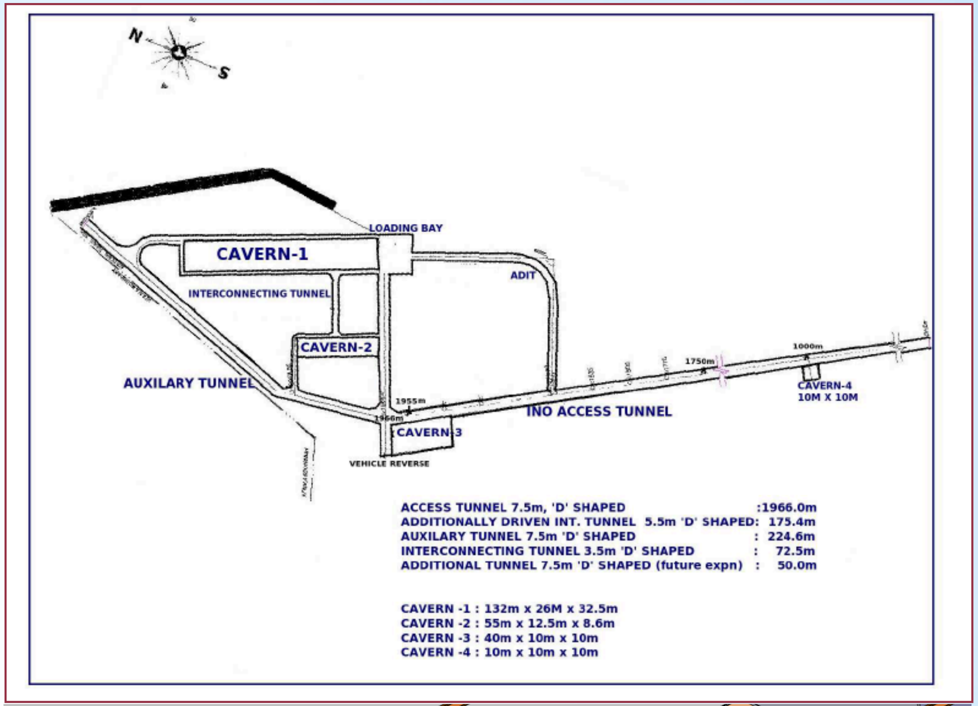


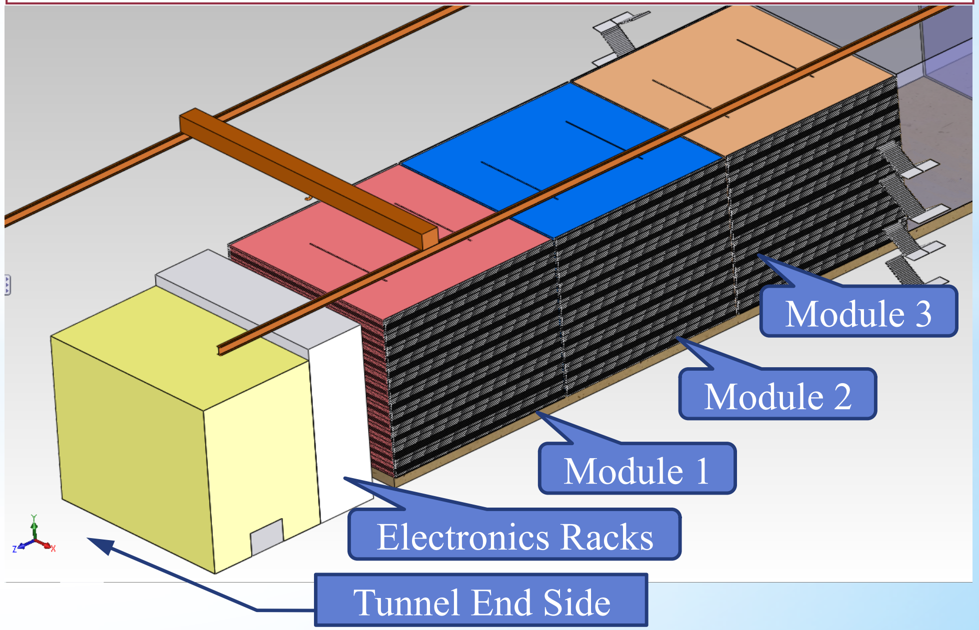


- ***Transport:*** *Flat terrain with good access from major roads*
- ***Geotechnical Issues:*** *Good rock quality, Cavern set in massive Charnockite rock under the 1589 m peak, Vertical cover approx. 1289 m, Tunnel length 1.91 km*
- ***Environmental Issues:*** *Portal set outside the Reserved Forest boundary, no disturbance. Surface facilities not on Forest Land. No clearing of forest*
- ***Weather :*** *Warm, low rainfall area, low humidity throughout the year*

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 1st module: 2018*





Recent Updates on the Site Front

- ★ *INO project approved by DST & DAE*
- ★ *All Environmental and Forest clearances obtained*
- ★ *26.82 hectares of revenue land at Pottipuram village transferred to DAE*
- ★ *Survey work for site preparation under progress & fencing work started*
- ★ *Funds transferred to the Tamil Nadu government for construction of approach roads & water connection to the INO site. Work already started*
- ★ *At Madurai, 12.5 hectares of land transferred to establish the IICHEP. Survey work over & construction of boundary wall started*
- ★ *Work order placed for geotechnical studies, pre-qualification bids invited for the construction of detector lab*
- ★ *IICHEP at Madurai already started its operation from a rental building*
- ★ *INO project engineers & scientific officers already stationed at this place and establishment work for RPC detector lab initiated*

Physics Issues with ICAL-INO in Phase 1

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

Recent discovery of large θ_{13} : A great news for ICAL-INO

What do we want to achieve?

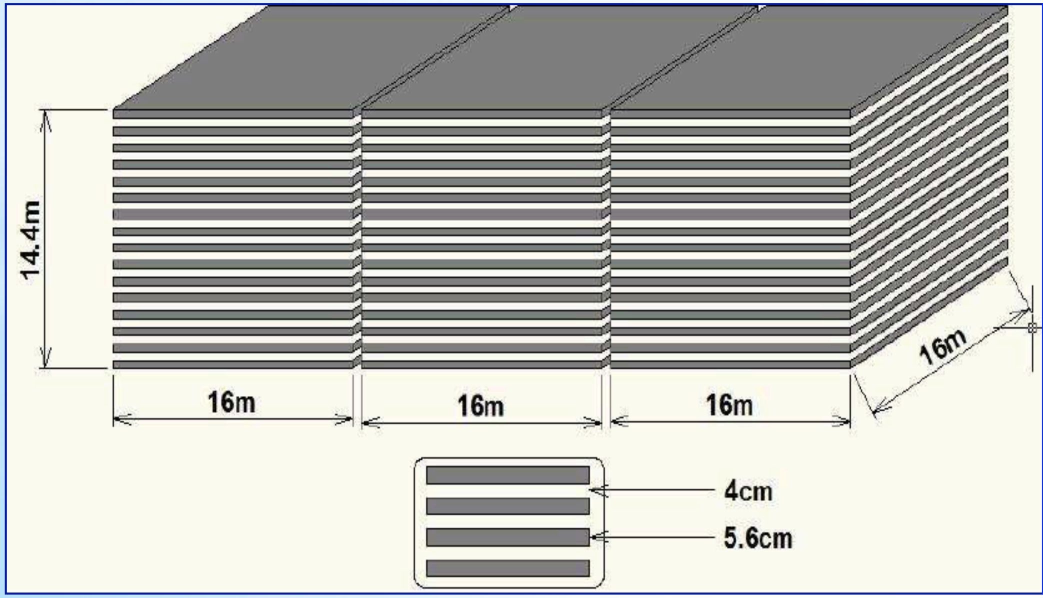
- ***Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately***
- ***Improved precision of atmospheric oscillation parameters***
- ***Determine neutrino mass hierarchy using matter effects via charge discrimination***
- ***Measure the deviation of 2-3 mixing angle from its maximal 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

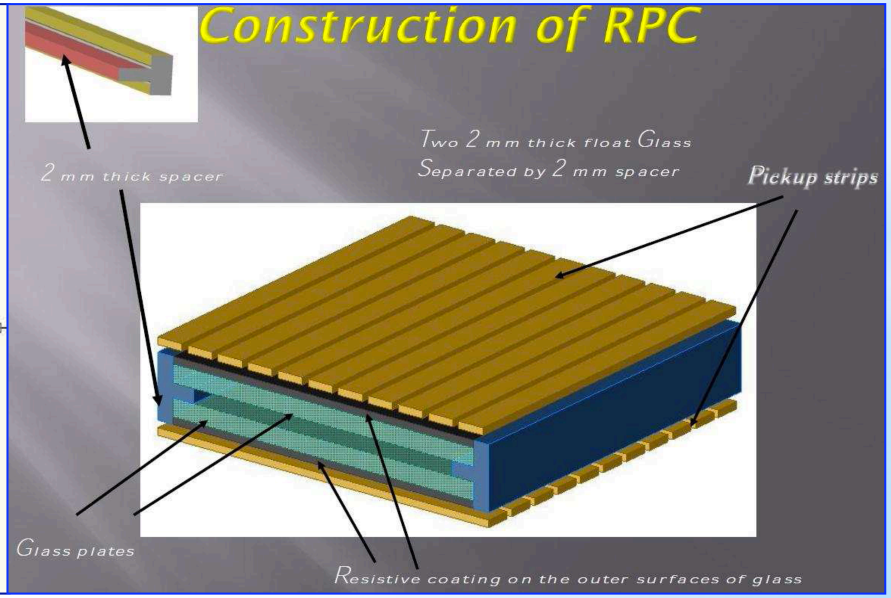
- *Should have large target mass (50 – 100 kt)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*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

Our choice

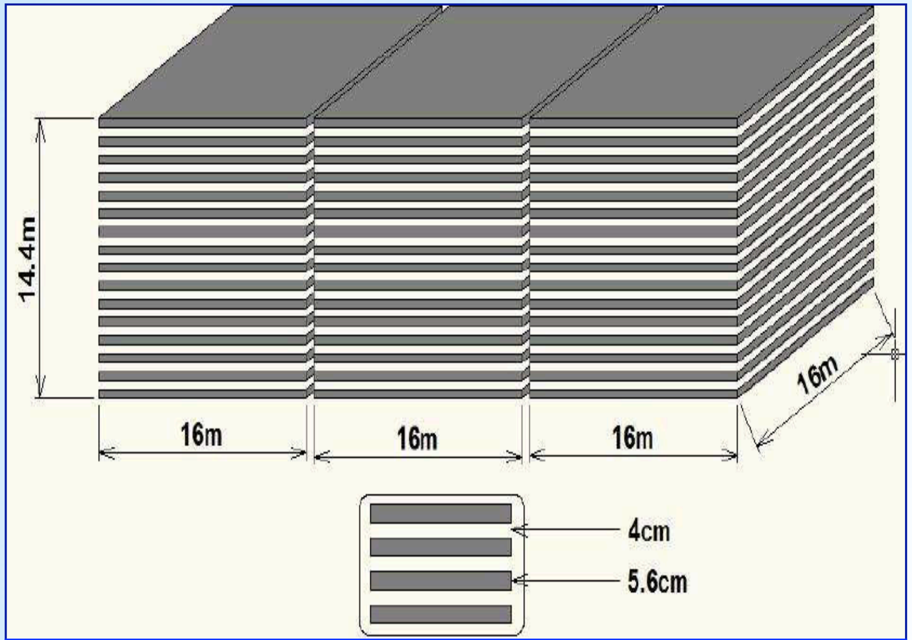
Magnetized iron (target mass): ICAL

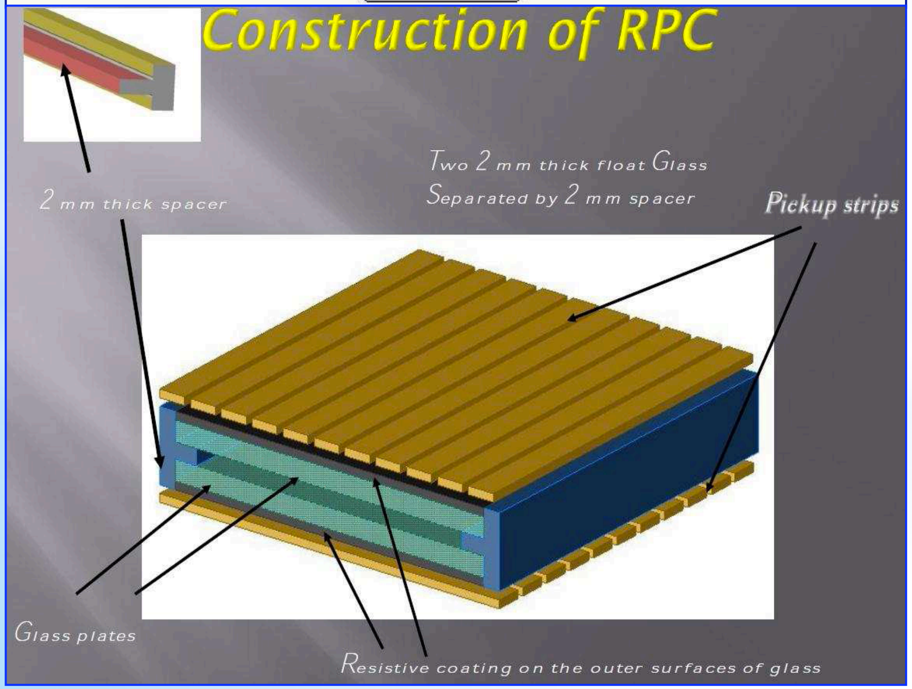


RPC (active detector element)



Specifications of the ICAL Detector





No. of modules	3
Module dimensions	16m × 16m × 14.5m
Detector dimensions	48.4m × 16m × 14.5m
No. of layers	150
Iron plate thickness	56mm
Gap for RPC trays	40mm
Magnetic field	1.3Tesla
RPC dimensions	1,950mm × 1,840mm × 24mm
Readout strip pitch	30mm
No. of RPCs/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
No. of RPC units	28,800 (97,505m²)
No. of readout strips	3,686,400

Rapid progress in all fronts

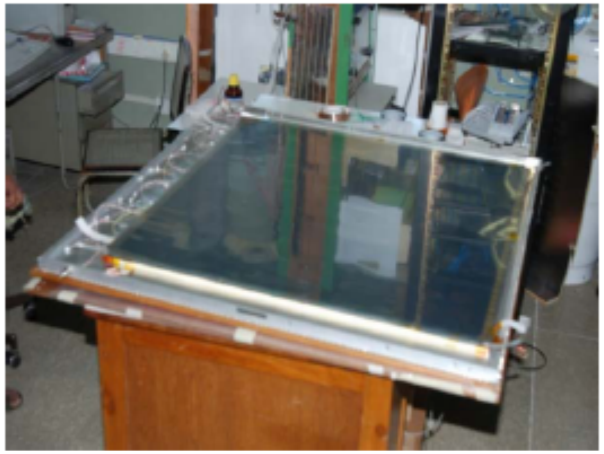
2011-2013: A productive phase for INO!

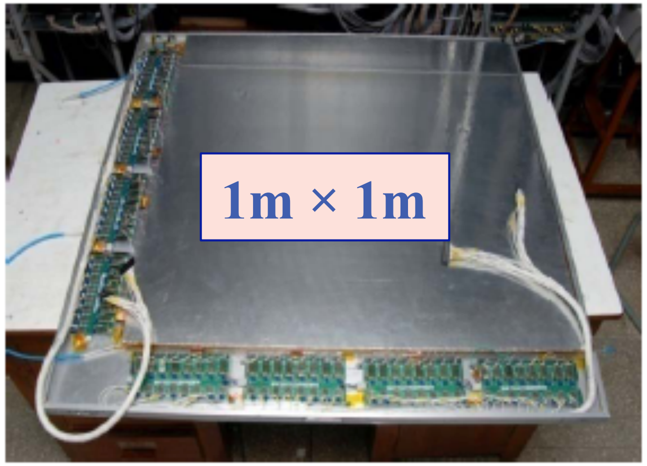
Several milestones achieved

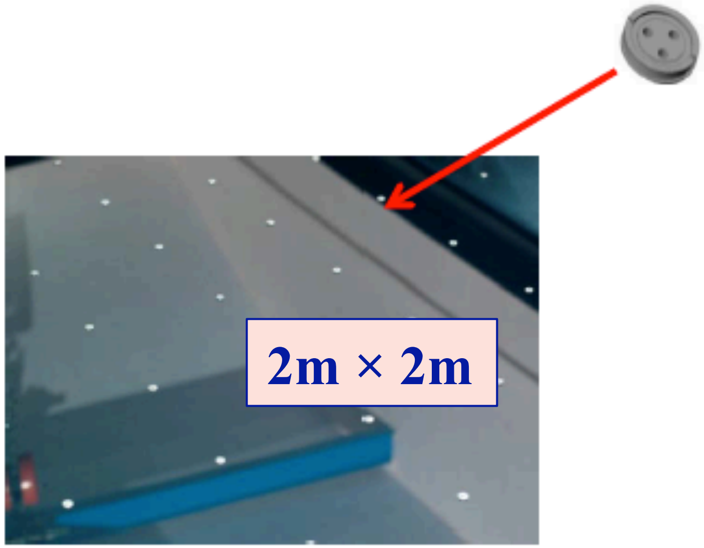
Current Status of RPC Detector Development

- *R&D almost over. Full size RPCs (2m X 2m) are now being fabricated not only in our lab but also by the Industry*
- *Identified several Industrial Partners: Keen in mass production of RPCs*
- *They are producing components needed for RPC making, also designing tools for mass production of RPCs. Spacers for new RPC design received*
- *Development of graphite coating by automatic spray painting*
- *Demonstration of successful operation of automatic button & glue dispenser*
- *Development of glass chamfering & engraving, pickup panel, tray design*
- *Computer modeling of RPC & its assembly in ICAL*
- *Physical RPC model to study push-pull assembly in ICAL magnet gap*
- *Floating tender for the production of 400 RPCs for the Engineering module of 8m × 8m × 20 layers (800 ton) to be assembled at Madurai*
- *Prototype for close loop gas circulation system is under test at TIFR*

Fabricating Glass RPCs at TIFR







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

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*

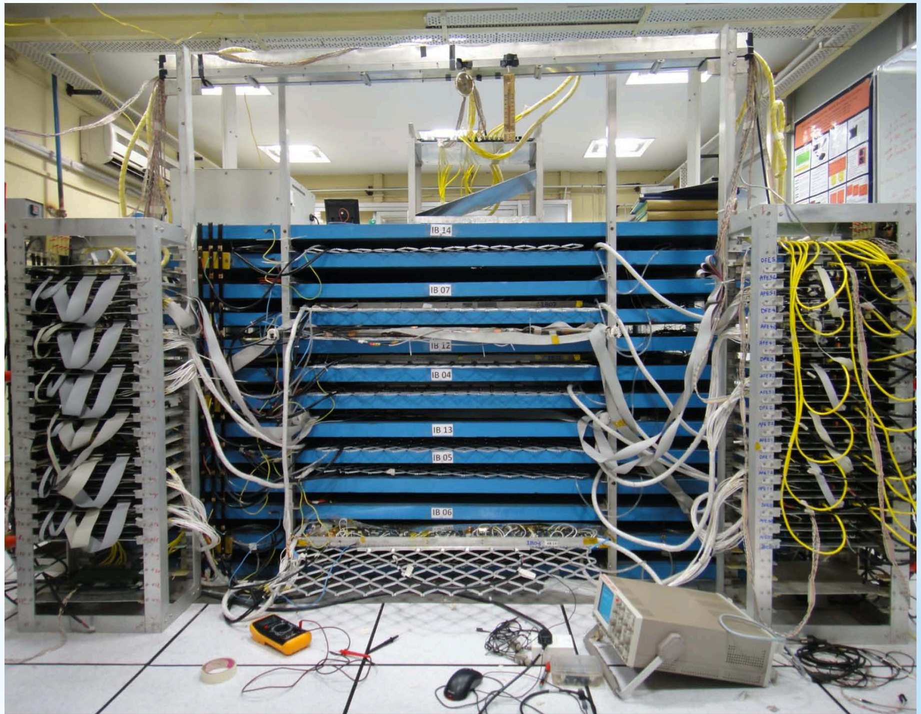
13 layers of soft iron
Each Iron Plate: 2.48m x 2.17m x 0.05m

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

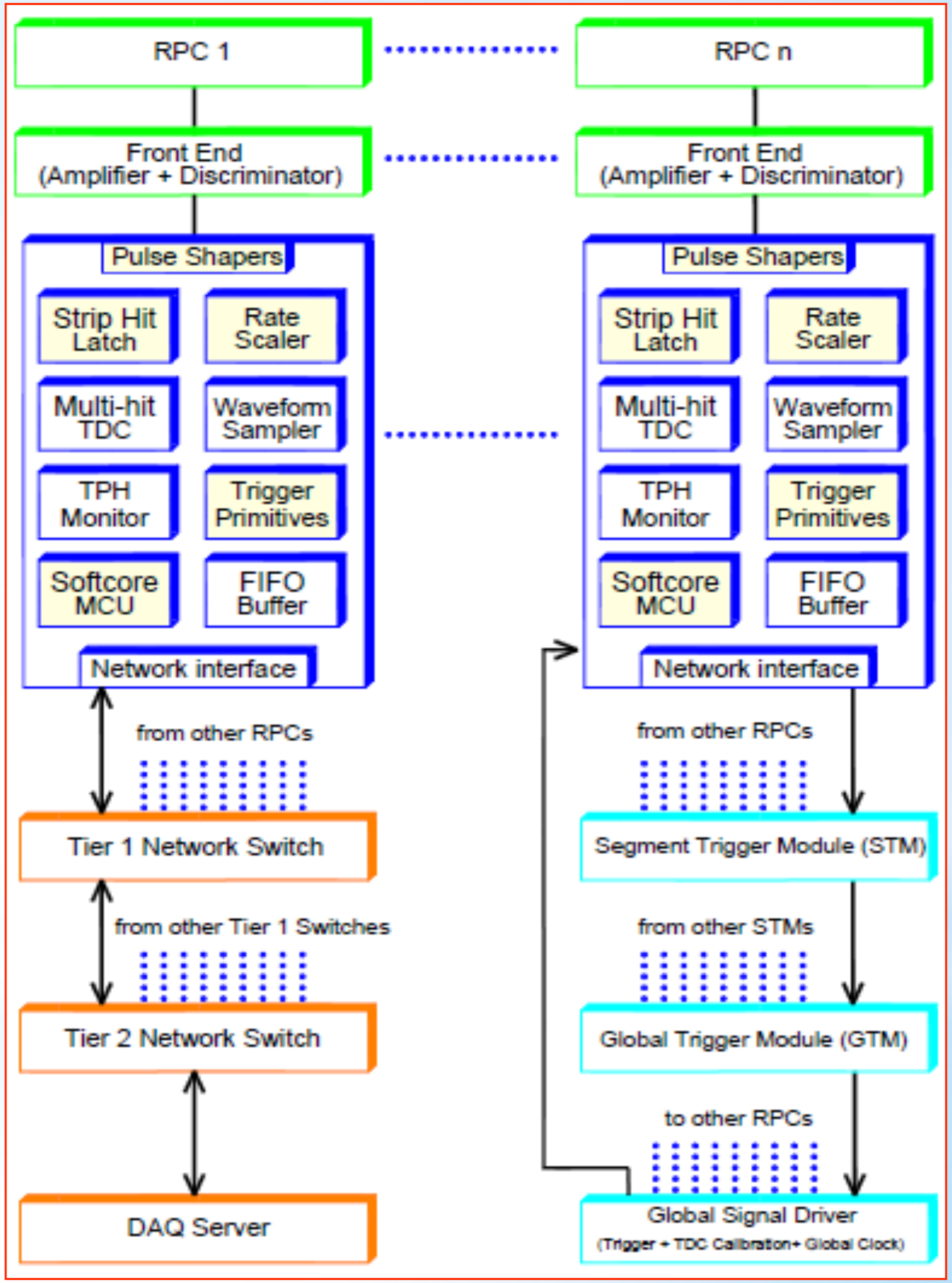


ICAL@INO Prototype Detector ~ 50 tons
Total Height 1.302 m

Overall Scheme of ICAL Electronics

❖ Major elements

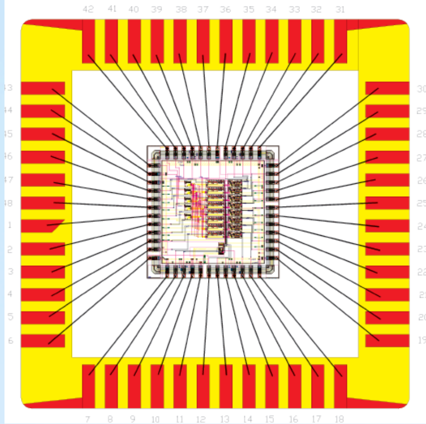
- Front-end board
- RPCDAQ board
- Segment Trigger Module
- Global Trigger Module
- Global Trigger Driver
- Tier1 Network Switch
- Tier2 Network Switch
- DAQ Server



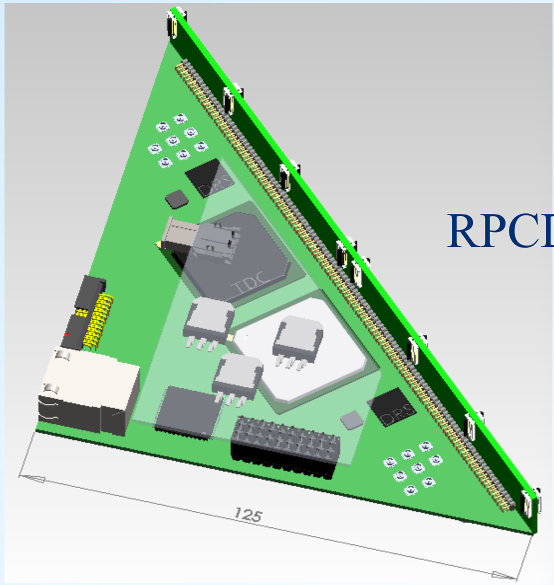
Current Status of ICAL Electronics

- **Eight channel amplifier + discriminator front-end ASIC chip designed, tested on the detector elements, ready to go for final iteration and production**
- **Single channel 125ps resolution TDC ASIC developed and tested. Design upgrade for a multi-channel and multi-hit chip needed for ICAL is in progress**
- **RPCDAQ is the heart of the front-end on-detector signal processing. Pilot production of this complex module is in progress**
- **ICAL trigger system is being implemented using look-up tables based in a bank of very high-end FPGAs. Final schematic design of this sub-system will be ready shortly**
- **Data network based on Ethernet interface designed. Bench marking and protocol implementation is currently in progress**
- **Work is in full swing on the power supply, back-end software and database management aspects**

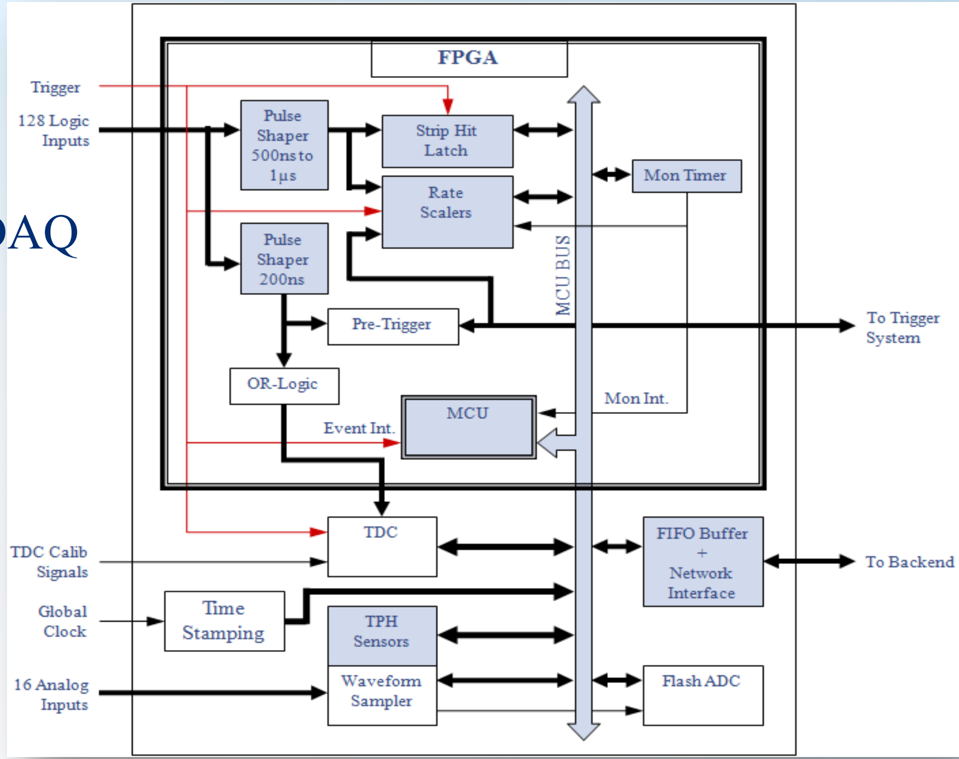
Various Components of ICAL Electronics

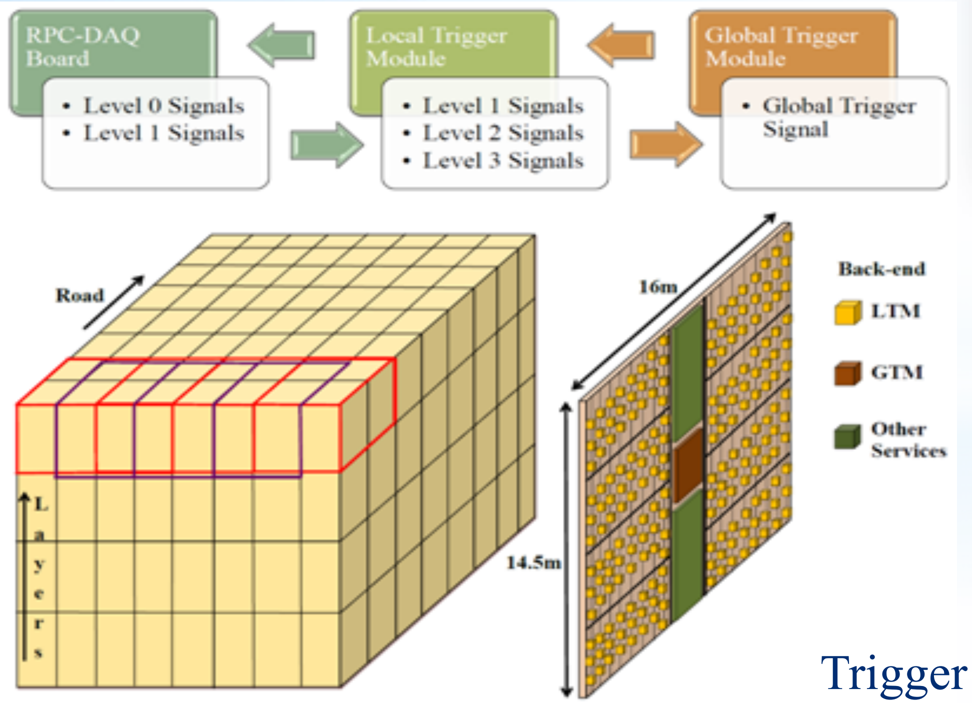


Front-end ASIC

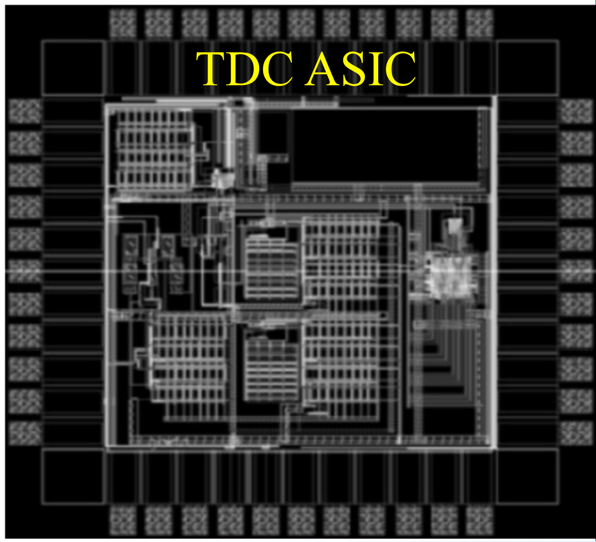


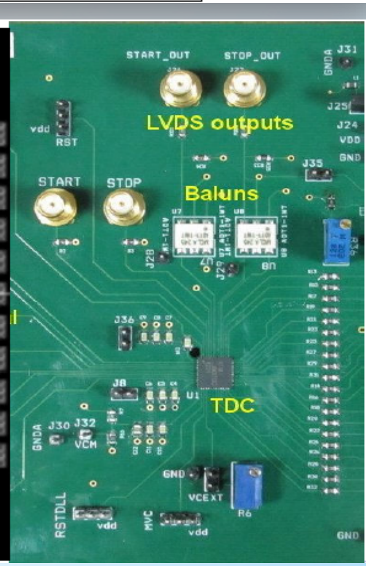
RPCDAQ





Trigger





Overview of Simulation Framework

NUANCE

work in progress
to adopt GENIE

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

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

Add detector efficiency and noise to the hits

Output:

i) Digitised output of the previous stage (simulation)

Event Reconstruction

(E,p) of ν + X = (E,p) of A + B + ...

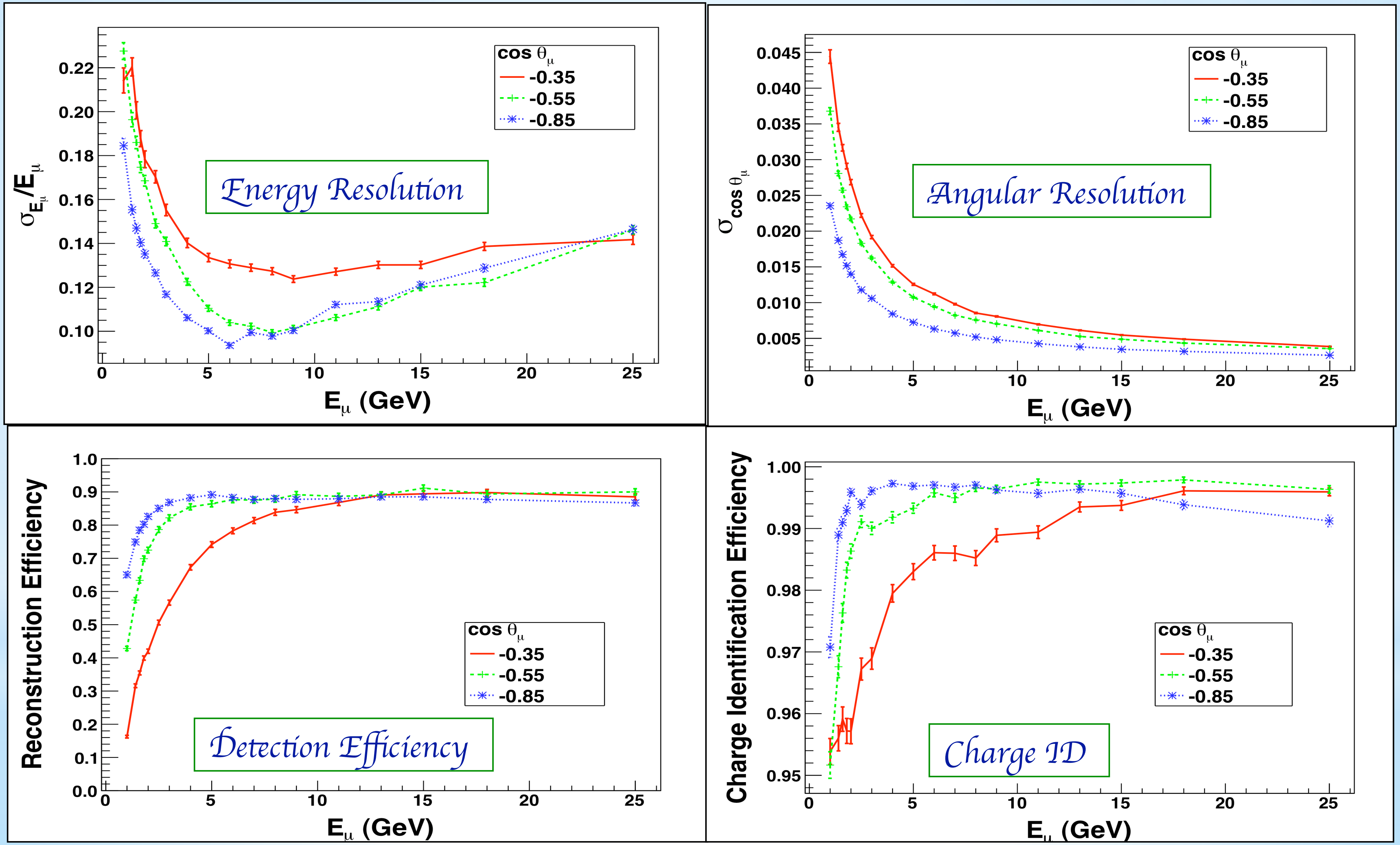
Fit the tracks of A + B + ... to get their energy and momentum.

Output:

i) Energy & Momentum of the initial neutrino

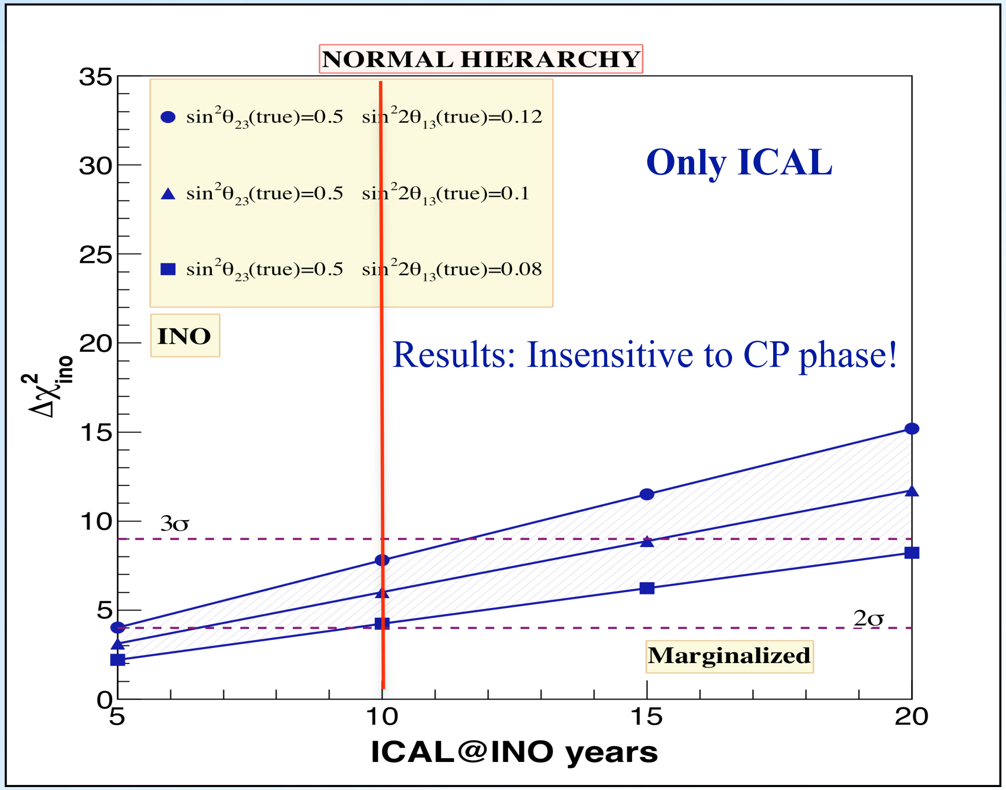
Simulation work is under progress in full swing!

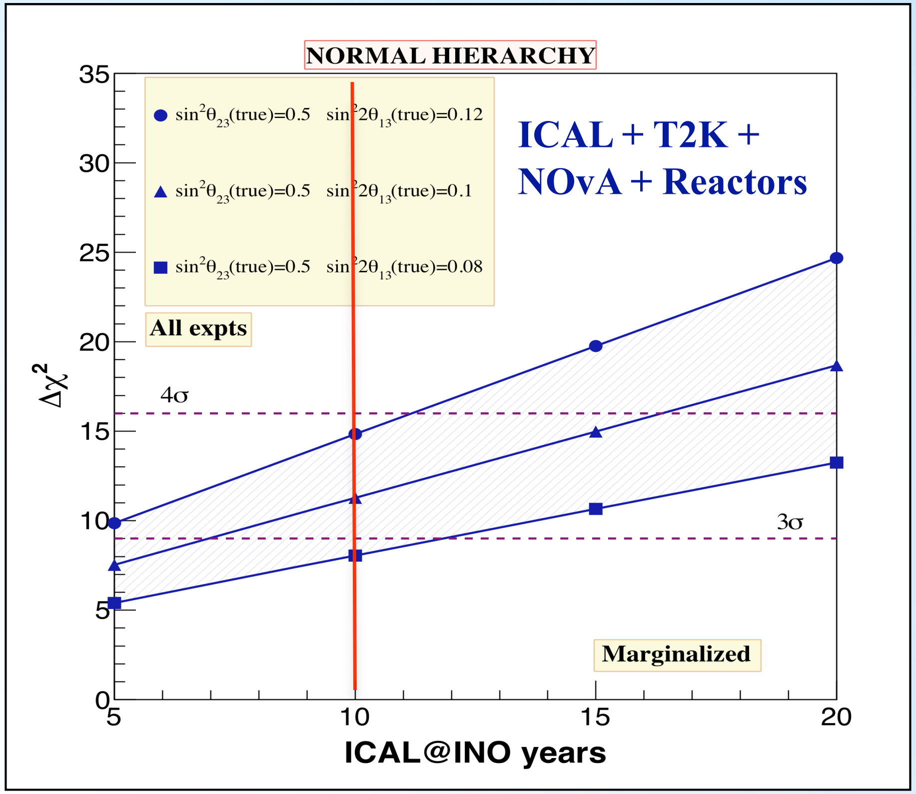
Muon Efficiencies and Resolutions



Animesh, Meghna, Kanishka, Tarak etal., in preparation

Mass Ordering with ICAL-INO





All systematic uncertainties are included!

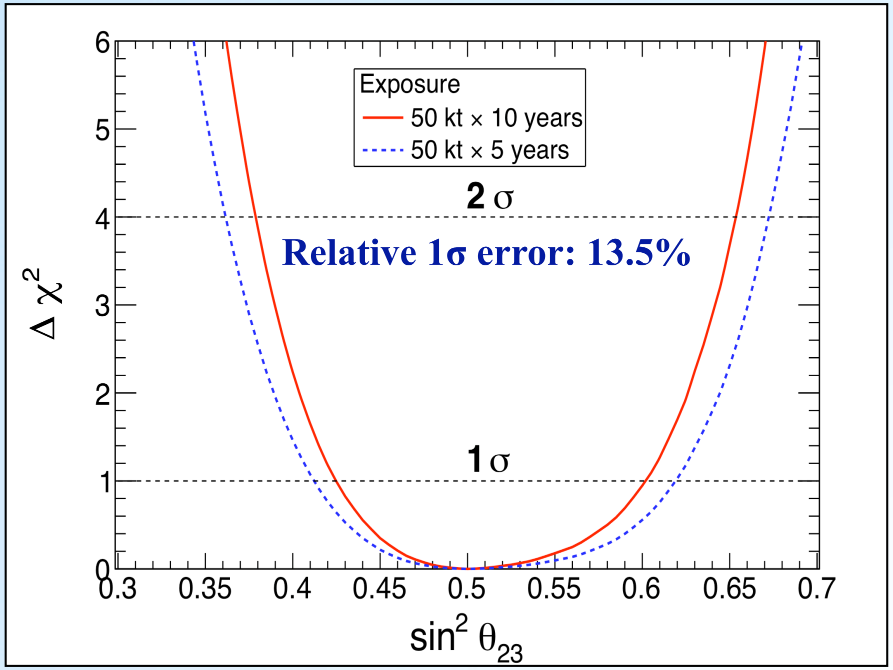
Ghosh, Thakore, Choubey, JHEP 1304 (2013) 009

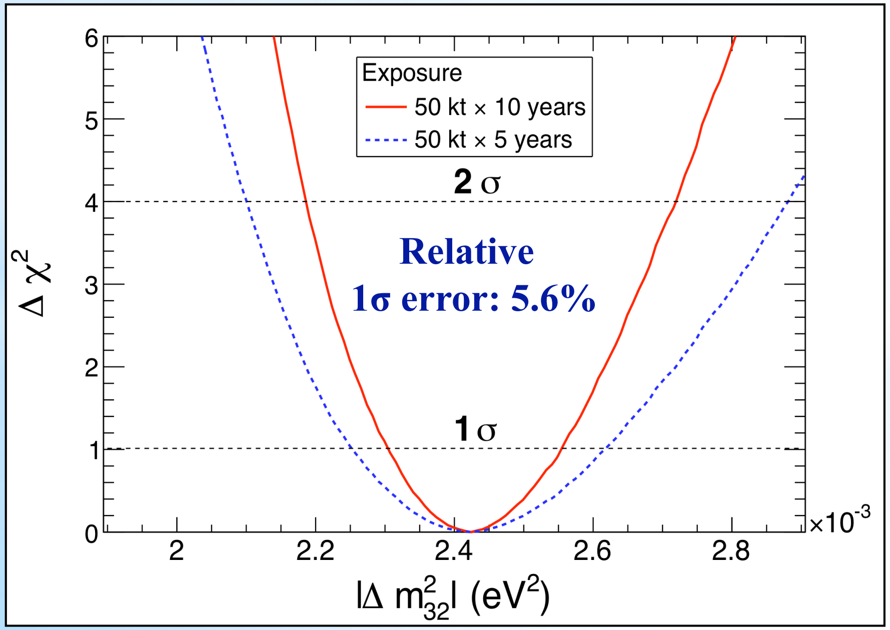
Events generated with NUANCE! Two Dimensional Muon analysis with ICAL resolutions!
E_μ = 20 energy bins in the range 1 GeV to 11 GeV, $\cos\theta_\mu$ = 80 angular bins in the range -1 to +1

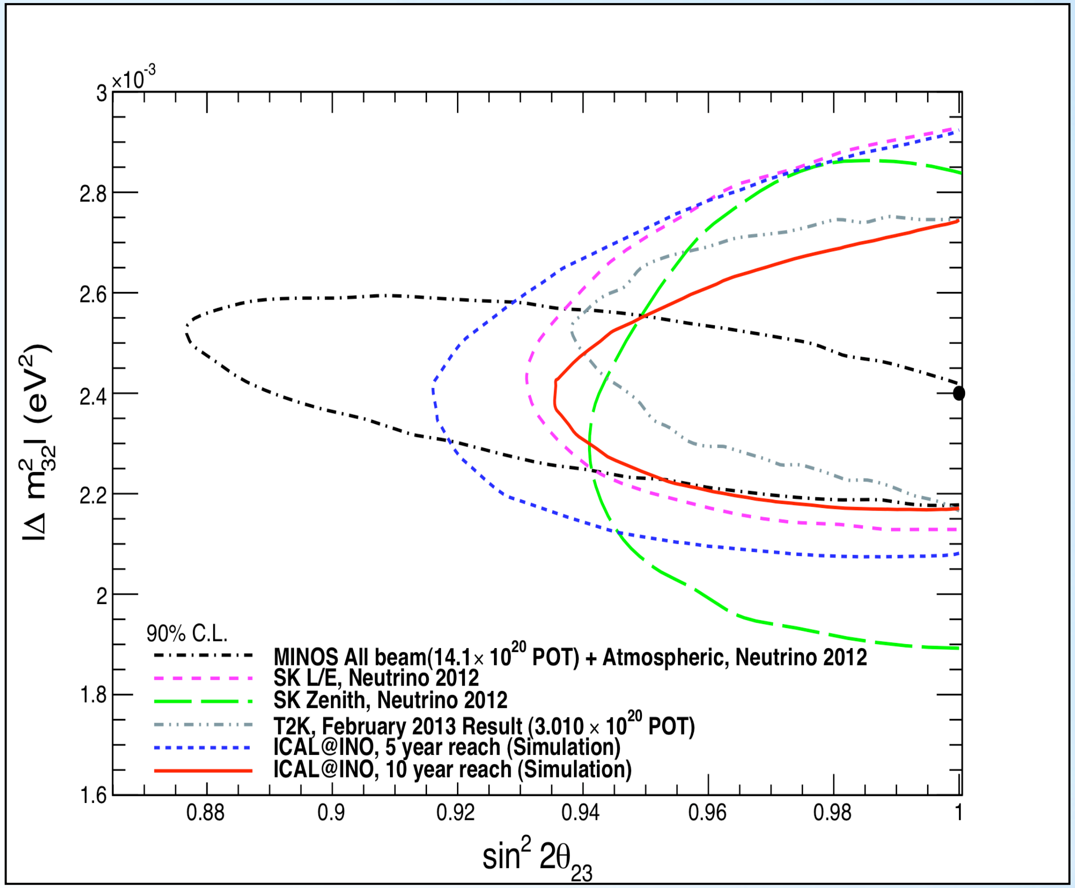
For $\sin^2 2\theta_{13} = 0.1$ & $\sin^2\theta_{23} = 0.5$, Only ICAL with 500 kt-years exposure: **2.5σ MH discovery**
ICAL + T2K + NOvA + Double Chooz + RENO + Daya Bay: **3.4σ MH discovery**

Information on MH from ICAL can increase CP violation reach for LBL experiments
Ghosh, Ghosal, Goswami, Raut, arXiv:1306.2500

Precision of Atmospheric Oscillation Parameters







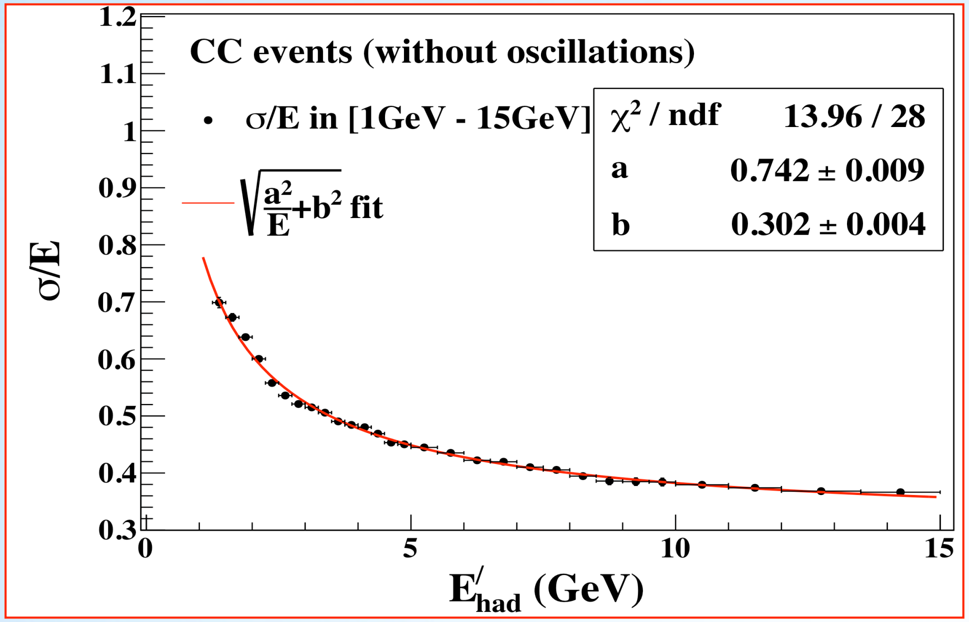
Thakore, Ghosh, Choubey, Dighe, JHEP 1305 (2013) 058

Two Dimensional Muon analysis w/ ICAL resolutions!

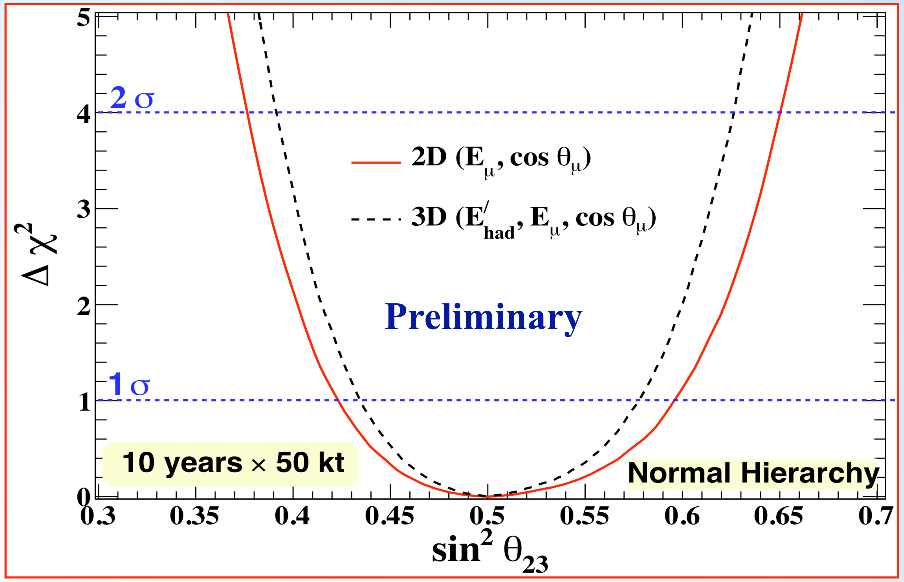
Precision complementary to LBL experiments!

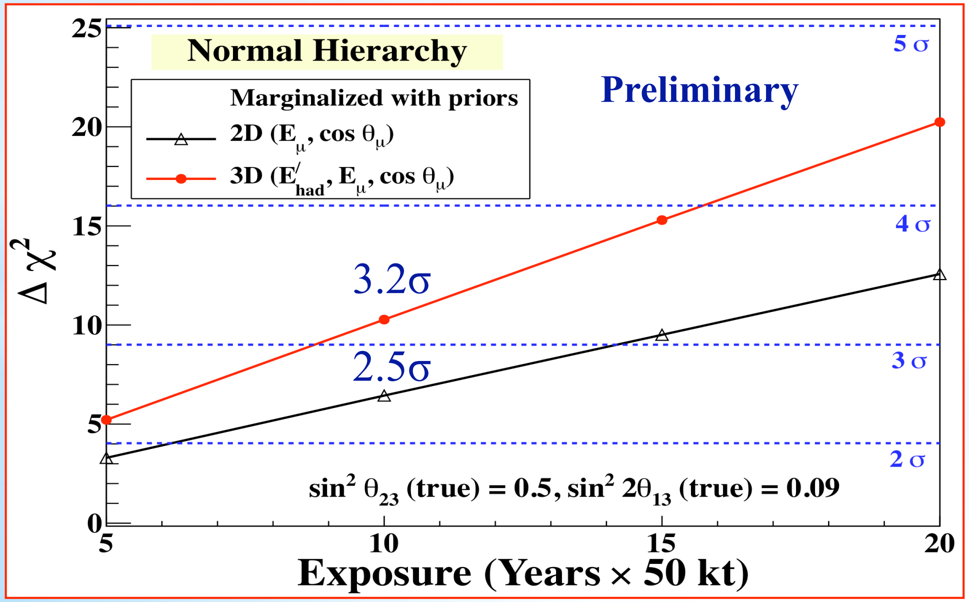
Sensitivity comparable to SK with a similar exposure!

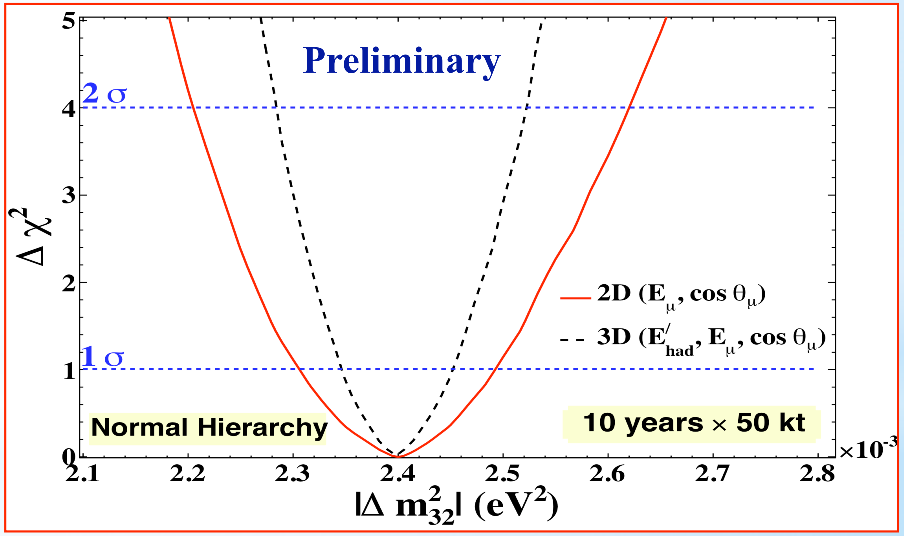
3D Analysis including information on Hadrons



Devi, Ghosh, Kaur, Lakshmi etal., 2013 JINST 8 P11003





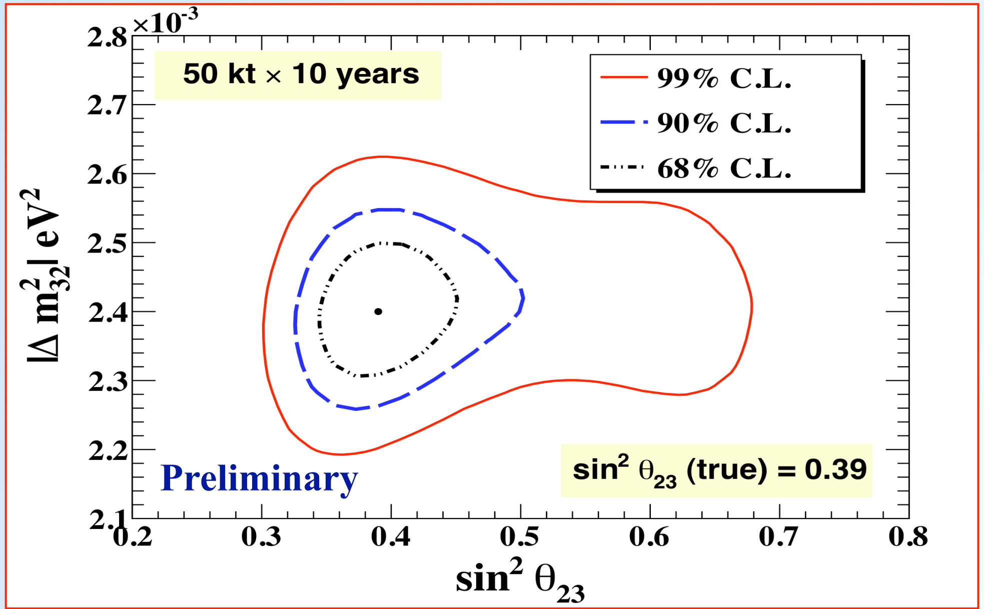


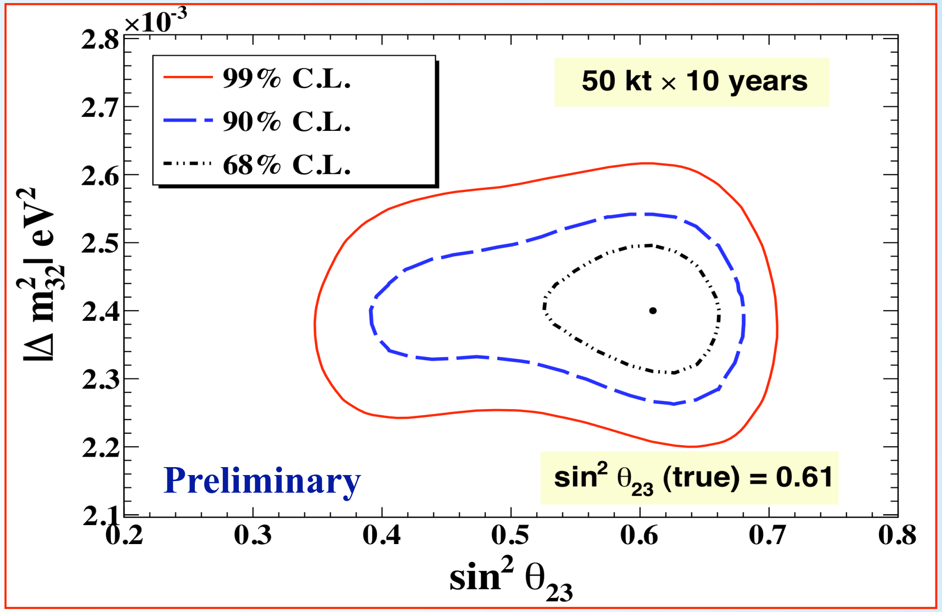
Devi, Thakore etal., in preparation

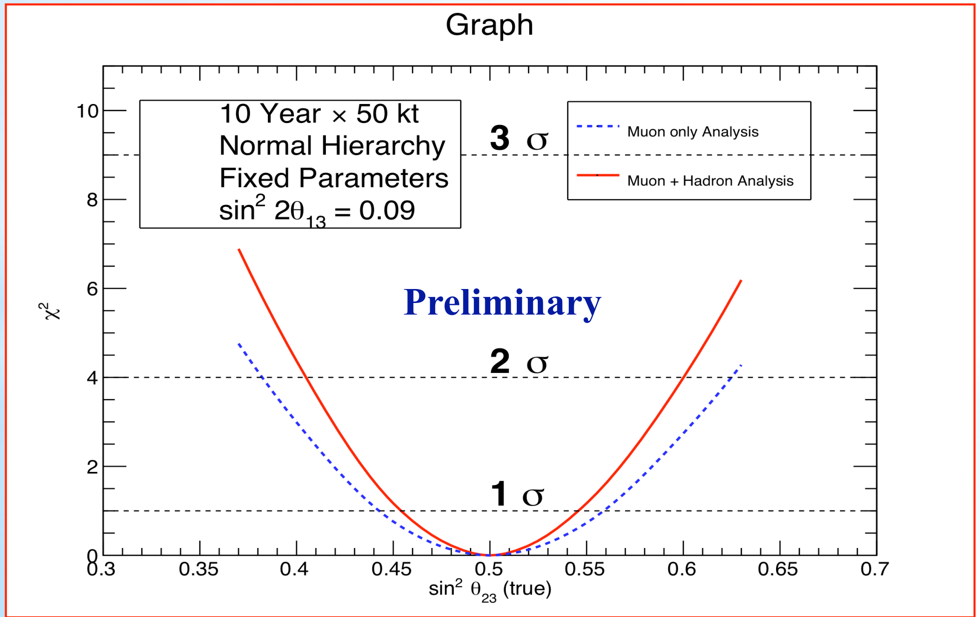
$E^{/}_{h} = E_\nu - E_\mu$ (from hadron hit calibration)

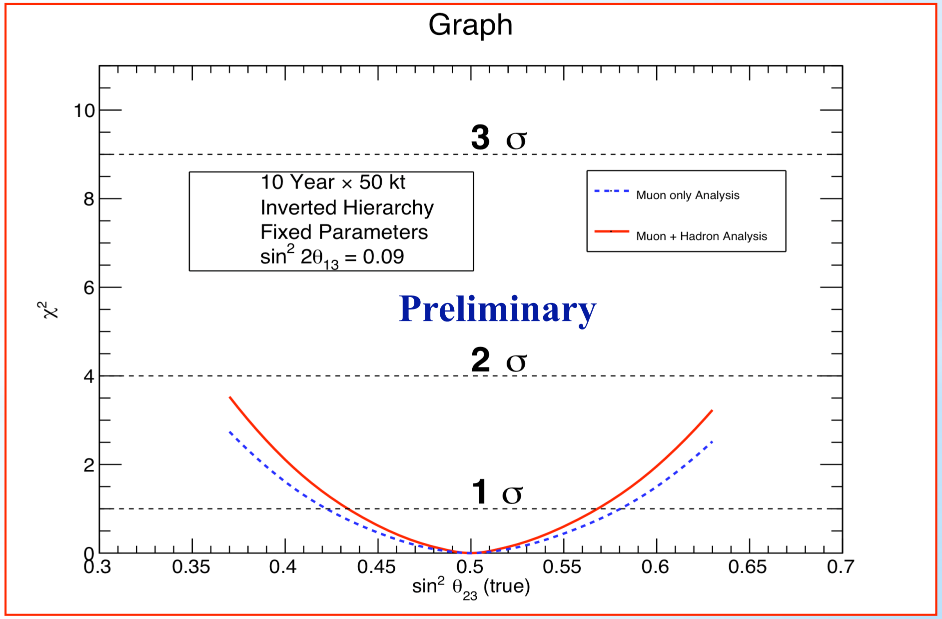
Significant improvement going from 2D to 3D

Octant of 2-3 Mixing Angle with ICAL-INO



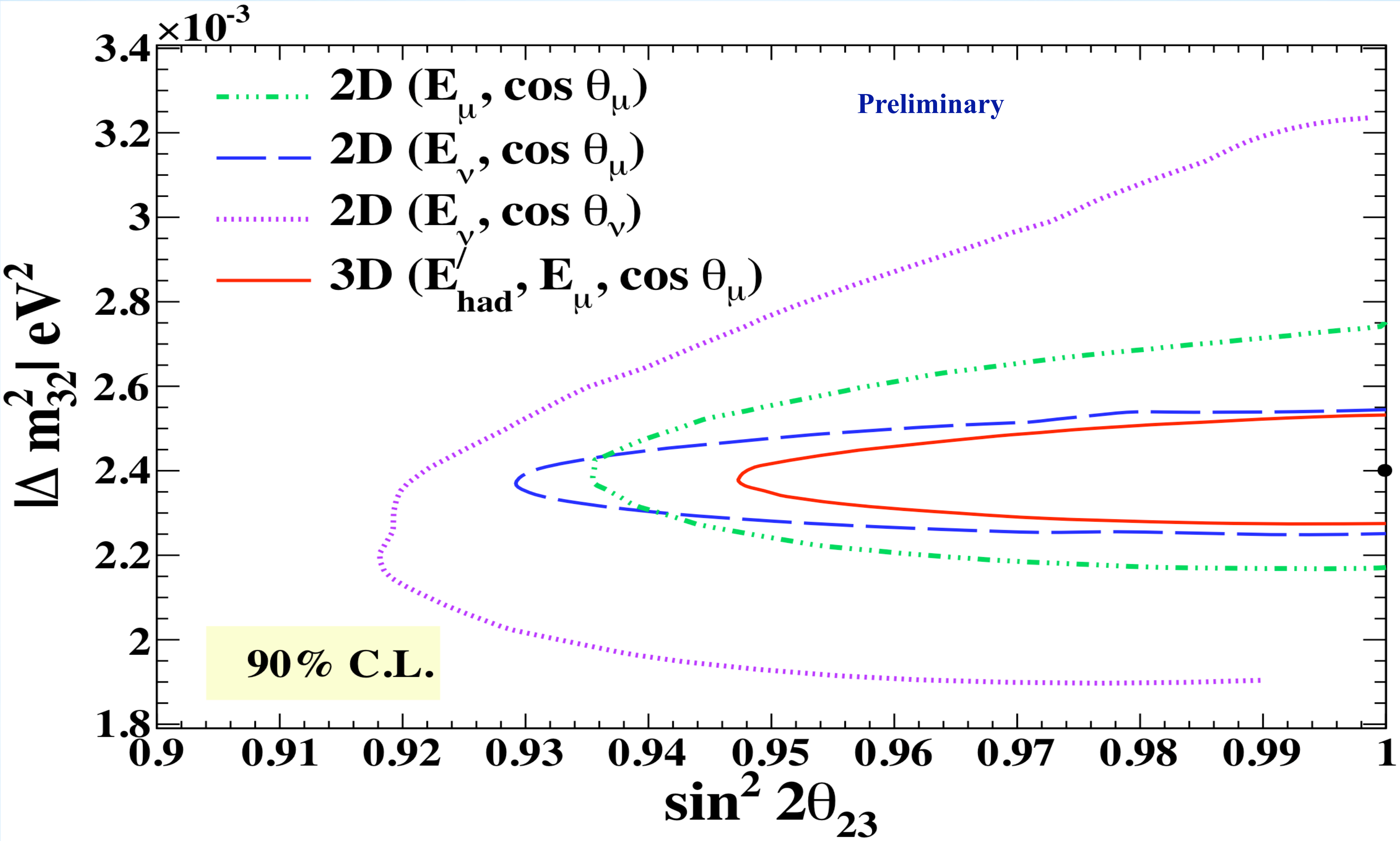






Devi, Thakore etal., in preparation

Improvement in Precision going from 2D to 3D Analysis



Devi, Thakore etal., in preparation

Exploring all possible modes of analysis! More results will be available soon!

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
	Civil work at Pottipuram							
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							
	Magnet							
8	Engineering Prototype							
9	Procurement of steel plates							
10	Machining and Transportation							
11	Copper Coils							
12	Assembly/Erection							
	Detector/Electronics							
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							

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 1st batch (2008) are at the final stage of writing their theses. Few of them have already received good post-doctoral offers from various experiments**
- **6th batch of 7 students have started their course work at TIFR this year**

Huge 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

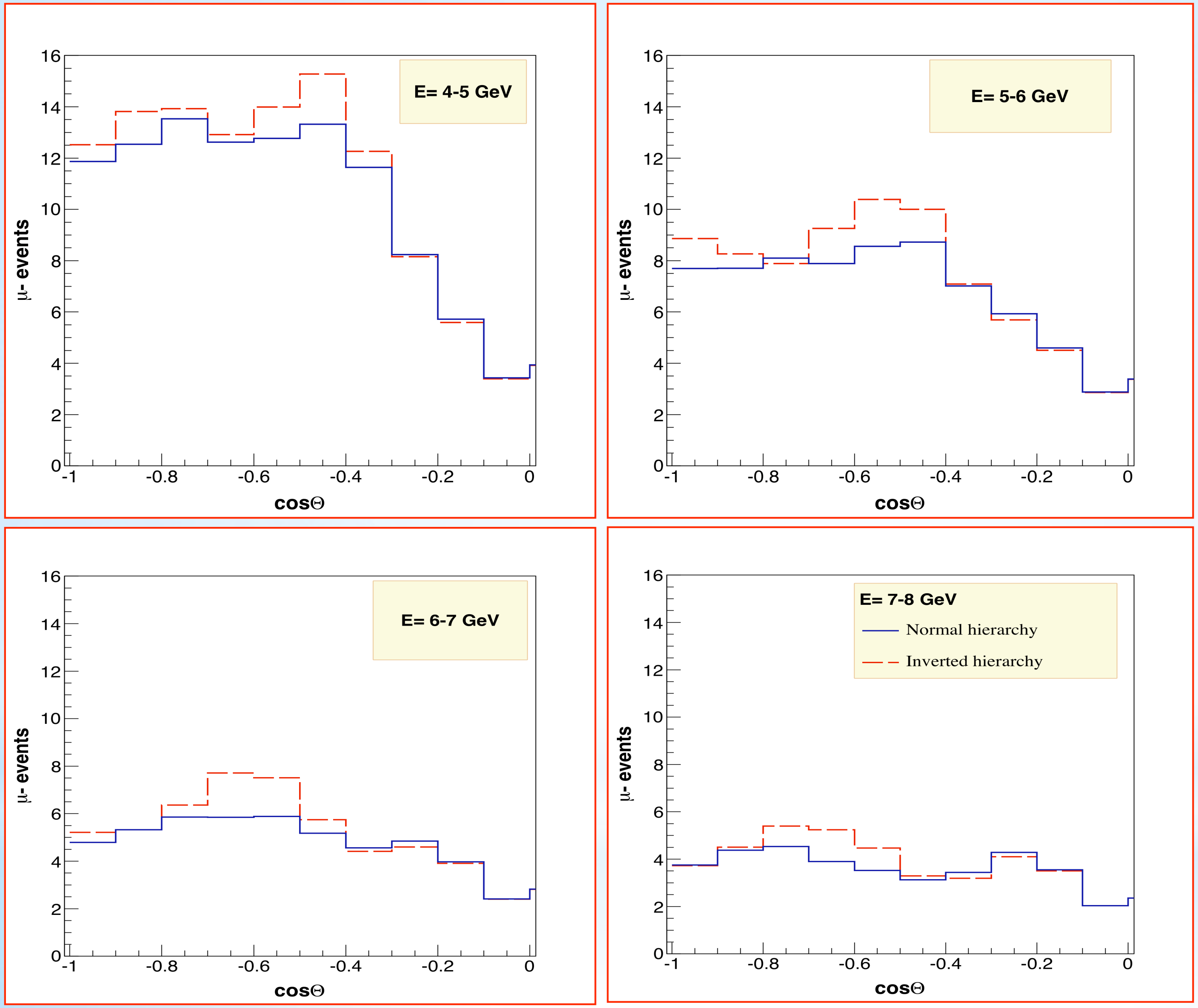
International collaboration most welcome

!! Looking Forward for Exciting Discoveries at INO !!

Thank You!

Backup Slides

Event Spectrum in ICAL-INO

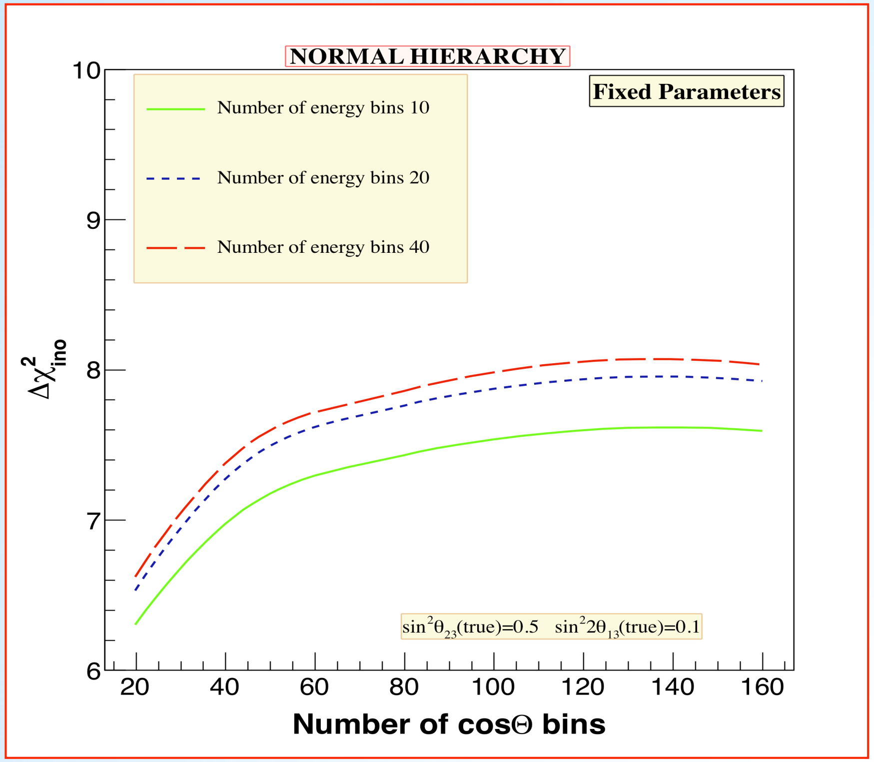


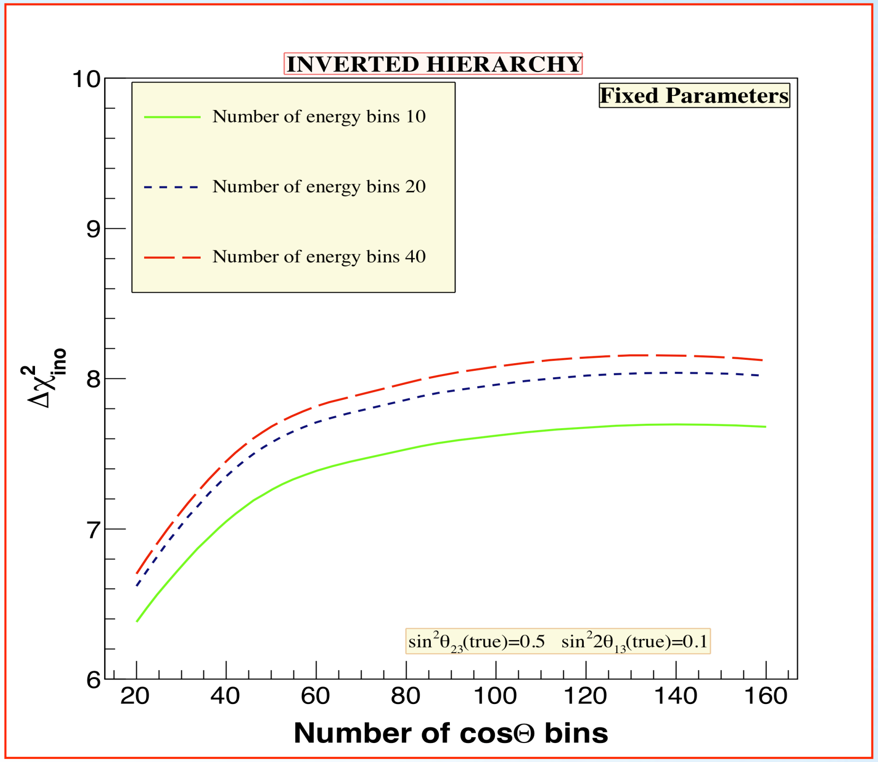
μ^- event spectrum for 10 years exposure

Comparison between Normal and Inverted hierarchy

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

Effect of Binning on the Mass Hierarchy





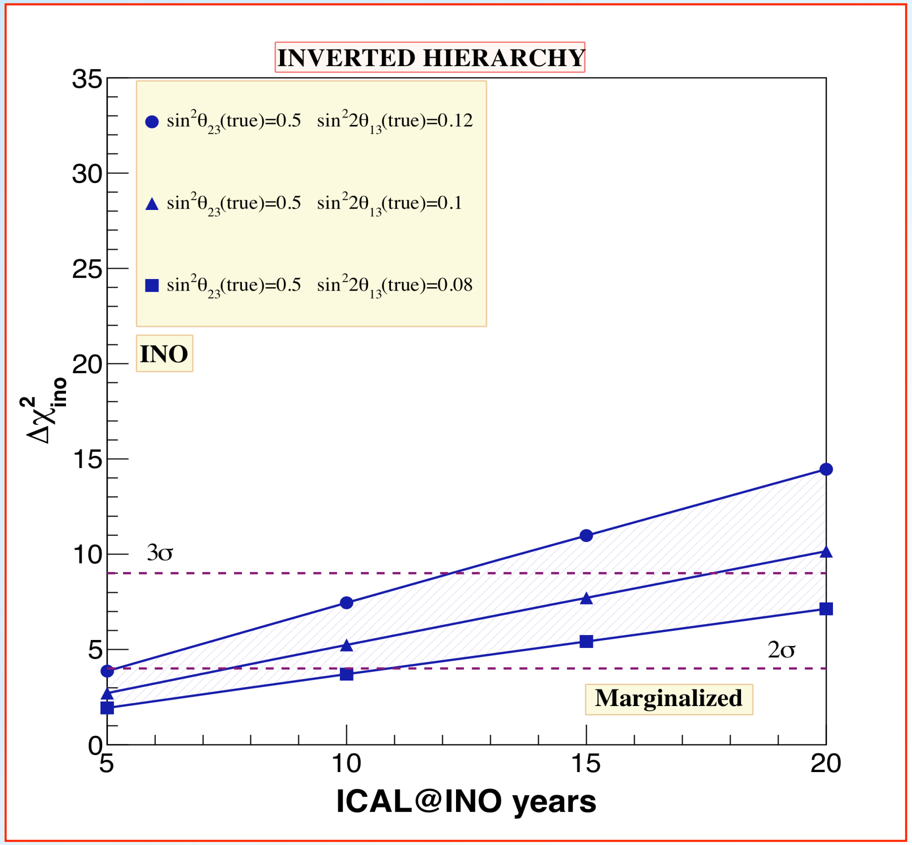
Ghosh, Thakore, Choubey, JHEP 1304 (2013) 009

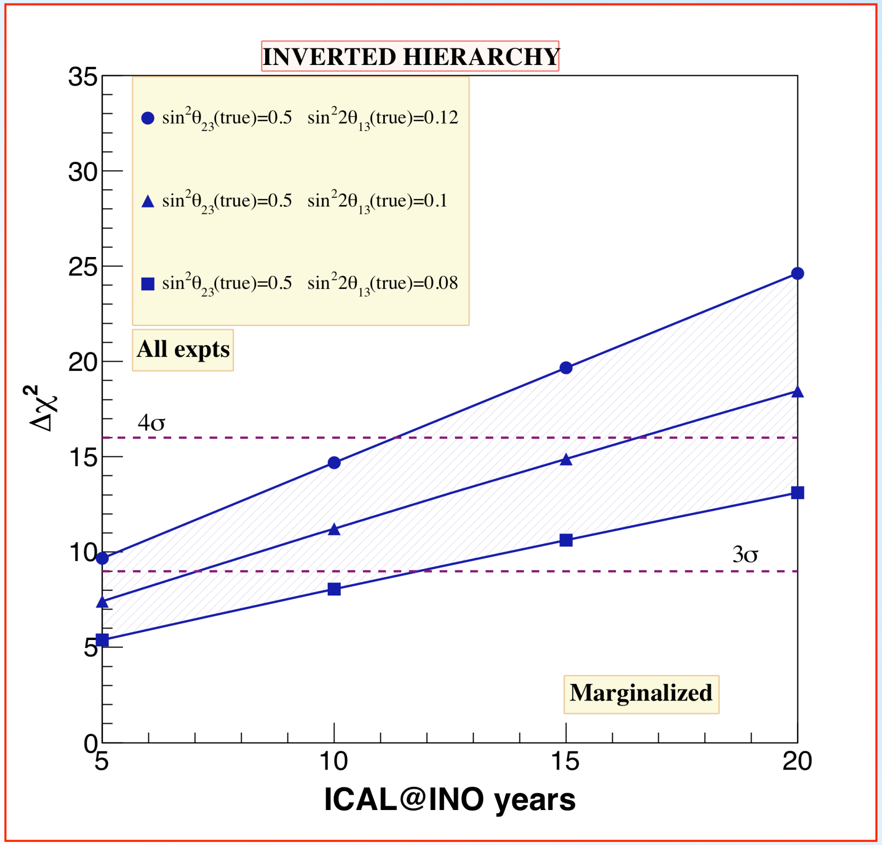
Optimal Choice:

E_μ = 20 energy bins in the range 1 GeV to 11 GeV

$\cos\theta_\mu$ = 80 angular bins in the range -1 to +1

Mass Ordering with ICAL-INO



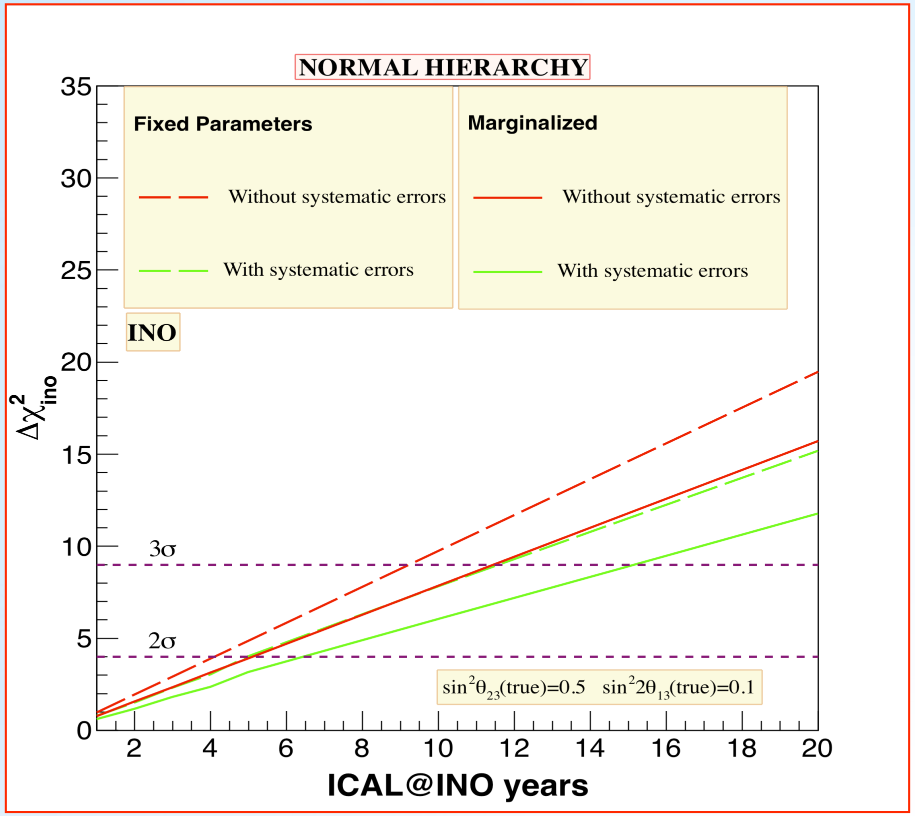


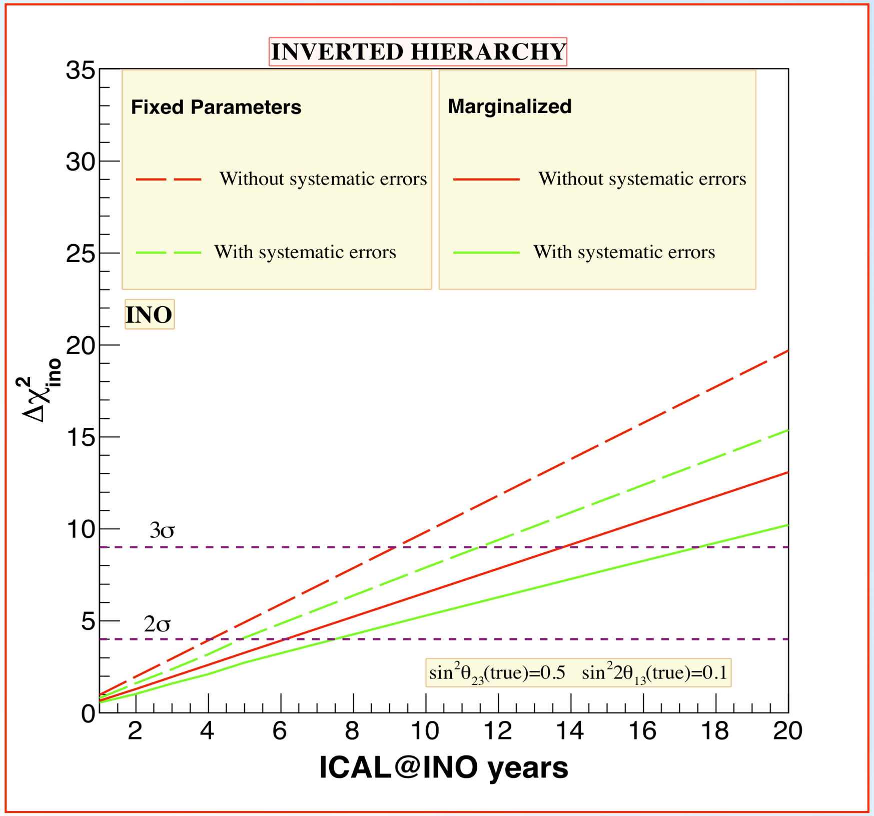
Ghosh, Thakore, Choubey, JHEP 1304 (2013) 009

For $\sin^2 2\theta_{13} = 0.1$ & $\sin^2\theta_{23} = 0.5$, Only ICAL with 500 kt-years exposure: **2.2σ MH discovery**

ICAL + T2K + NOνA + Double Chooz + RENO + Daya Bay: **3.3σ MH discovery**

Impact of Systematic Uncertainties





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Overall flux normalization: 20%, overall cross-section normalization: 10%

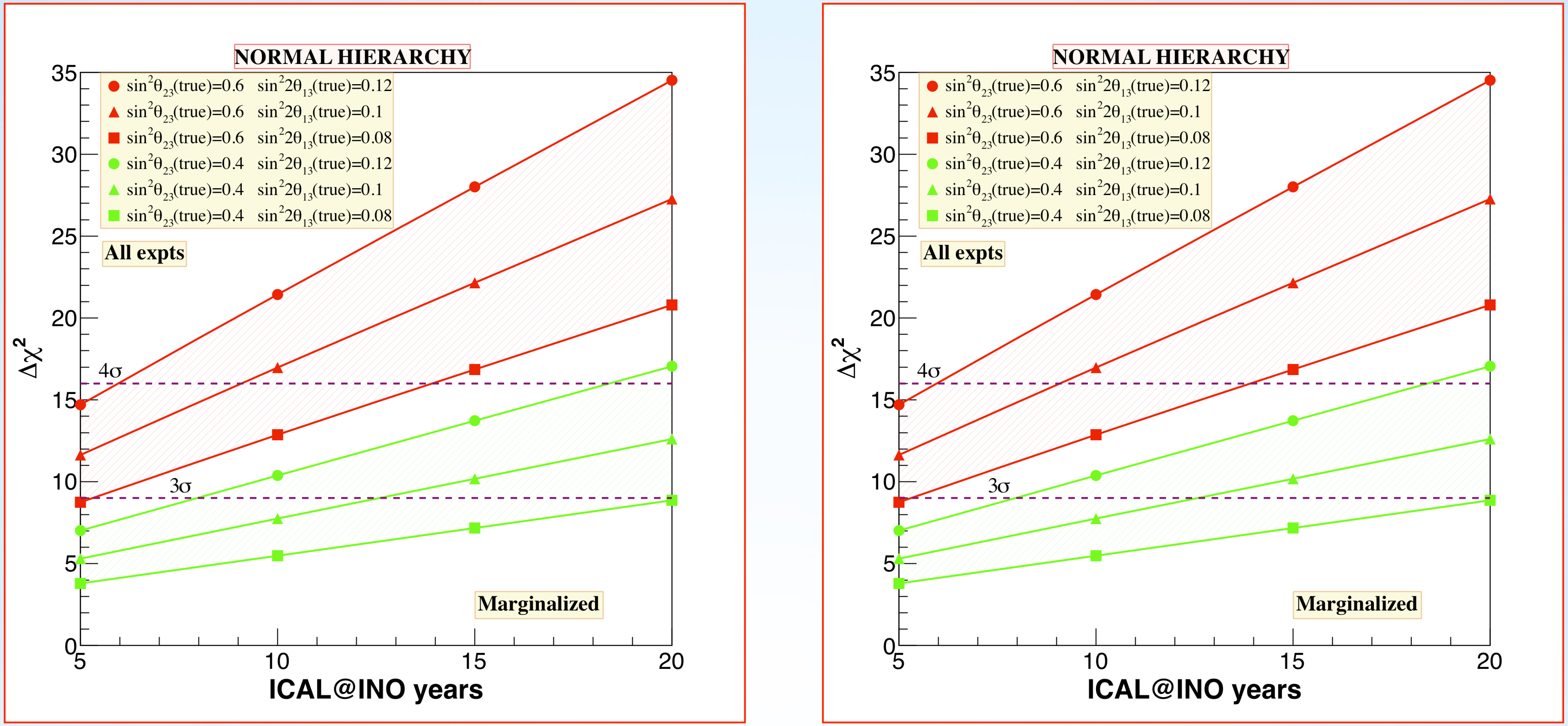
5% uncertainty on the zenith angle dependence of the fluxes

Energy dependent tilt factor: $\Phi_\delta(E) = \Phi_0(E)\,[E/E_0]^\delta \approx \Phi_0(E)\,[1+\delta \ln E/E_0]$

where E_0 = 2 GeV and δ is the 1σ systematic error which we took 5%

Overall 5% systematic uncertainty

Impact of Non-Maximal 2-3 Mixing Angle



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

With 10 years of running of ICAL-INO: 2.3σ to 4.6σ MH discovery depending on the true values of the oscillation parameters