India-based Neutrino Observatory (INO):

Physics Reach and Status Report

D. Indumathi

The Institute of Mathematical Sciences, Chennai

For the INO Collaboration

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

Outline of talk

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- The India-based Neutrino Observatory
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- Physics possibilities at ICAL: atmospheric neutrinos
- The ICAL Detector: Current status

Parameters of the 3 ν framework

The ν_e, ν_μ and ν_τ flavours do not have definite masses:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i \ .$$

where ν_1, ν_2 and ν_3 have well-defined masses: m_1, m_2 and m_3, some are non-zero. $U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$ is the mixing matrix.

The Earth matter effect mainly occurs in the θ_{13} parameter:

(1) $$(\sin\ 2\theta_{13})_m = \frac{(\sin\ 2\theta_{13})}{\sqrt{[\cos 2\theta_{13} - (A/\Delta m^2_{32})]^2 + (\sin 2\theta_{13})^2}}$$

where

$$A = 7.6 \times 10^{-5}\ \rho\ E\ eV^2\ ; \quad \Delta m^2_{32} = m^2_3 - m^2_2\ ,$$

ρ = earth density (gms/cc); E = neutrino energy in GeV.

A Schematic of Neutrino Properties

Neutrino masses are not well-known. Oscillation studies only determine the mass-squared differences: $\Delta m_{ij}^2 = m_i^2 - m_j^2$ and the mixing angles θ_{ij}. Phase(s) unknown.

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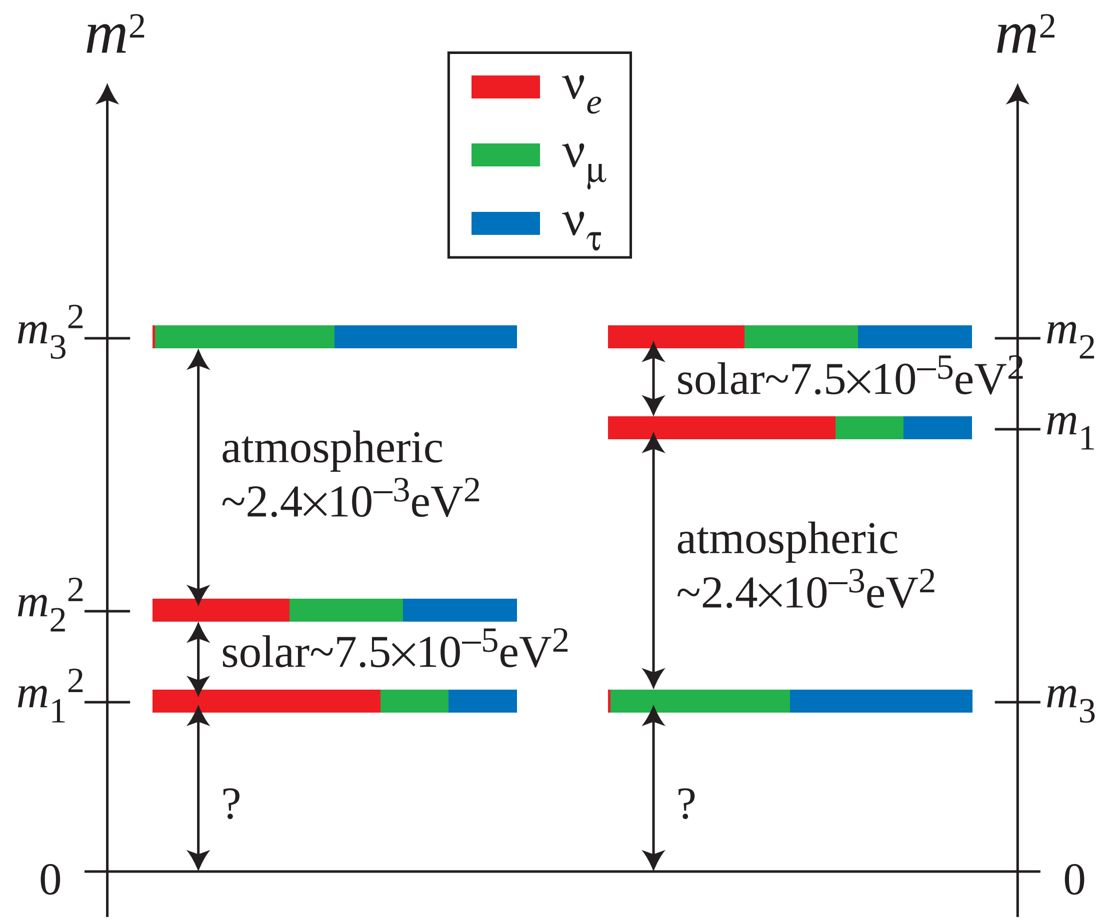

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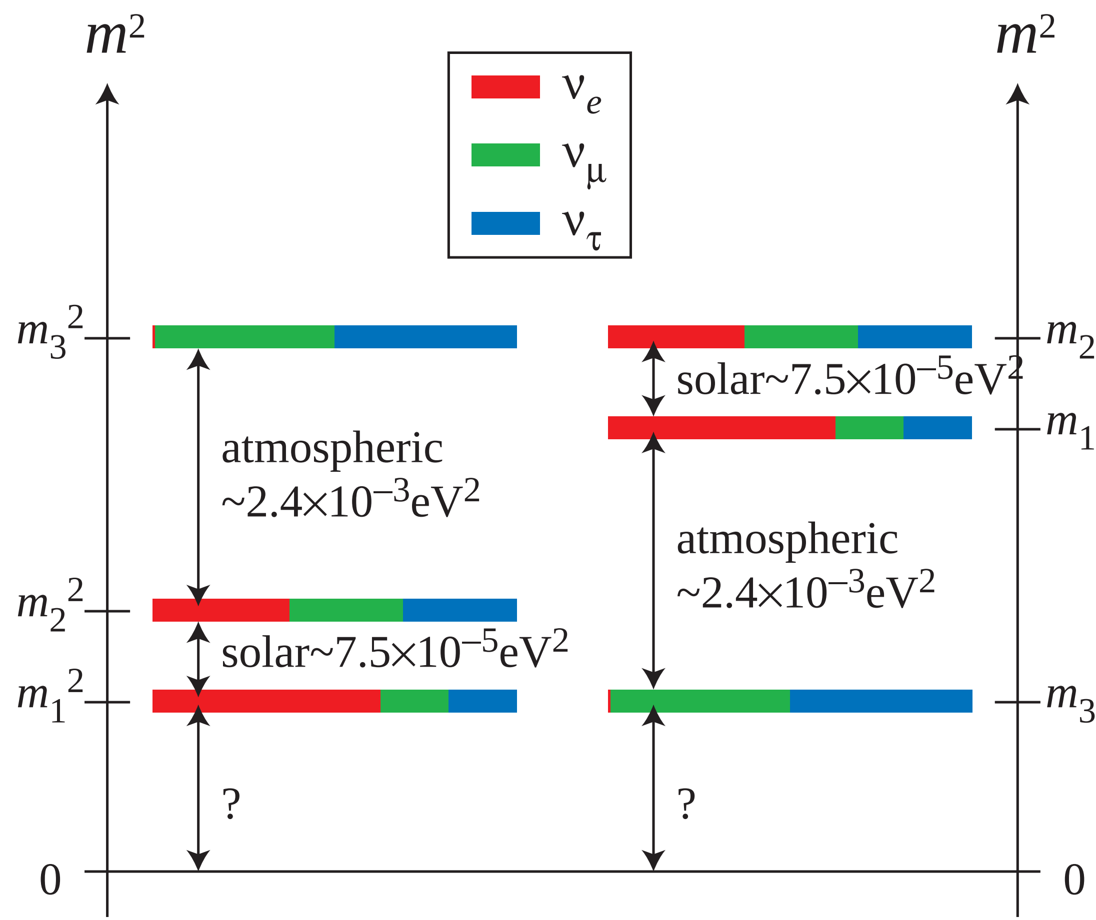
$\Delta m^2_{21} \sim 0.76 \times 10^{-4}$ eV^2 ;
$|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2 ;
$\sum_i m_i < 0.7$–2 eV.



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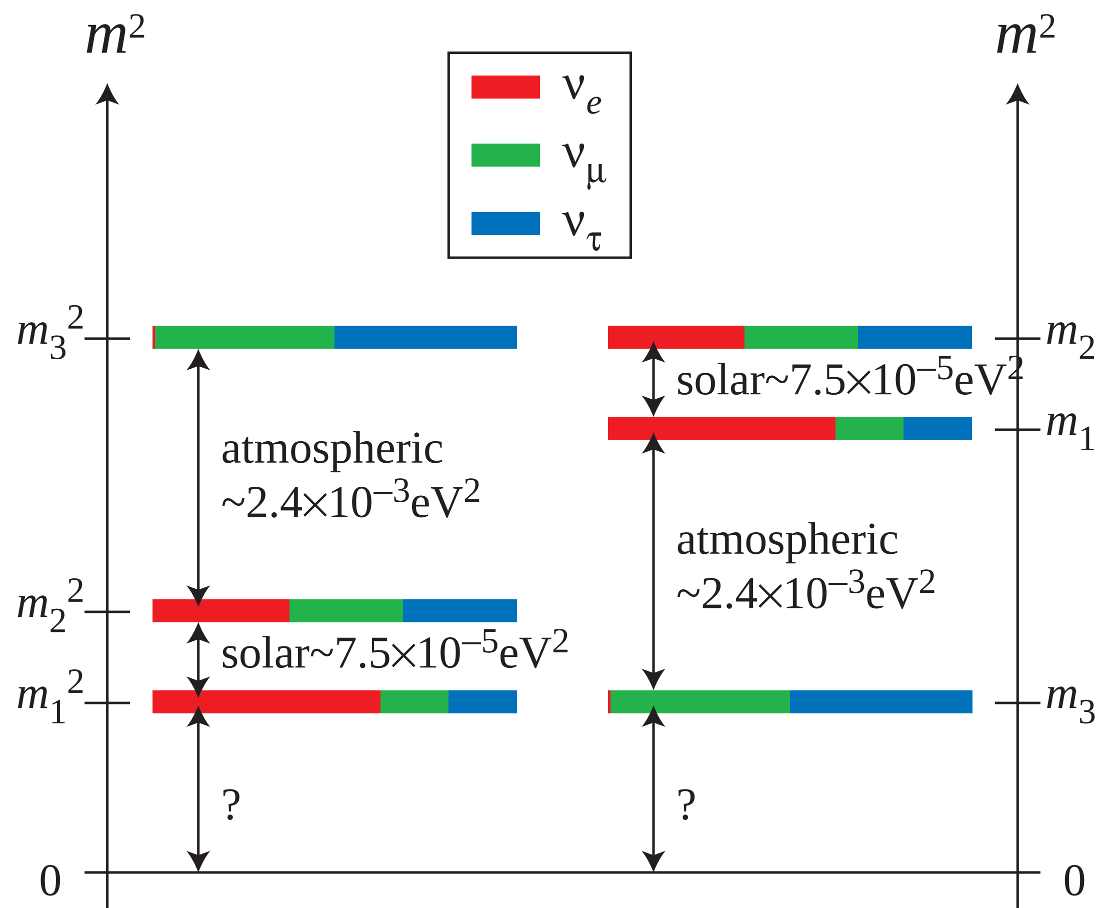
- $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV (Degenerate hierarchy)
- $m_1 < m_2 \ll m_3$ (Normal hierarchy)
- $m_3 \ll m_1 < m_2$ Inverted hierarchy



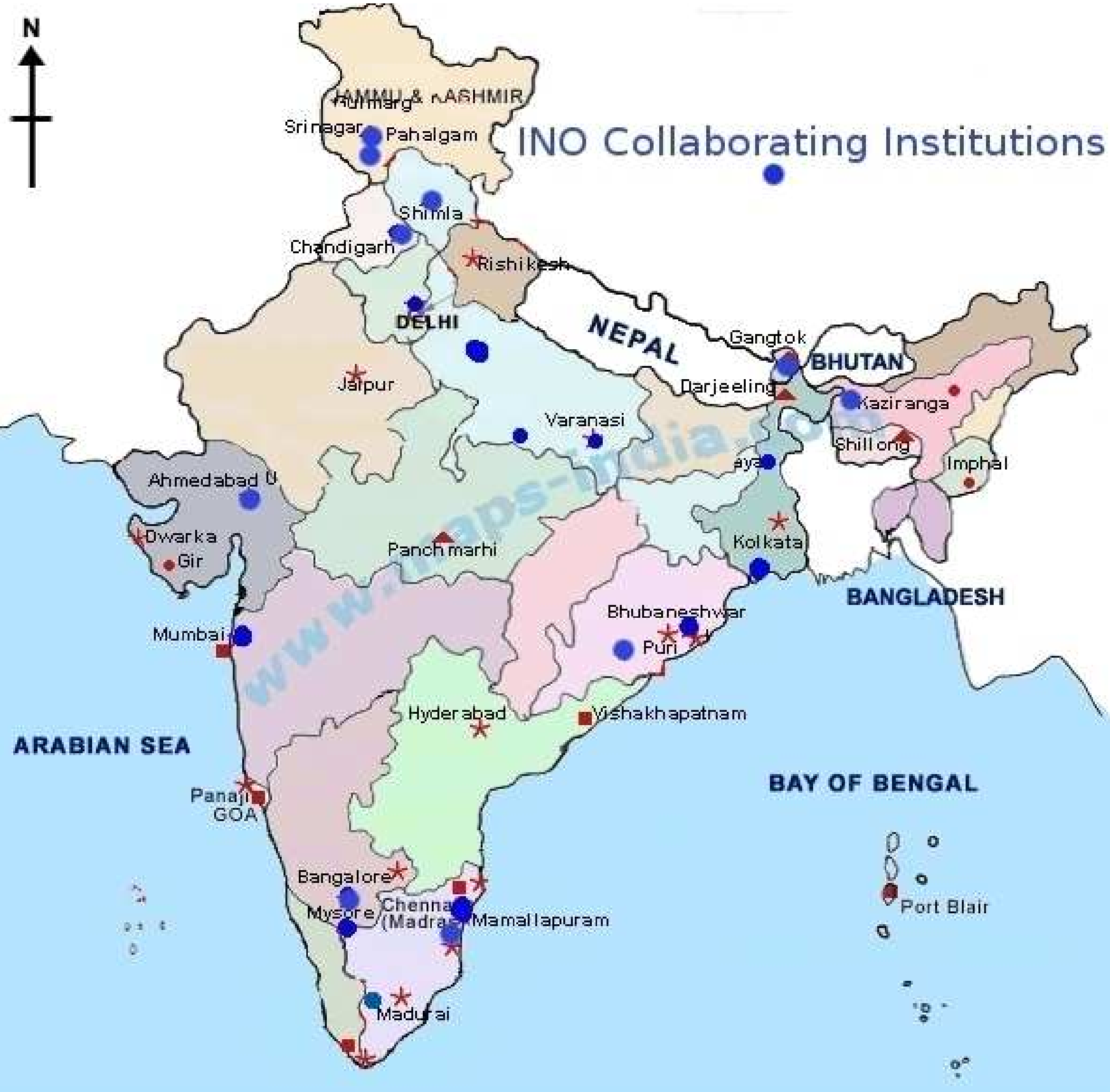
(Nu-Fit, JHEP 12 (2012) 123 [arXiv:1209.3023]

India-based Neutrino Observatory

The INO Project

- Project funded by the Dept. of Science and Technology and Dept. of Atomic Energy, Govt. of India
- Immediate goal: Creation of an underground laboratory for research in neutrino physics
- Will develop into a full fledged underground laboratory over the years for other studies in physics, biology and geology
- Main detector proposed is magnetised Iron CALorimeter (ICAL) to primarily study atmospheric neutrinos
- Will incorporate Inter-Institutional Centre for High Energy Physics (IICHEP) at Madurai, a nearby city
- INO Graduate School: Some INO students have already graduated!

The INO Collaboration



Collaborating Institutions:

- Aligarh MU
- BARC
- Calicut U
- HRI
- IIT (Madras)
- IOP
- Lucknow U
- PRL
- SINP
- Utkal U
- Benaras HU
- Calcutta U
- Delhi U
- IIT (Bombay)
- IMSc
- Kashmir U
- Mysore U
- Panjab U
- TIFR
- VECC

The choice of detector: ICAL

Use (magnetised) iron as target mass and RPC as active detector element. Reminder: KGF; MONOLITH detectors.

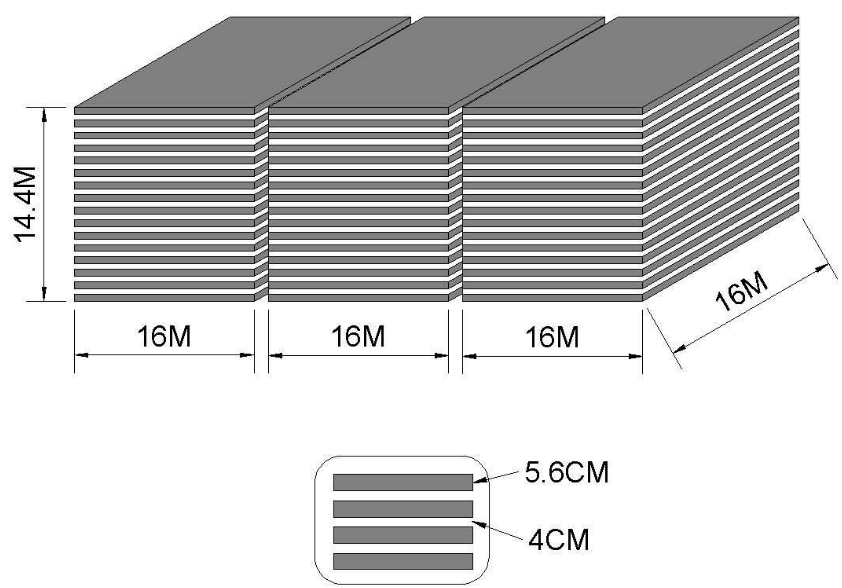
Atmospheric neutrinos have large L and E range. So ICAL has

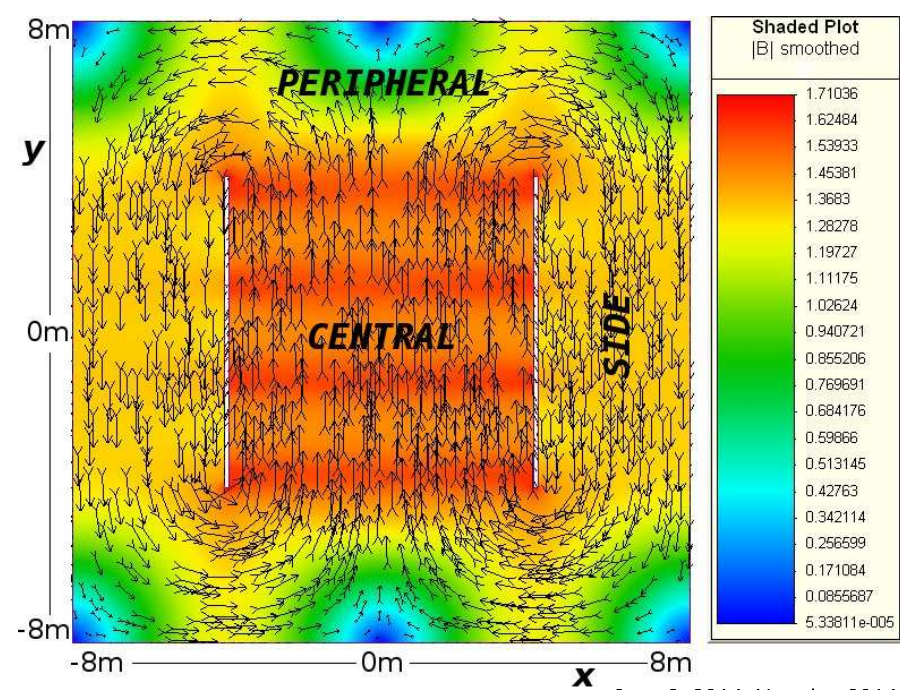
- Large target mass: current design 52 kton;
- Nearly 4π coverage in solid angle (except near horizontal);
- Tracks of upto ~ 20 GeV muons contained inside detector; note that the most interesting region for observing matter effects in the 2–3 sector is 3–15 GeV;
- Good tracking and energy resolution;
- $\sim ns$ time resolution for up/down discrimination; good directionality;
- Good charge resolution; magnetic field ~ 1.5 Tesla;
- Ease of construction (modular; 3 modules of 17 kTons each).

Mostly sensitive to muons, very little sensitivity to electrons; some to hadrons.

The ICAL detector

- 52 kton detector, with 151 layers of 5.6 cm iron plates magnetised to ~ 1.5 T, in three modules.
- Magnetic field mostly uniform in central region of each layer, in y-direction; changing in both magnitude and direction, and falling to zero in periphery.
- Active detector elements are Resistive Plates Chambers (RPCs).



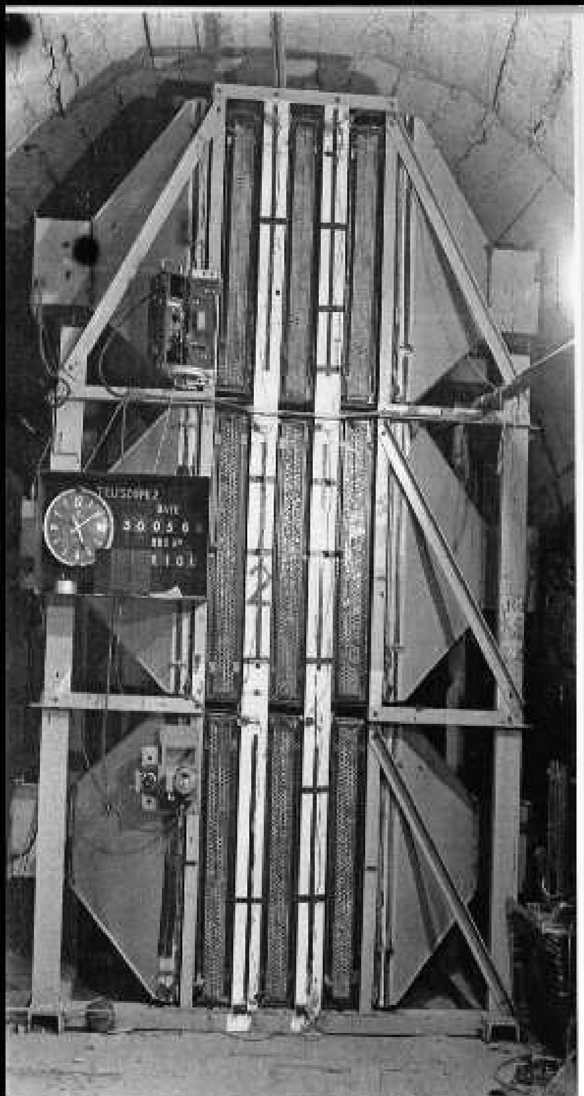


Specifications of the ICAL detector

ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 14.4 m
Detector dimension	48 m $\times$ 16 m $\times$ 14.4 m
No. of layers	150
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	$\sim$ 30,000
No. of electronic readout channels	3.9 $\times 10^6$

Needs large industry interface.

Atmospheric neutrinos – India connection



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

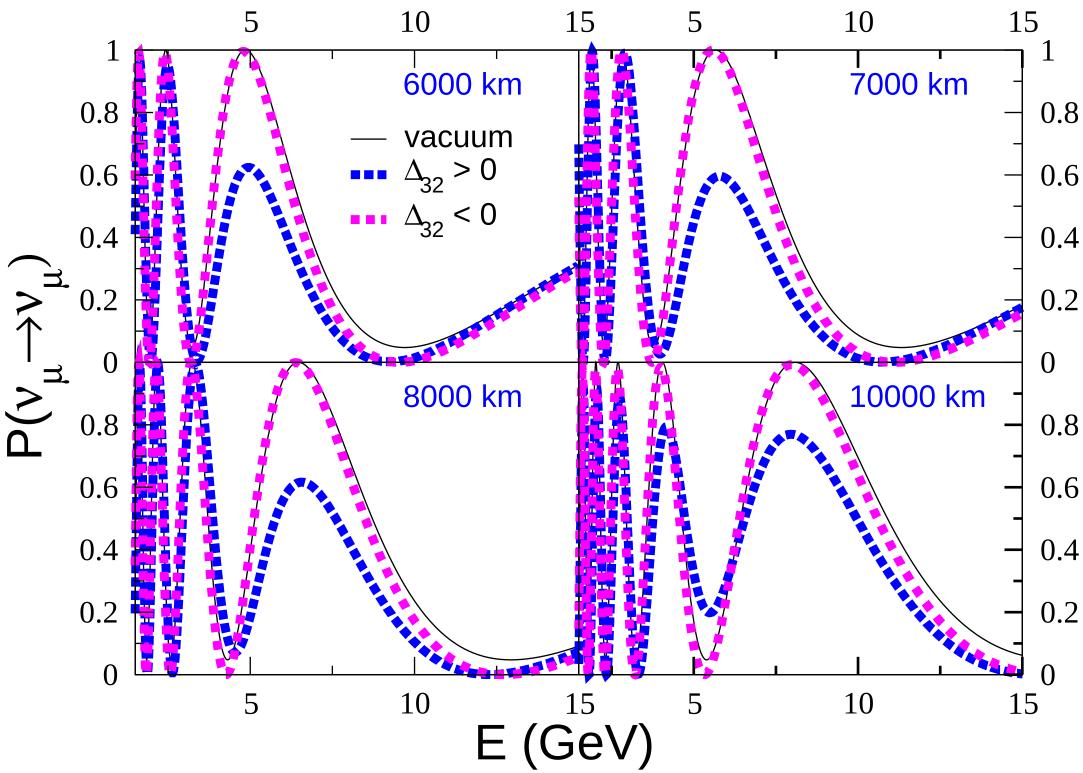
and

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

Matter effect with atmospheric neutrinos



Matter effects involve the participation of all three (active) flavours; hence involve both $\sin\theta_{13}$ and δ_{CP}, in general. *(R. Gandhi et al., PRL 94 (2005) 051801, PR D73 (2006) 053001.)*

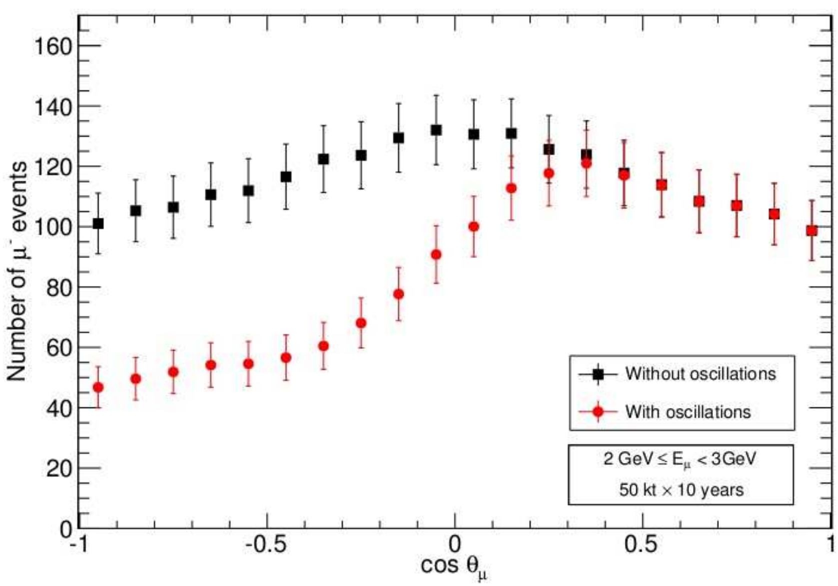
- Used NUANCE neutrino generator with Honda 3d (SK) fluxes for analysis (Theni Honda flux is getting finalised)
- 1000 year unoscillated events were generated and then smeared according to muon/hadron resolutions obtained by the simulations group.
- Events were scaled to suitable number of years and oscillated with fixed input values of oscillation parameters and hierarchy.

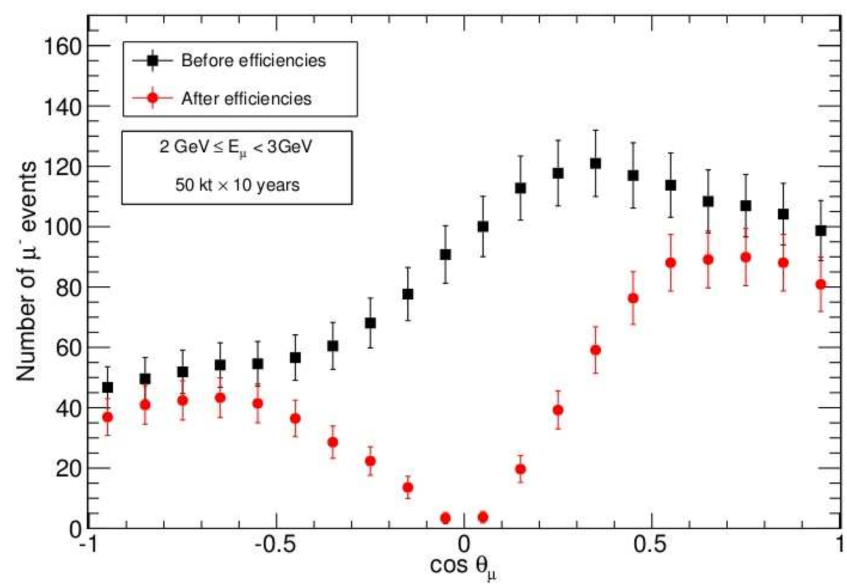
Inputs and Events generation

Δm^2_{eff}	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	δ_{CP}
2.4×10^{-3} eV^2	0.5	0.1	0°

$$\Delta m^2_{eff} = \Delta m^2_{32} - (\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{32}\sin 2\theta_{12}\tan\theta_{23})\Delta m^2_{21}.$$

- Nuance event rates in 10 years in energy bin $2 < E < 3$ GeV.





- Horizontal events are poorly reconstructed.

Definitions

$$\chi^2_{\rm tot} \; = \; \min_{\{\xi_j\}} \sum_{i=1}^{N_{bin}} \left[2\left(N_i^{th} - N_i^{ex} \right) + 2N_i^{ex} \ln \left(\frac{N_i^{ex}}{N_i^{th}} \right) \right] + \sum_{j=1}^{k} \xi_j^2 \,,$$

where

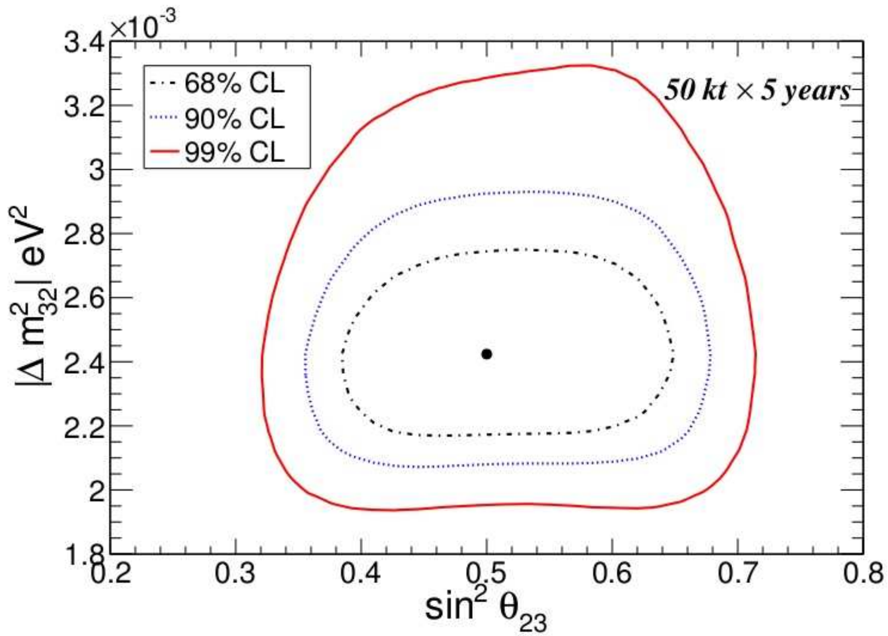
$$N_i^{th} = N_i^{\prime th} \left(1 + \sum_{j=1}^{k} \pi_i^j \xi_j \right) + \mathcal{O}(\xi_k^2) \,.$$

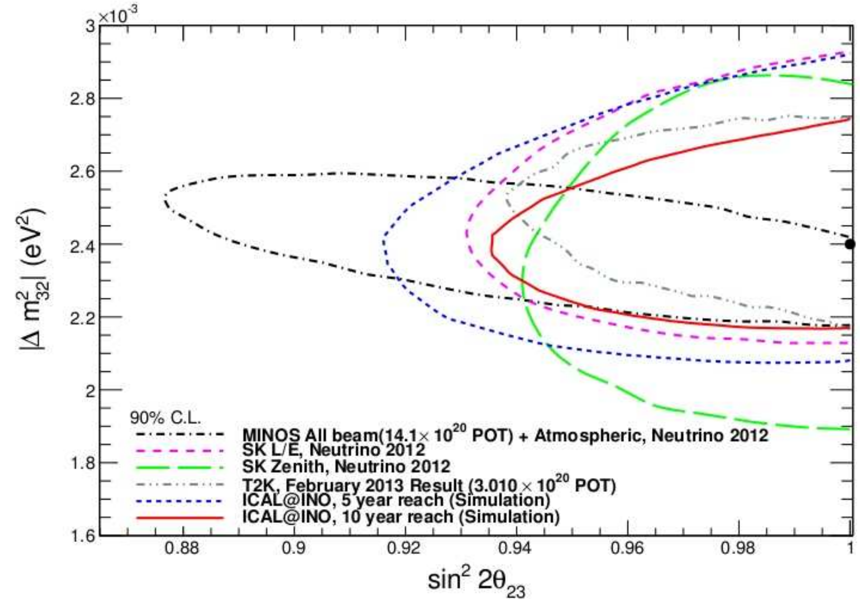
Systematics through the pull method:

Overall flux normalisation:	20%
Overall cross section normalisation:	10%
Zenith angle dependence of fluxes:	5%
Energy spectrum tilt:	5%
Overall systematic uncertainty:	5%

Precision measurement

of “atmospheric" parameters using muons only





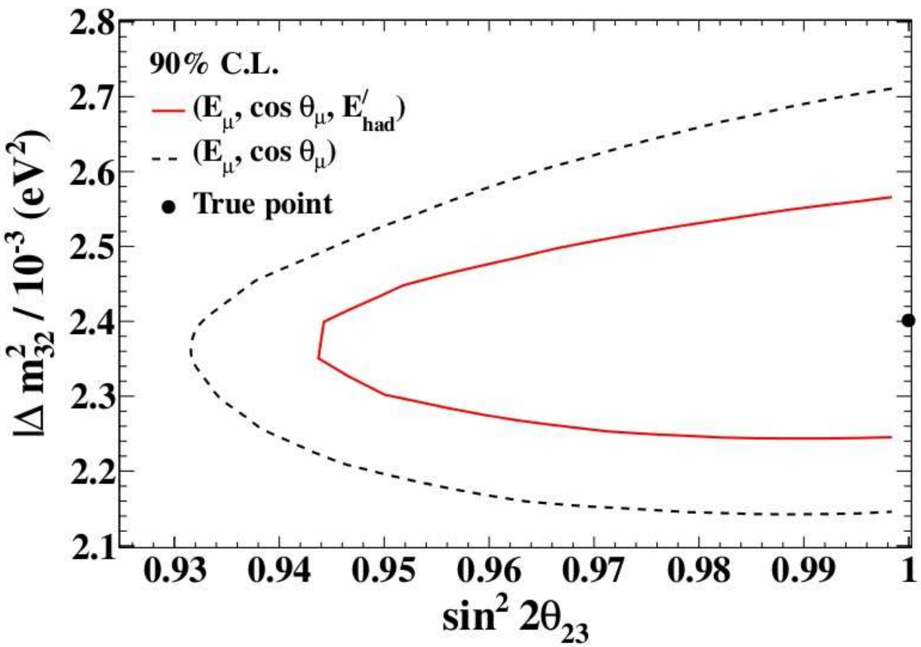
- True hierarchy is assumed normal
- $\sin^2 2\theta_{23}$ more highly constrained than Δm^2_{32}.
- Symmetric plot (LHS) because of choice of input $\sin^2 2\theta_{23} = 1$.
- Results on Δm^2_{32} somewhat improved if E_ν is considered rather than E_μ: $E_\nu = E_\mu + E'_{had}$.

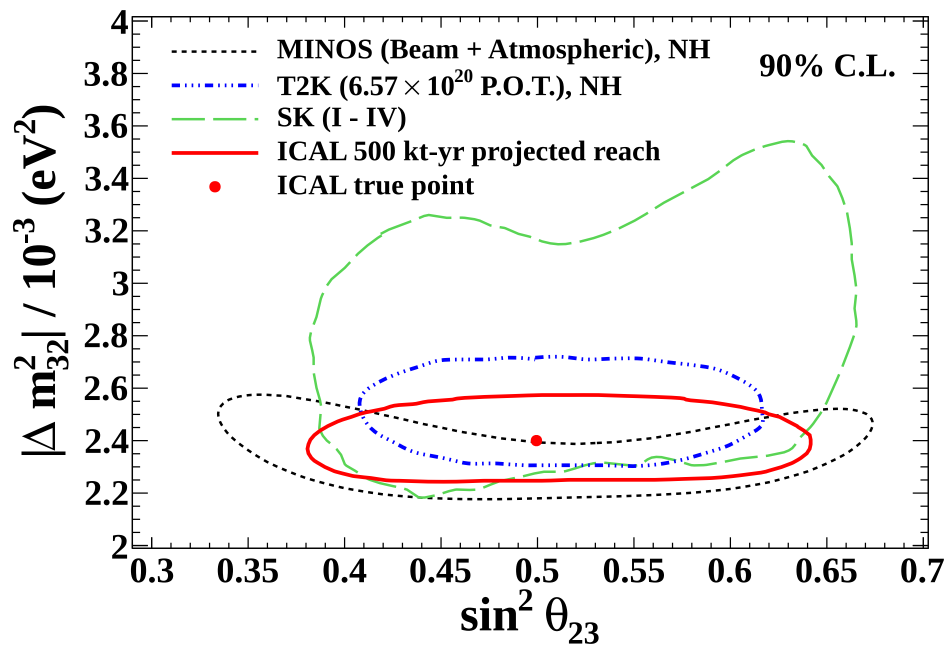
T. Thakore, A. Ghosh, S. Choubey, A. Dighe, JHEP 1305 (2013) 058, arXiv:1303.2534

Precision: Impact of hadrons

This analysis uses correlated information on E_μ, $\cos\theta_\mu$ and $E'_{had} = E_\nu - E_\mu$.

Precision reach improves, compared to muon-only analysis.



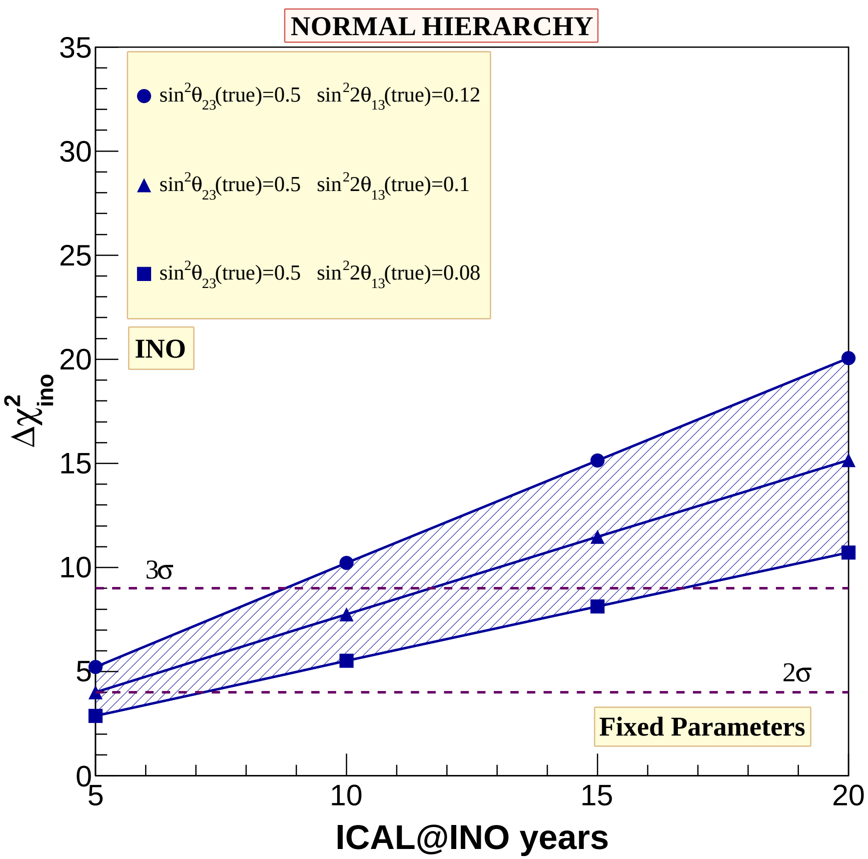


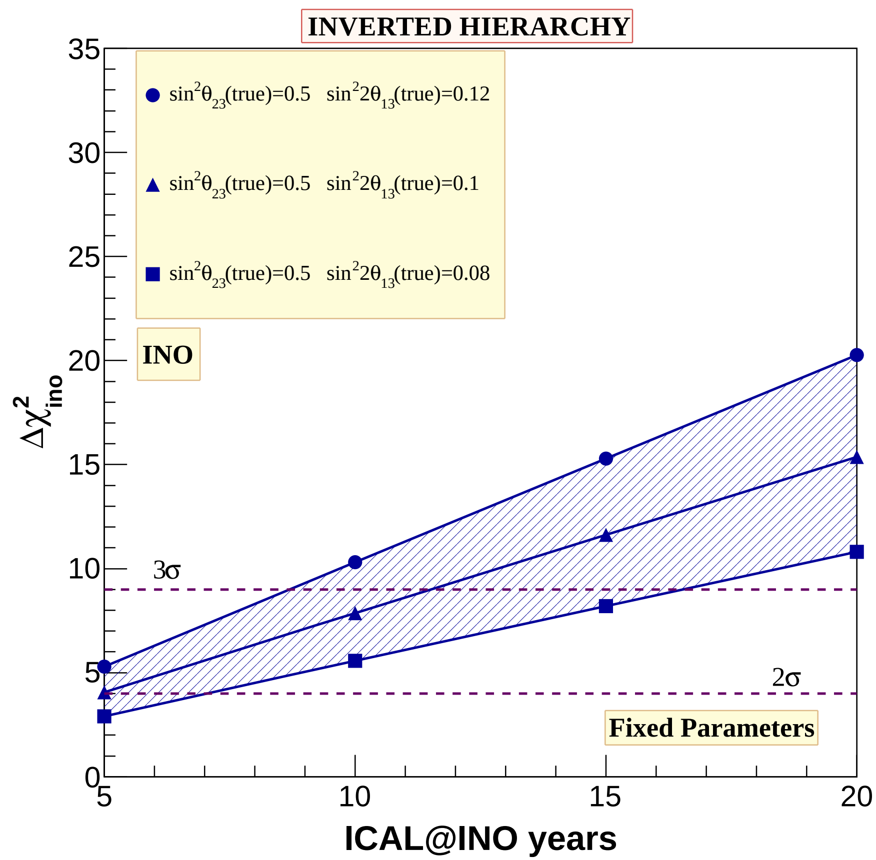
Note: 8% prior on $\sin^2 2\theta_{13}$ and normal hierarchy assumed as true.

M.M. Devi, Tarak Thakore, Sanjib Agarwalla, Amol Dighe, 2014

Mass Hierarchy: Muons only

Fixed Parameters

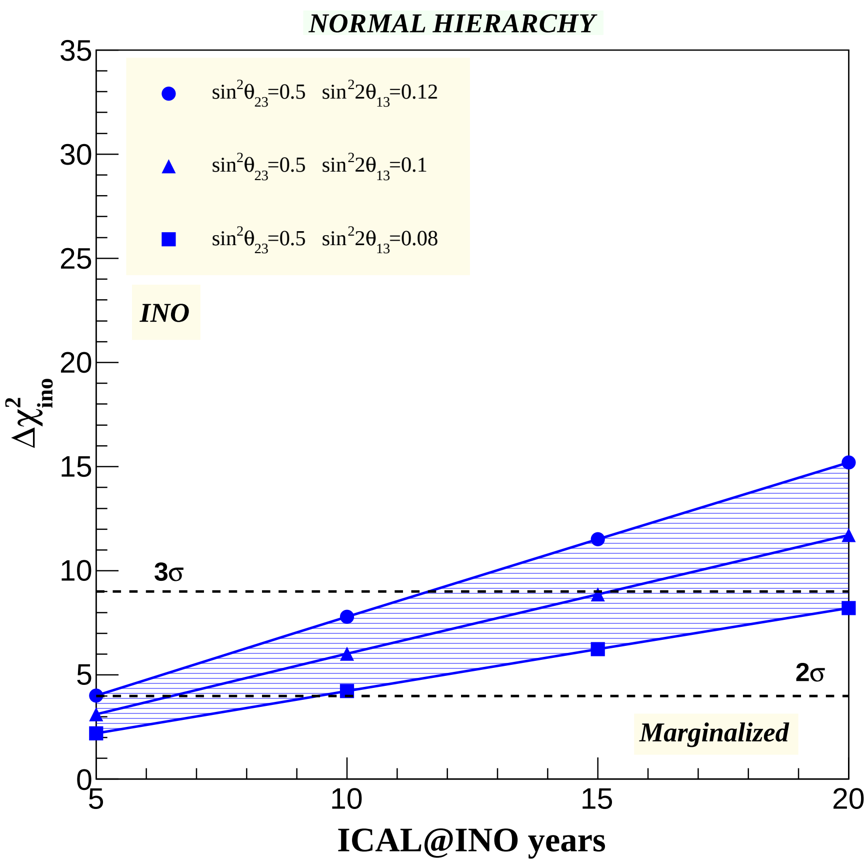


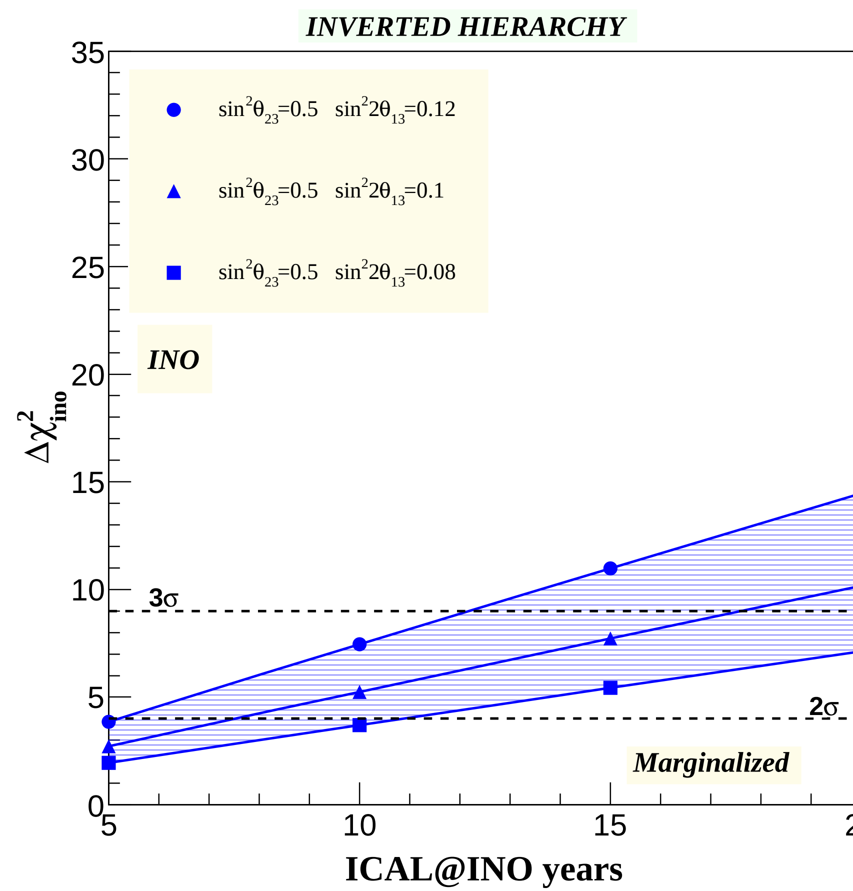


A. Ghosh, T. Thakore, S. Choubey, arXiv: 1212.1305, 2012.

Hierarchy with marginalised parameters

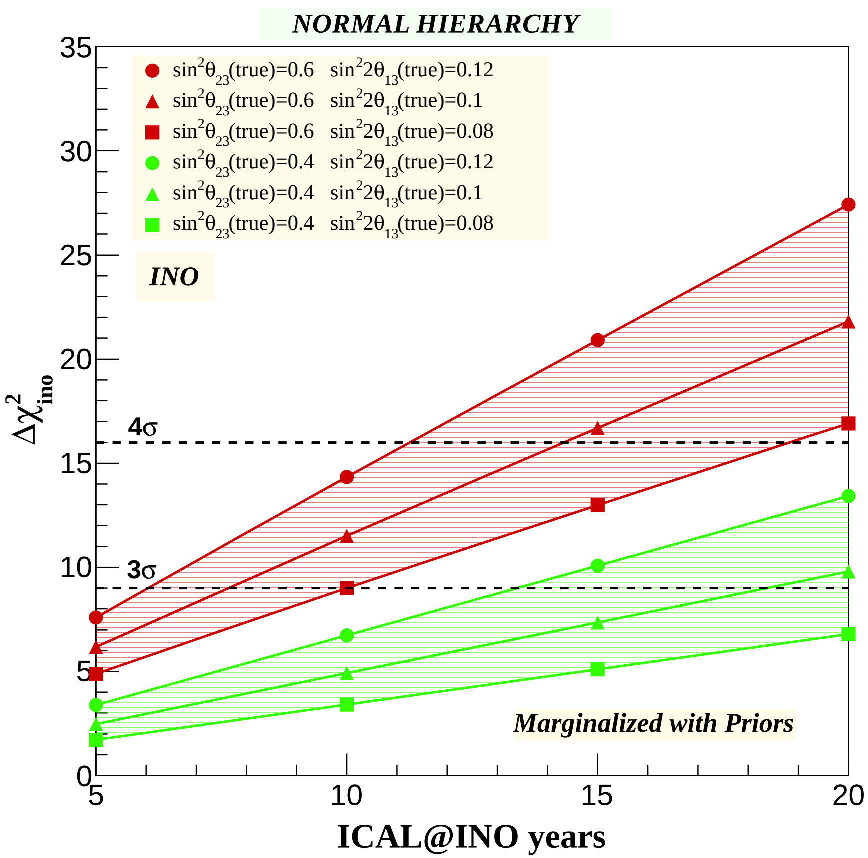
Marginalised over current 3σ ranges of $|\Delta m^2_{eff}|$, $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$.

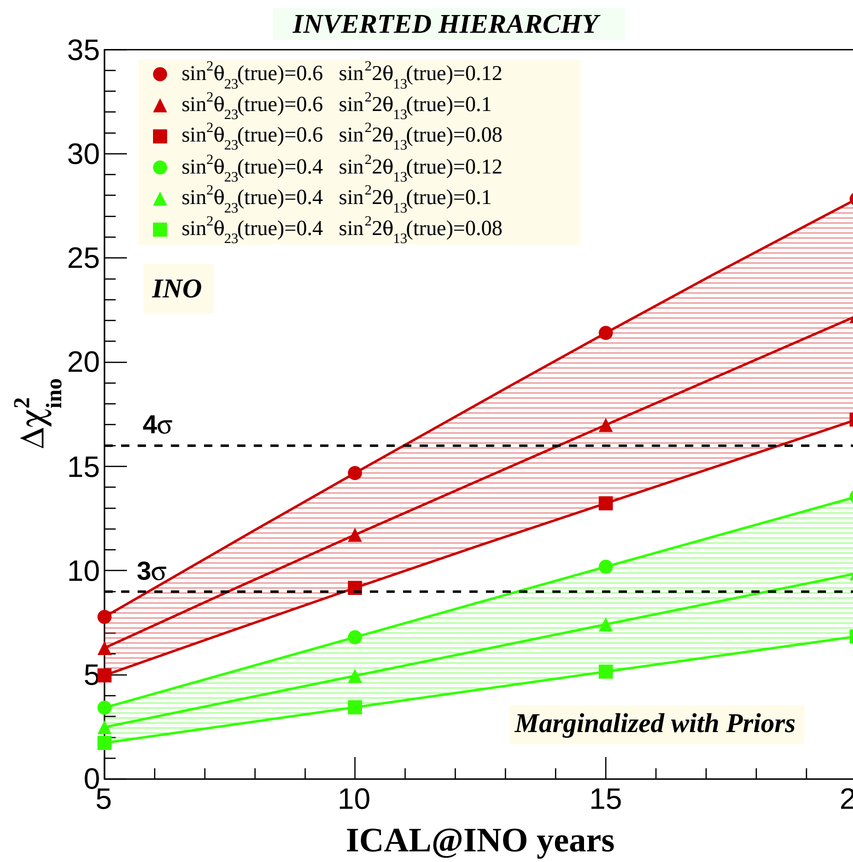




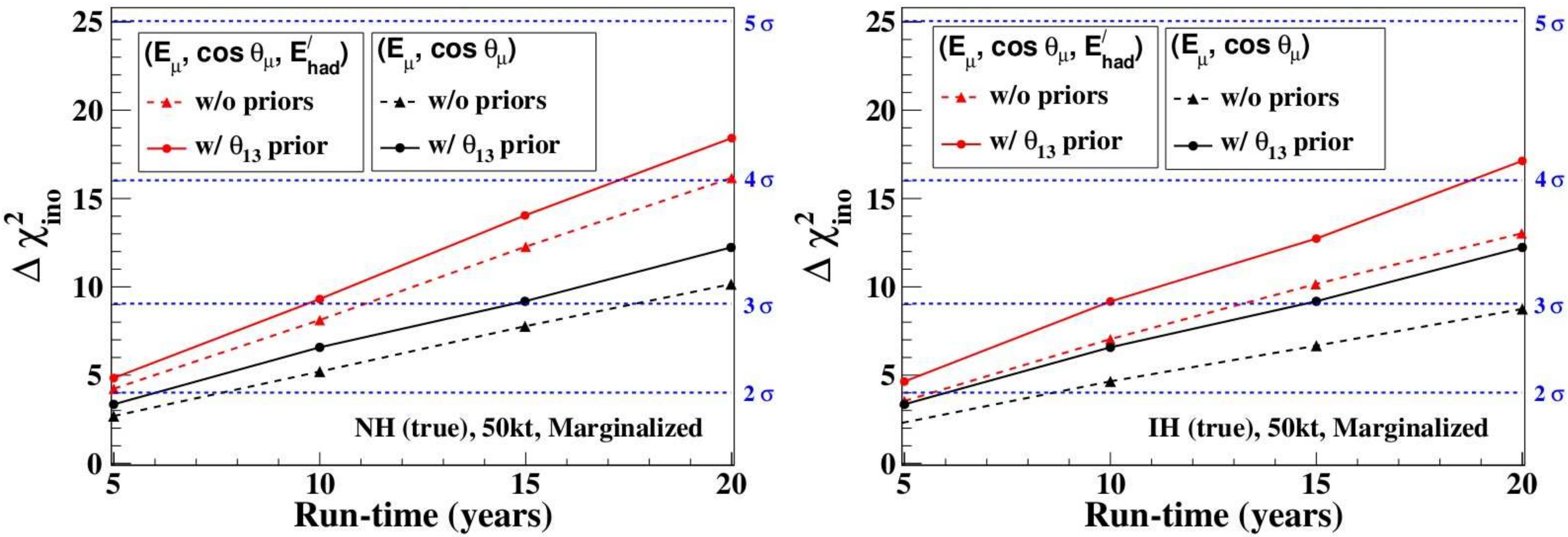
Hierarchy as a function of $\sin^2\theta_{23}$

The hierarchy reach improves as a function of both $\sin^2\theta_{23}$ (true value) as well as $\sin^2 2\theta_{13}$.



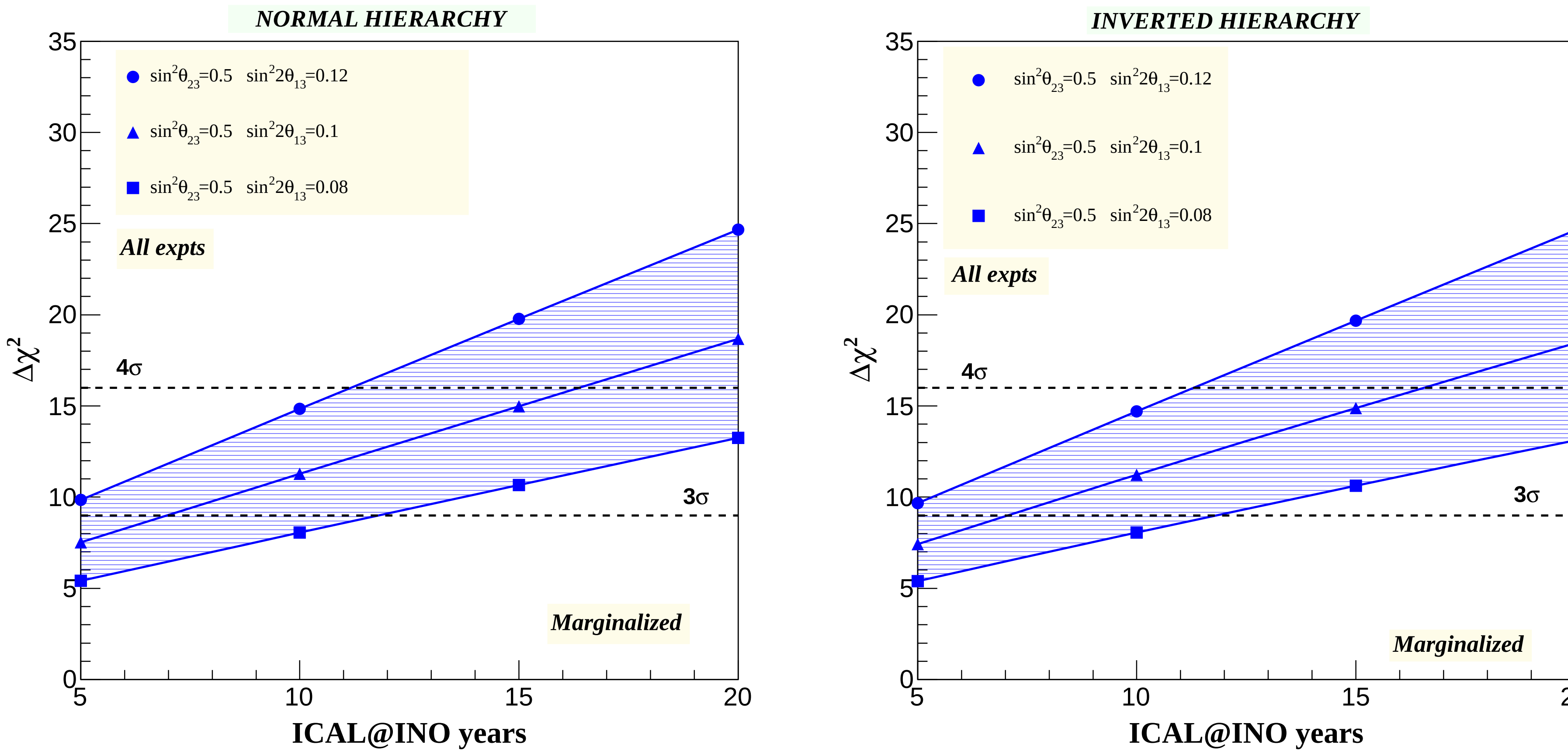


Impact of hadrons: Hierarchy



- A 3-σ hierarchy reach is obtainable with 500 kT-years of ICAL exposure on including hadron energy information.
- On including 8% priors on $\sin^2 2\theta_{13}$, result improves for both hierarchies.
- Results without hadron *correlated* information were about 2.5σ at $\sin^2\theta_{23} = 0.5$, $\sin^2 2\theta_{13} = 0.1$.

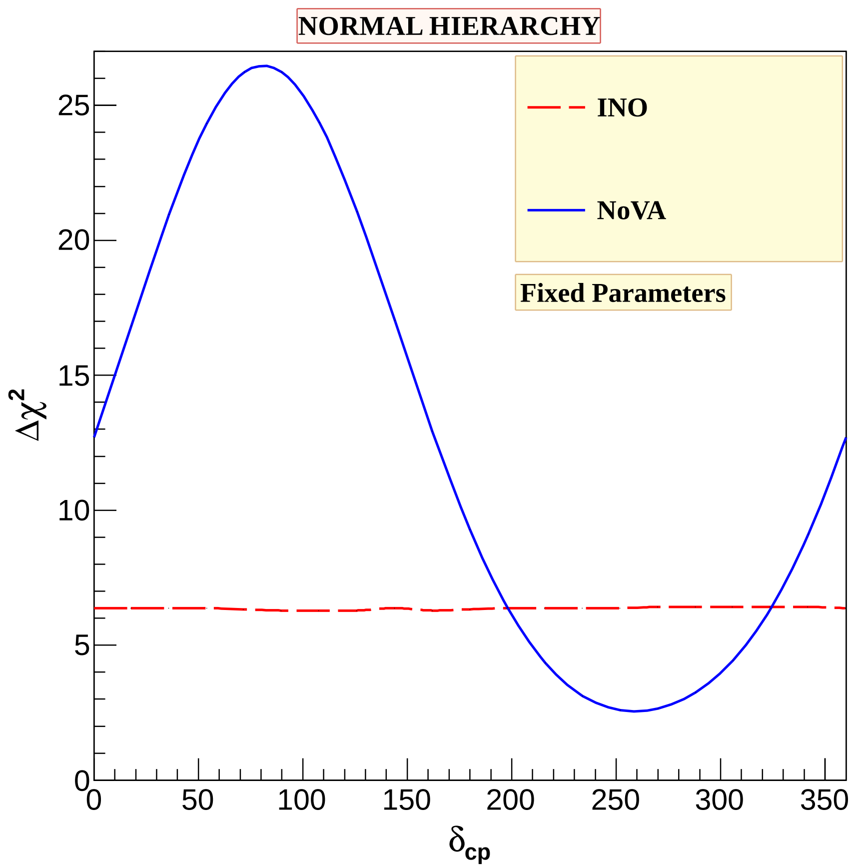
Hierarchy with other experimental inputs

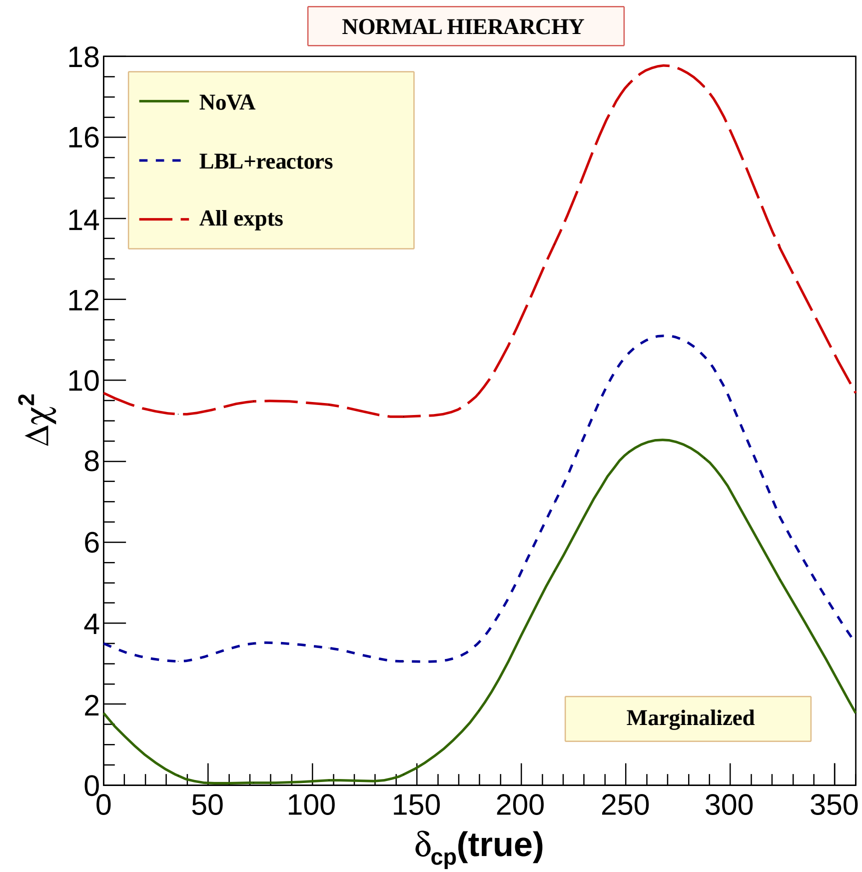


Expts	NOvA	T2K	DB	RENO	DC	ICALμ	ALL
$\Delta\chi^2(\Delta m^2_{eff})$	2.59	0.26	0.53	0.12	0.02	7.76	11.28
$\Delta\chi^2(\Delta m^2_{31})$	2.49	0.31	0.63	0.14	0.02	7.95	11.53

A. Ghosh, T. Thakore, S. Choubey, arXiv: 1212.1305, 2012.

δ_{CP} and Hierarchy





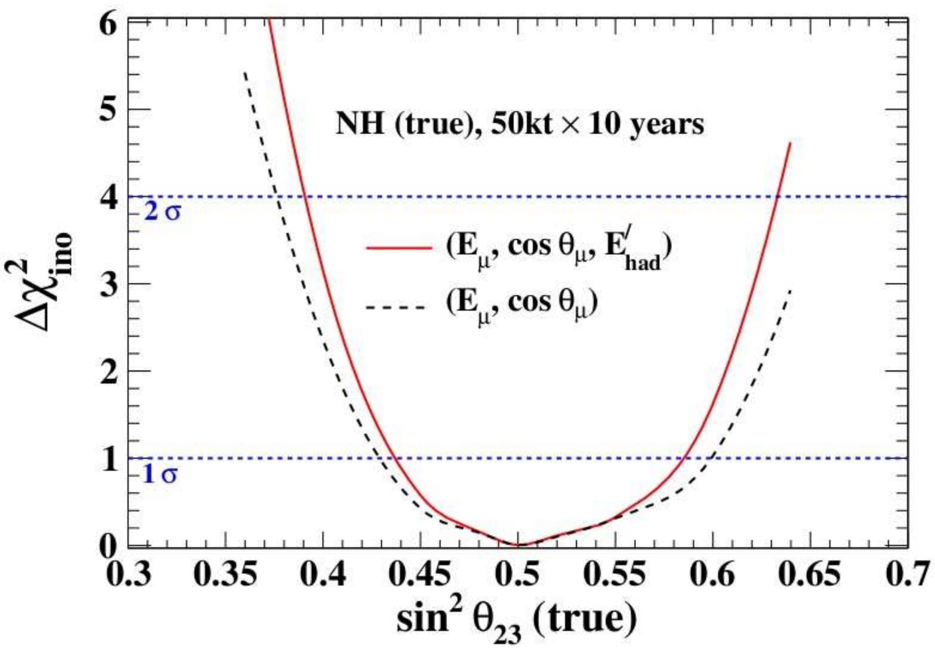
- Again, this is with “muons only".

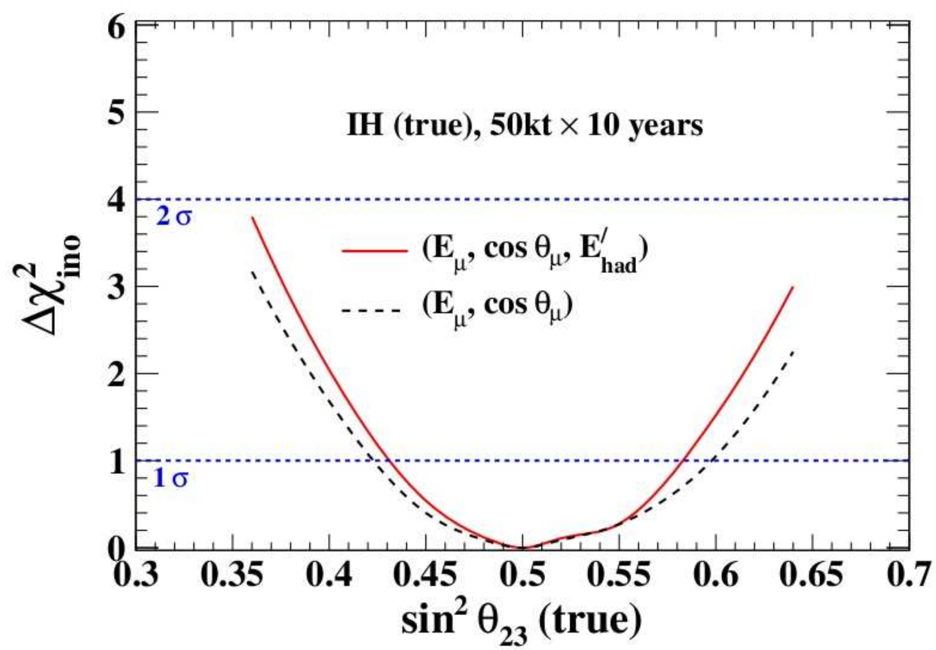
A. Ghosh, T. Thakore, S. Choubey, 2012.

The octant of θ_{23}

$$P^m_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \left[\sin^2 \theta^m_{13} \sin^2 \Delta^m_{21} + \cos^2 \theta^m_{13} \sin^2 \Delta^m_{32}\right] - \sin^4 \theta_{23} \sin^2 2\theta^m_{13} \sin^2 \Delta^m_{31} ,$$

$$P^m_{e\mu} \approx \sin^2 \theta_{23} \sin^2 2\theta^m_{13} \sin^2 \Delta^m_{31} ,$$

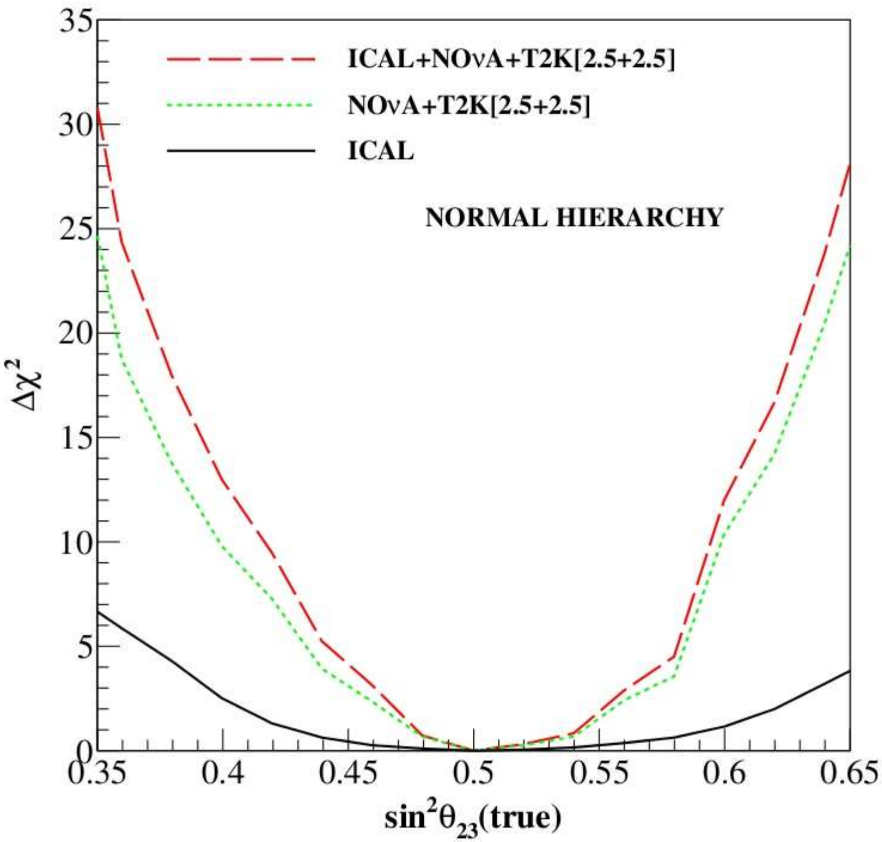


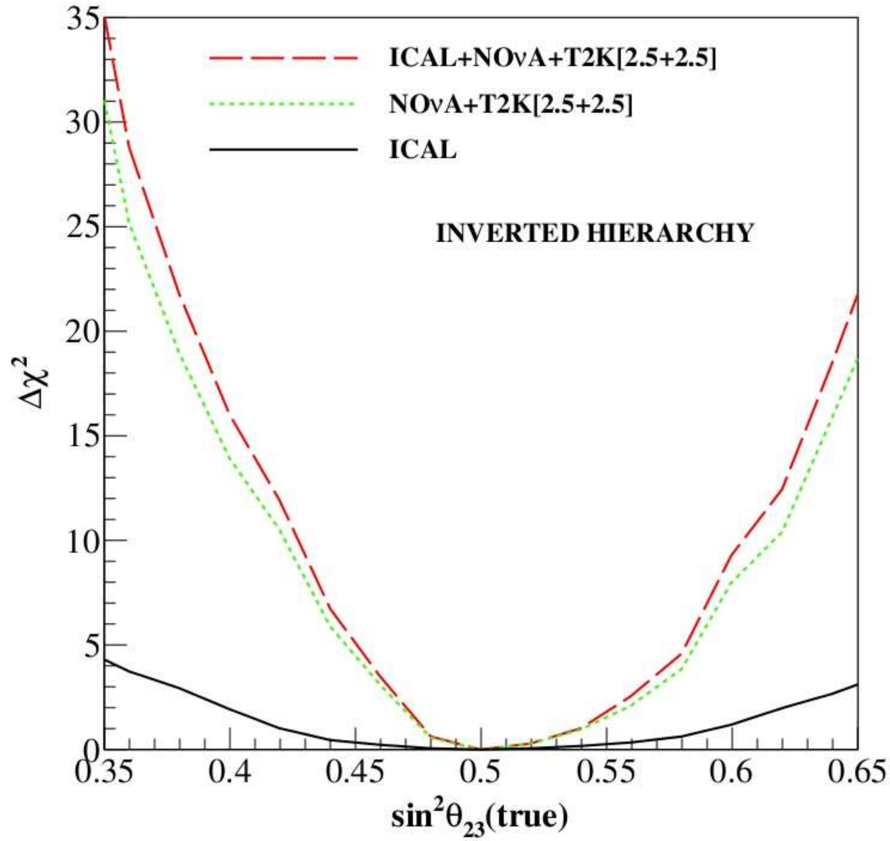


M.M. Devi, Tarak Thakore, Sanjib Agarwalla, Amol Dighe, 2014

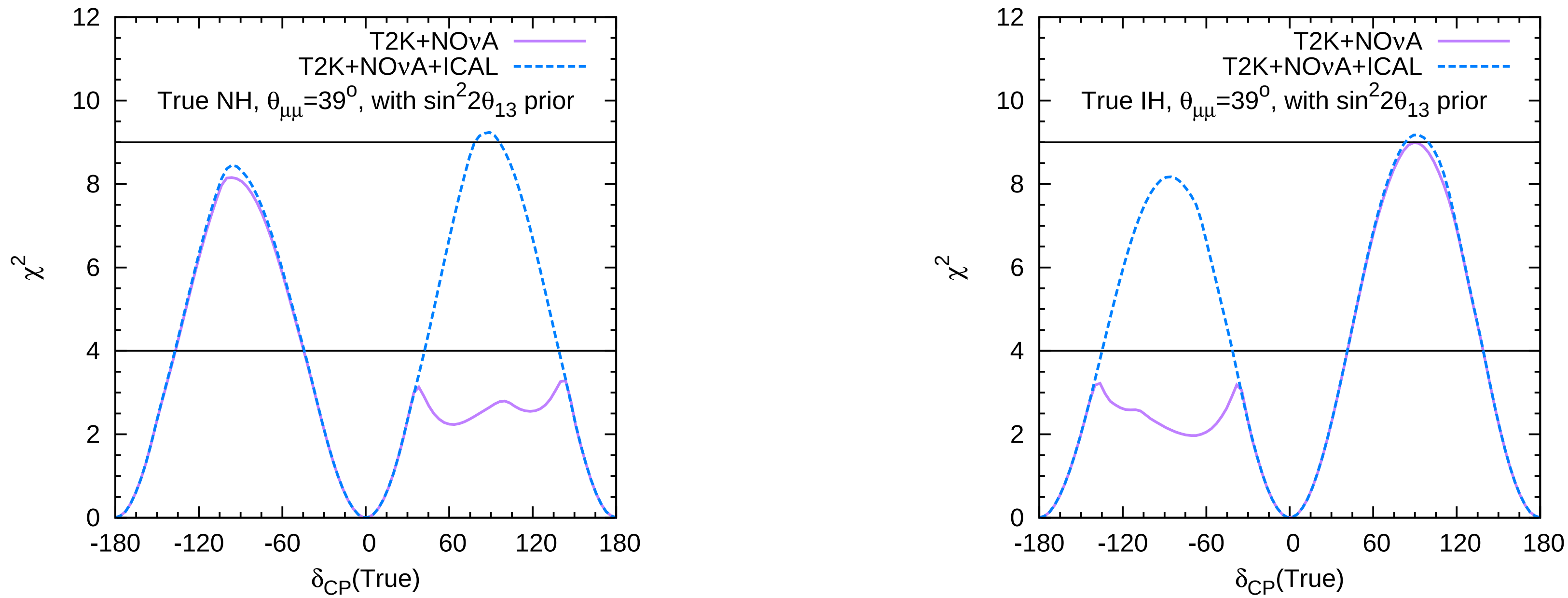
The octant of θ_{23}: other experiments

ICAL (500 kT-years muon only, with T2K (2.5 years each of ν and $\overline{\nu}$, and NOνA (3 years each).





The CP phase: impact of ICAL



- ICAL 500 kT-year with muon only, with T2K (5 years ν only) and NOνA (3 years each)
- Significantly depends on $\sin\theta_{atm} = \sin\theta_{23}\cos\theta_{13}$ and worsens as θ_{atm} increases.

M. Ghosh, P. Ghoshal, S. Goswami and S. K. Raut, Phys. Rev. D **89***, 011301 (2014); arXiv:1306.2500 [hep-ph], and arXiv:1401.7243*

Lorentz and CPT Violation with ICAL

$$\mathcal{L}^{CPTV}_{\nu,eff} = \bar{\nu}^{\alpha}_{L}\, b^{\alpha\beta}_{\mu}\, \gamma^{\mu}\, \nu^{\beta}_{L}\ ,$$ *(S. Coleman, S.L. Glashow, PRD59, 116008 (1999))*

$$H_f = \frac{1}{2E}.U_0.D(0, \Delta m^2_{21}, \Delta m^2_{31}).U_0^{\dagger} + U_b.D_b(0, \delta b_{21}, \delta b_{31}).U_b^{\dagger} + D_m(V_e, 0, 0)\ .$$

- 6 mixing angles $(\theta_{12}, \theta_{23}, \theta_{13}, \theta_{b12}, \theta_{b23}, \theta_{b13})$ and seven phases.
- D, D_m and D_b are diagonal; b_i are e.values of $\mathbf{b}$); $\delta b_{i1} \equiv b_i - b_1$ for $i = 2, 3$; δb_{21} appears with Δm^2_{21}.
- So study δb_{31} for (all phases taken as zero):

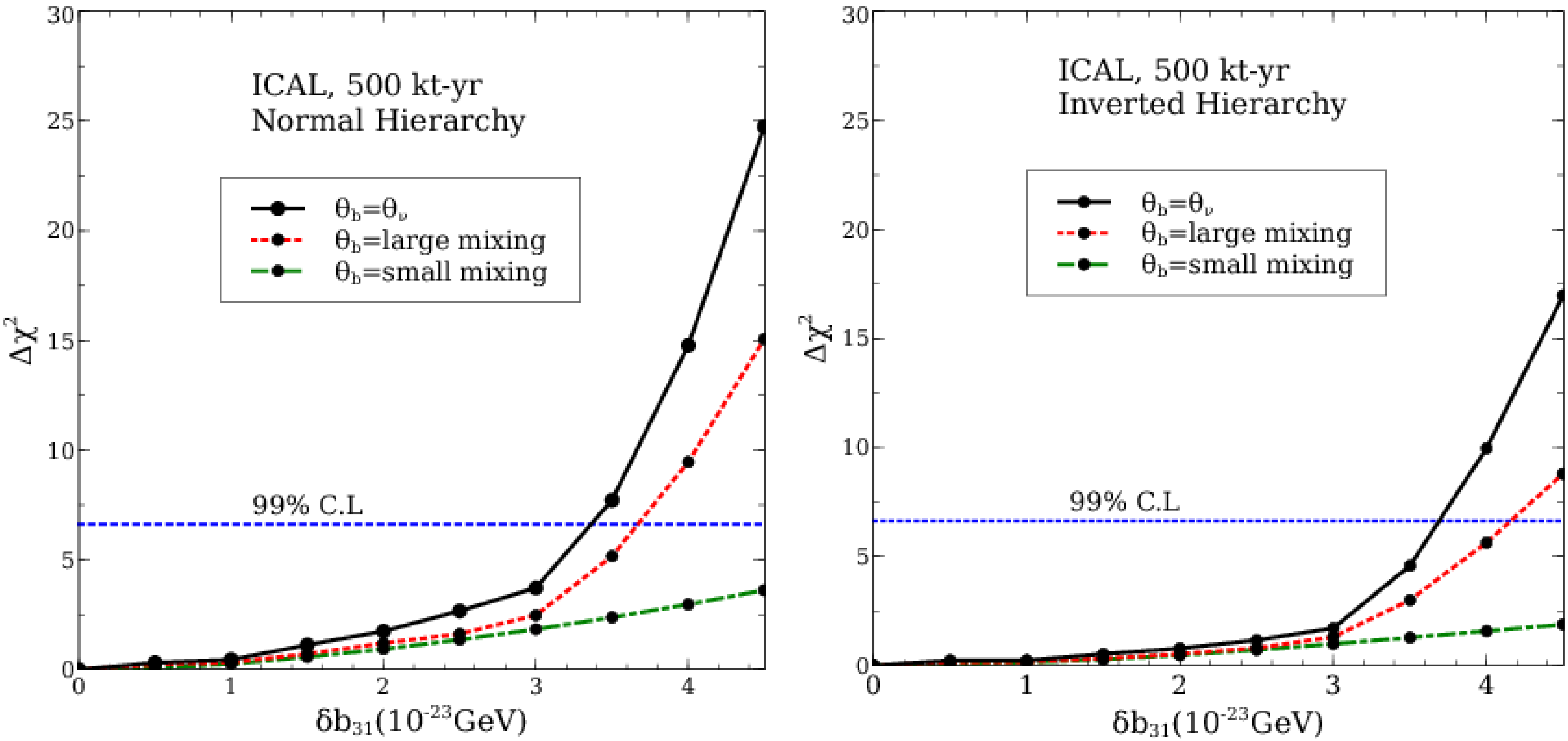
  (1) small mixing: ($\theta_{b12} = 6\,^{\circ}, \theta_{b23} = 9\,^{\circ}, \theta_{b13} = 3\,^{\circ}$),

  (2) large mixing: ($\theta_{b12} = 38\,^{\circ}, \theta_{b23} = 45\,^{\circ}, \theta_{b13} = 30\,^{\circ}$) and

  (3) Identical to the mixing angles in the PMNS matrix: ($\theta_{bij} = \theta_{ij}$)
- Minimise χ^2 w.r.t both μ^- and μ^+ events *separately*; then can eliminate effects that originate from earth matter CPT asymmetry (cid)

A. Chatterjee, R. Gandhi, Jyotsna Singh, JHEP, 2014, to appear

CPTV: limits



- Bounds on δb_{31} for different θ_b and different (known) hierarchy.
- Results are marginalized over θ_{23}, θ_{13}, δ_{cp}, Δm^2_{31} and δb_{21}.
- For both types of hierarchy, ICAL should be sensitive to $\delta b_{31} \geq 3.8 \times 10^{-23}$ GeV.

Other physics possibilities

- Measuring the cosmic ray muon background
- Probing ultrahigh energy cosmic rays through the pair-meter technique
- Searches for monopoles, dark matter, etc., at ICAL
- Constraining long-range leptonic forces by introducing a matter-dependent term in the oscillation probability even in the absence of U_{e3}, so that neutrinos and anti-neutrinos oscillate differently.

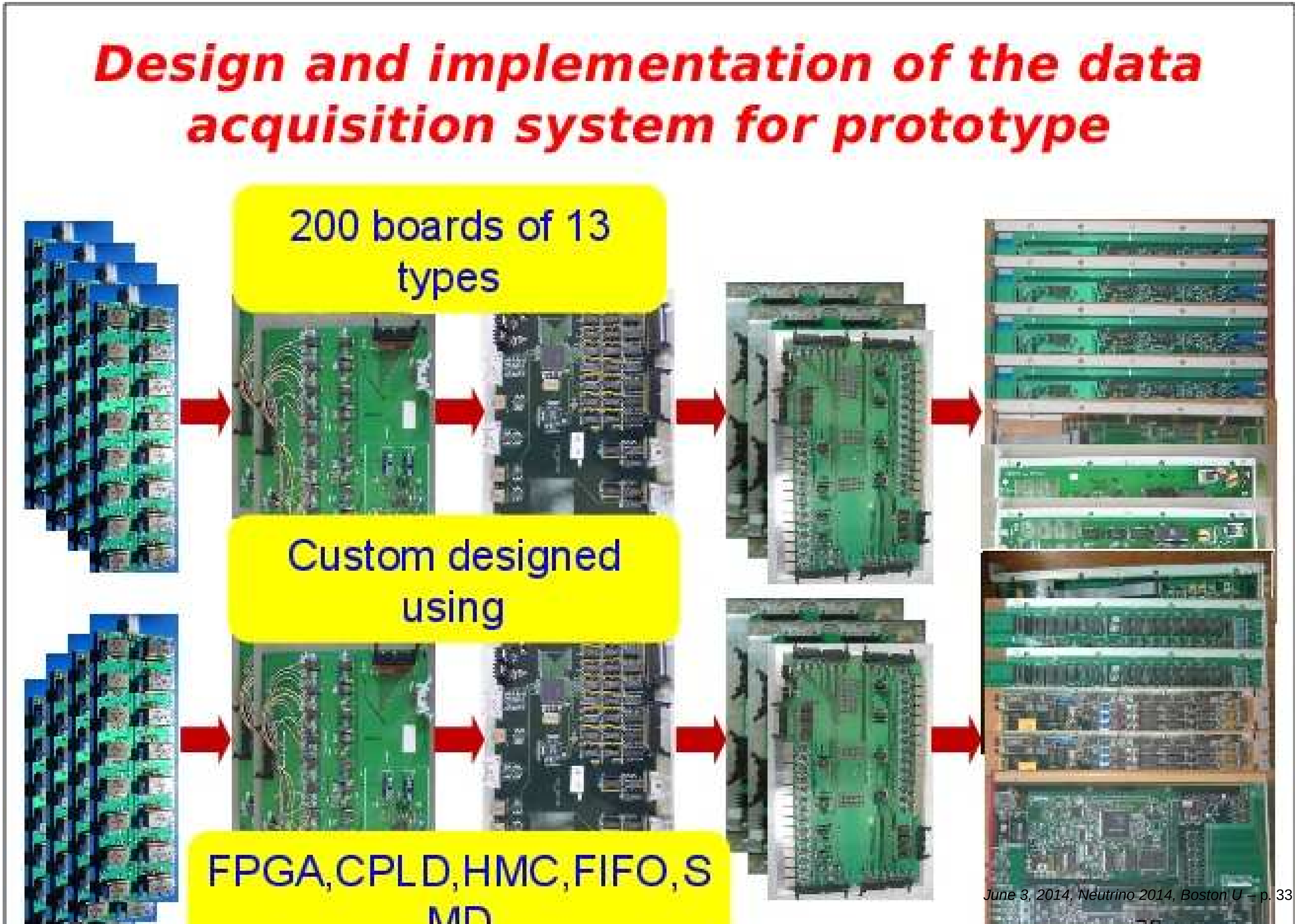

India-based Neutrino
Observatory Project
Current Status

IIChEP at Madurai

INO Site at Pottipuram, Theni

RPC, fully assembled, $2m \times 2m$

DAQ, design and implementation



Coil, jointing effects

Detector Structure

- Mechanical design and assembly project report prepared by Tata Consulting Engineers (TCE), Mumbai

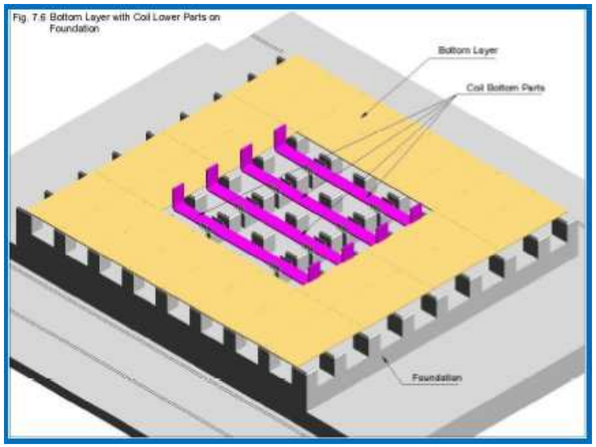


Fig. 7.6 Bottom Layer with Coil Lower Parts on Foundation

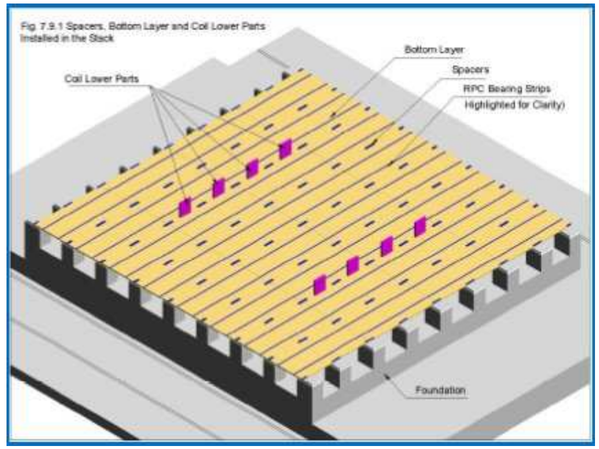


Fig. 7.9.1 Spacers, Bottom Layer and Coil Lower Parts Installed in the Stack

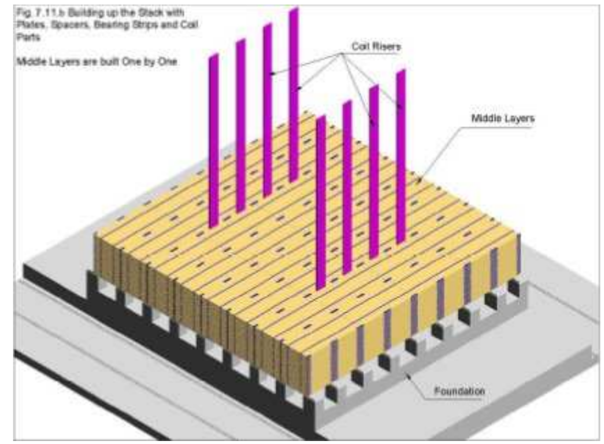


Fig. 7.11.b Building up the Stack with Plates, Spacers, Bearing Strips and Coil Parts

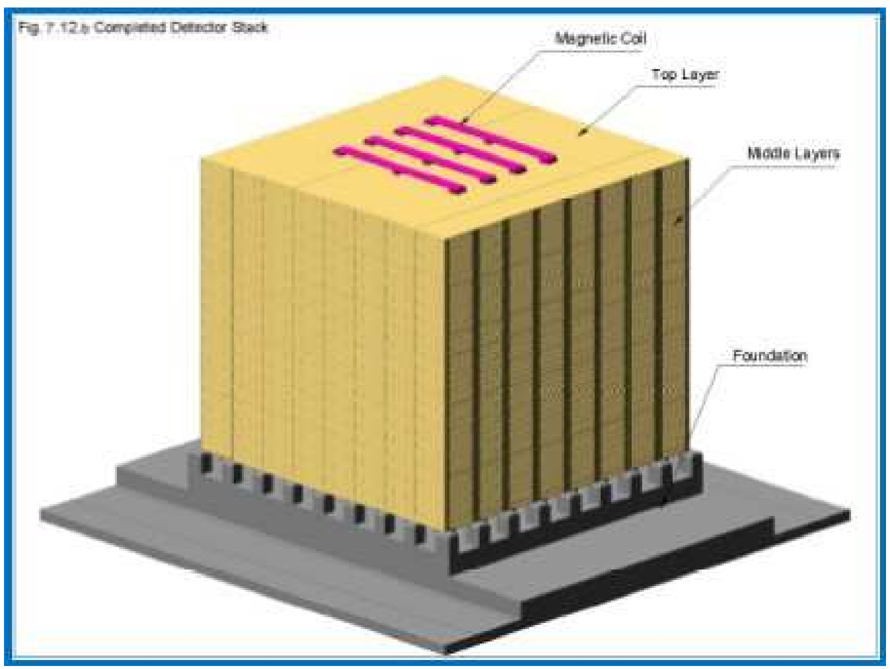


Fig. 7.12.b Completed Detector Stack

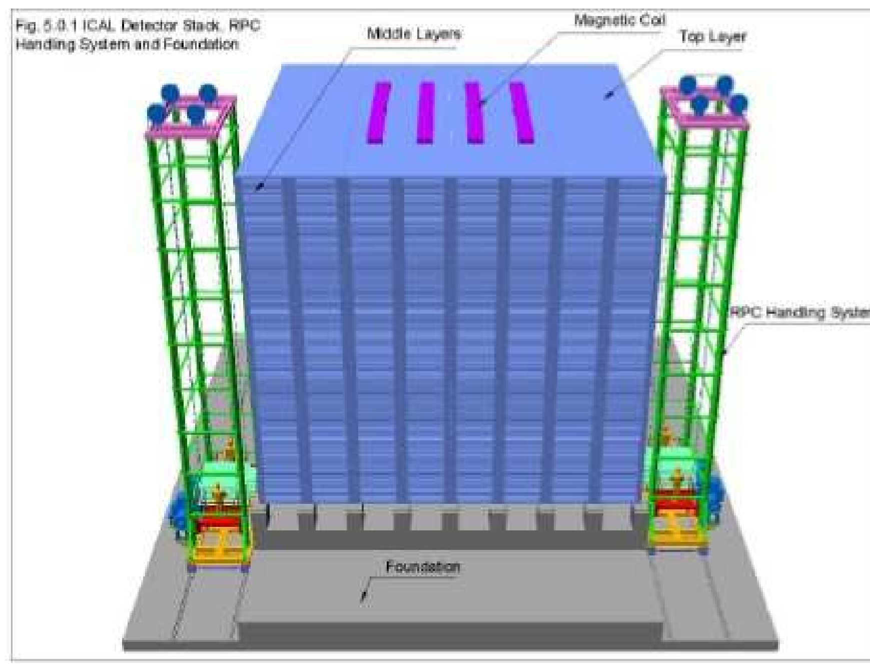


Fig. 5.0.1 ICAL Detector Stack, RPC Handling System and Foundation

Current Status

- Preproject activities started with an initial grant of USD ~ 10 million
  - Site infrastructure development
  - Development of IICHEP at Madurai (110 km from INO lab)
  - Construction of an 1/8 scale prototype module at Madurai. Will test all aspects of engineering module and test efficiency of industrially-produced RPCs apart from physics studies.
- Detector R & D is now complete
- DPR for Detector and DAQ system is ready
- Industrial production of RPCs and associated front end electronics to start soon
- Full project approval by the Department of Atomic Energy, India. Awaiting final clearance from PM's cabinet committee to start construction.
- We have a strong physics programme; all eager to begin!

Additional Slides

Neutrino Oscillations

(2) $$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \ .$$

Here U is the 3×3 unitary matrix which may be parametrised as (ignoring Majorana phases):

(3) $$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta_{CP}} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta_{CP}} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} .$$

δ_{CP} is the CP violating (Dirac) phase and M_ν is diagonalised in the charged-lepton mass basis by U:

(4) $$U^\dagger M_\nu U = \mathrm{diag}(m_1, m_2, m_3).$$

Matter Effects

First consider matter of constant density ρ (in gms/cc). Then we can replace the vacuum values by the corresponding matter-modified effective ones obtained by diagonalising the matter dependent matrix (Hamiltonian):

(5) $$U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

where

(6) $$A = 2\sqrt{2} G_F n_e E = 7.63 \times 10^{-5} \text{ eV}^2 \; \rho(\text{gm/cc}) \; E(\text{GeV}) \text{ eV}^2.$$

Mixing angles in matter

Further simplification arises because $\Delta m^2_{21} \ll \Delta m^2_{31}$ and we can treat the propagation in matter as a one mass-scale problem involving only $\Delta m^2_{32} \approx \Delta m^2_{31}$. The matter dependent mixing angle $\theta_{12,m}$ may be approximately written as

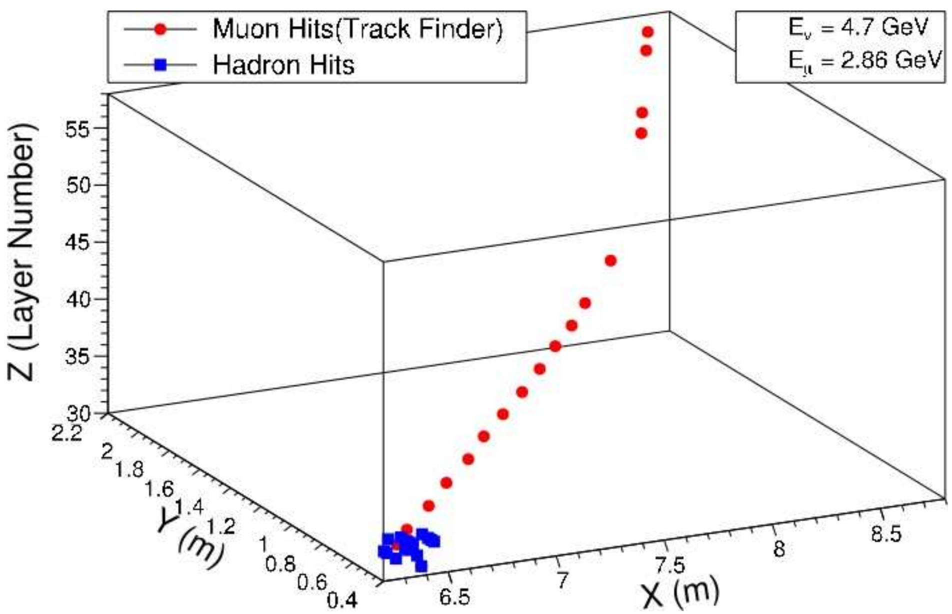
(7) $$\sin 2\theta_{12,m} \approx \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - (A/\Delta m^2_{21})\cos^2\theta_{13})^2 + \sin^2 2\theta_{12}}}\ .$$

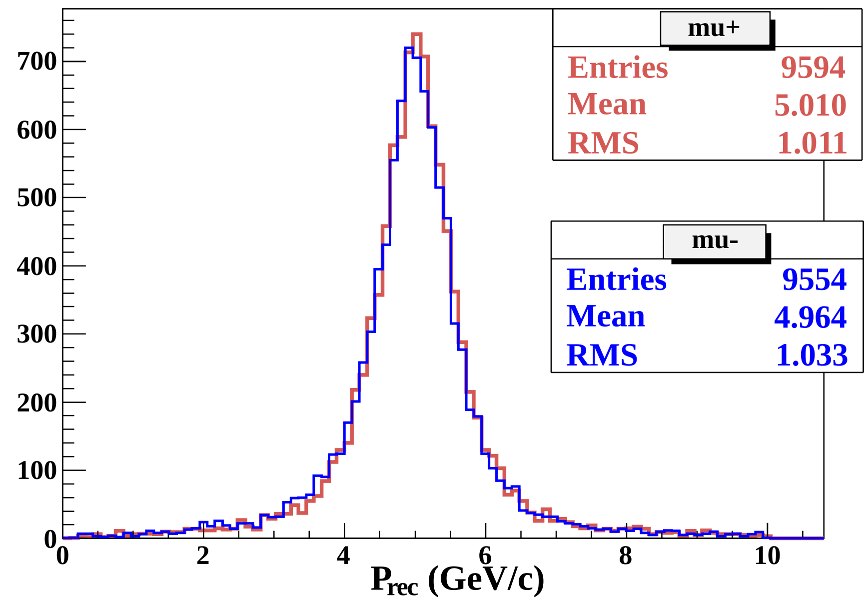
The effect of matter on the angle θ_{13} is non-trivial and is given by

(8) $$\sin 2\theta_{13,m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - (A/\Delta m^2_{31}))^2 + (\sin 2\theta_{13})^2}}\ .$$

(9) $$\sin 2\theta_{23,m} \approx \sin 2\theta_{23}\ .$$

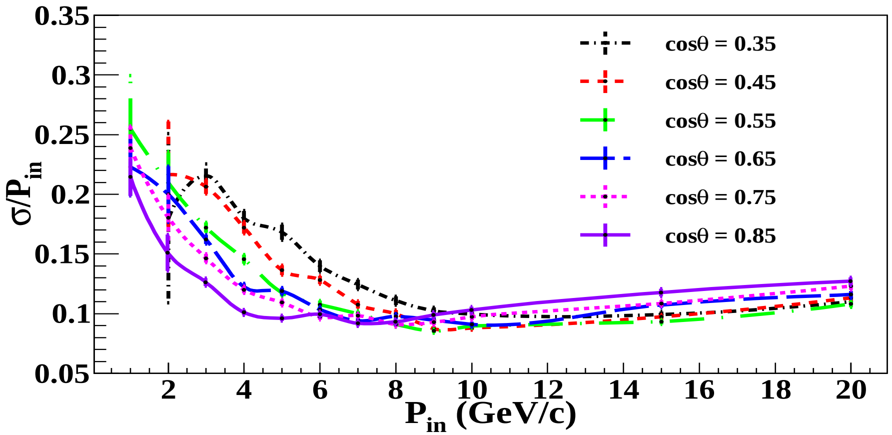
ICAL Simulations



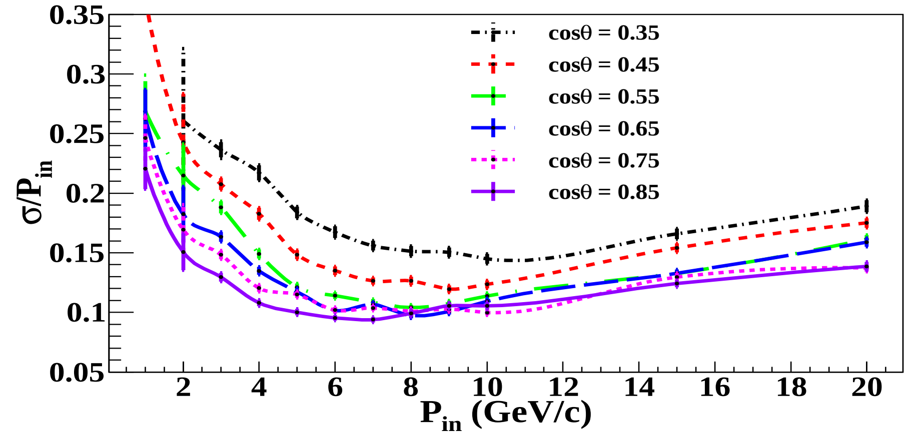


- GEANT4-based simulation of ICAL detector. Magnetic field map through simulations using MAGNET6.0 code.
- Neutrino events generated using NUANCE neutrino generator
- Muons leave long, clean tracks in detector. Calibrated through range or bending in magnetic field (Kalman filter)
- Hadrons are calibrated through the hits they leave: do not traverse many iron layers

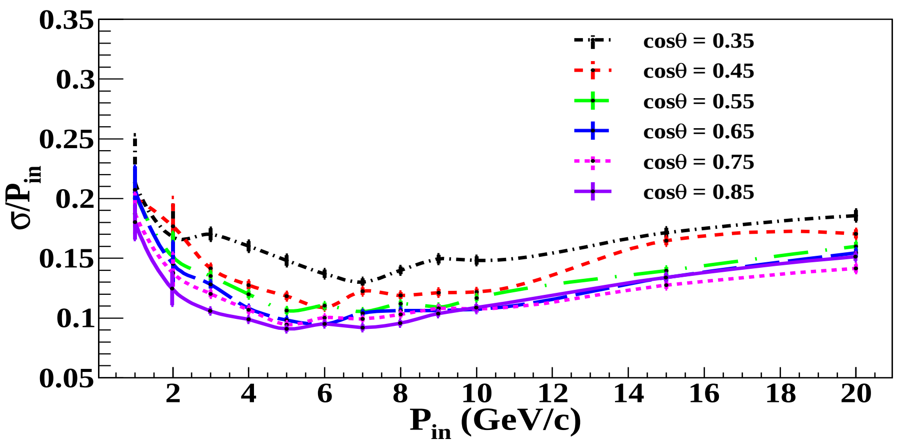
Muon Resolutions



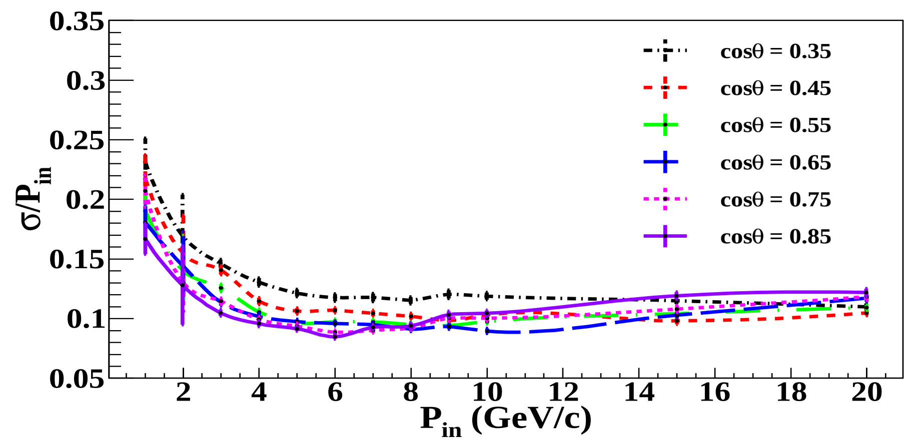
(a) $|\phi| \leq \pi/4$



(b) $\pi/4 < |\phi| \leq \pi/2$



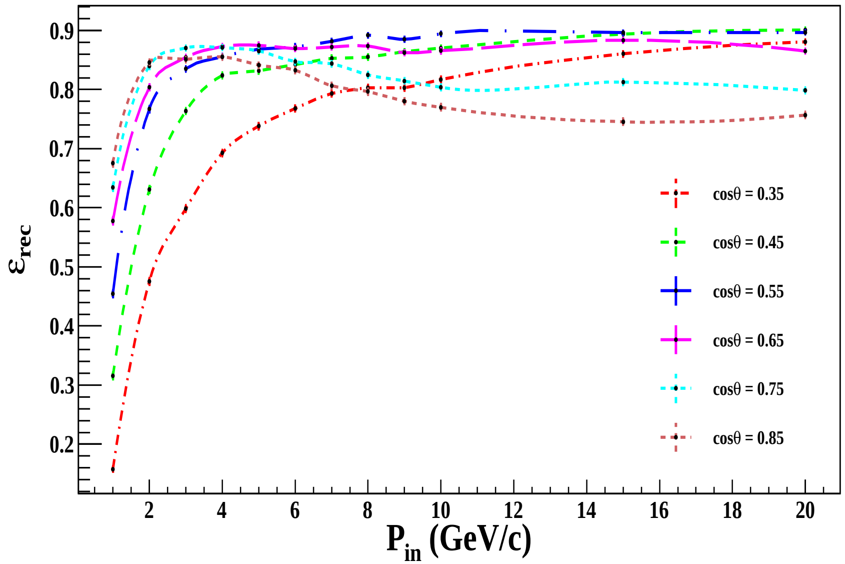
(c) $\pi/2 < |\phi| \leq 3\pi/4$

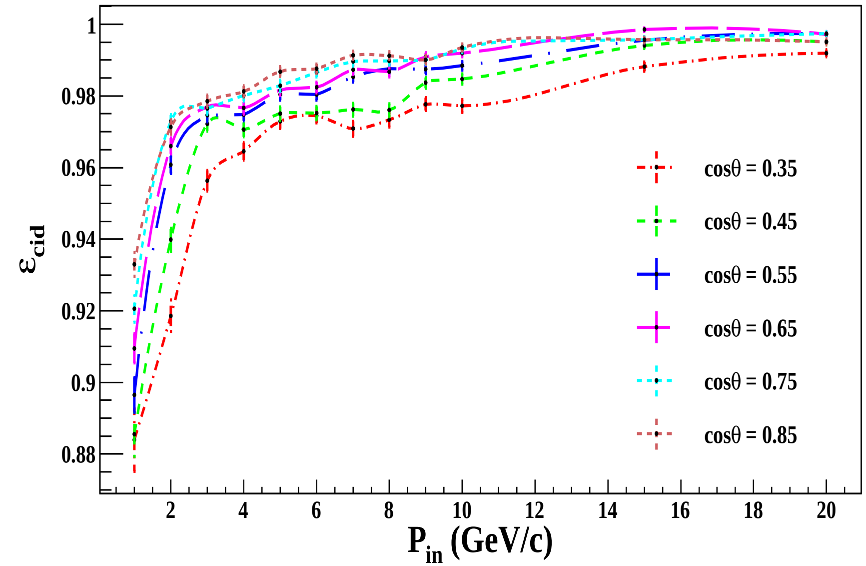


(d) $3\pi/4 < |\phi| \leq \pi$

Note angular resolutions are a degree or better for $E > 4$ GeV.

Efficiencies

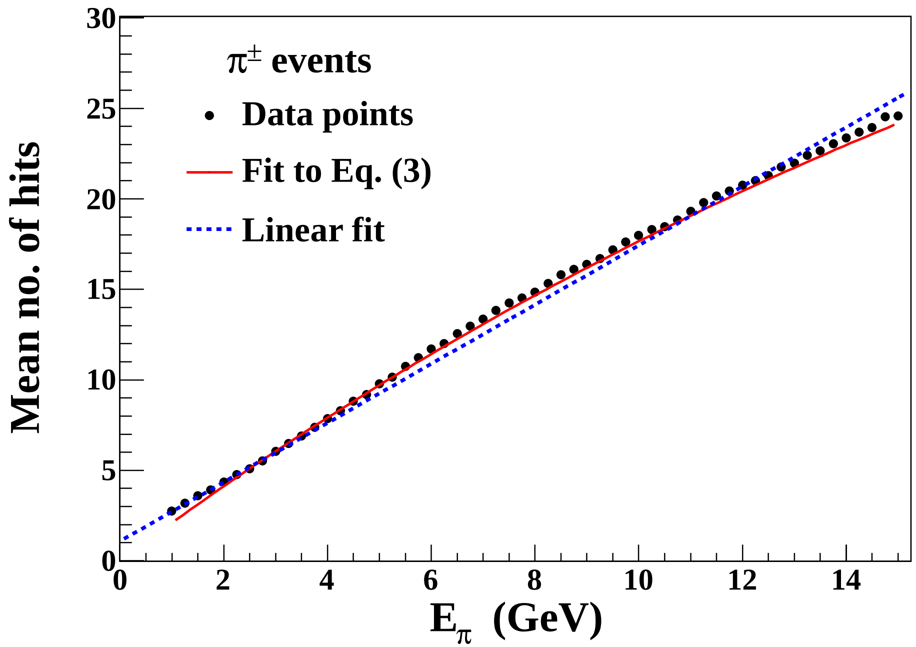


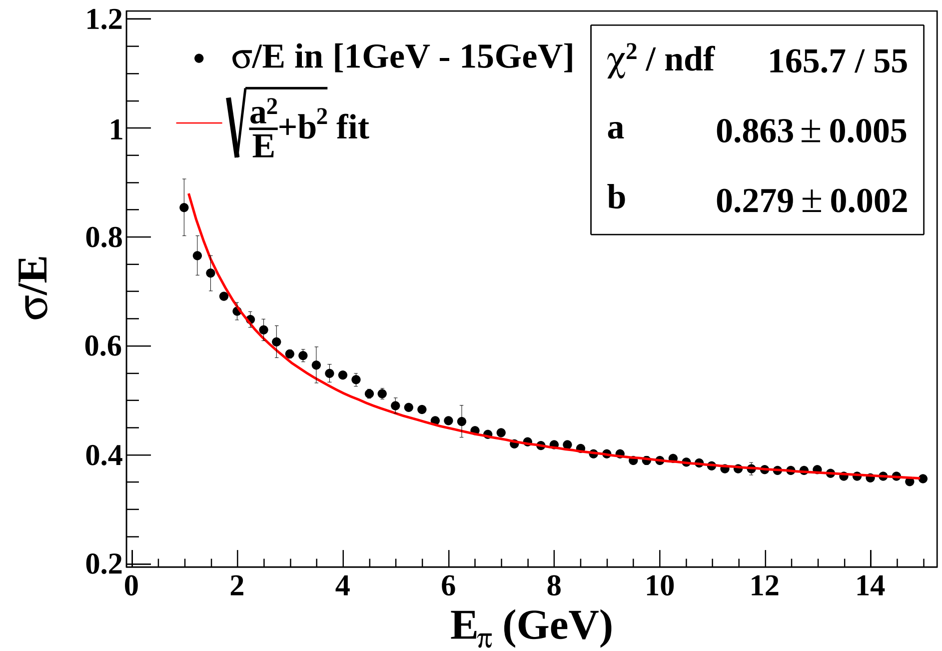


Both reconstruction and relative charge id efficiencies are shown here; scales are different.

A. Chatterjee et al., to appear in JINST

Hadron Resolutions





- The energy is calibrated to the mean number of hits
- The width is fitted to $\frac{\sigma}{E} = \sqrt{\frac{a^2}{E} + b^2}$, with a as the stochastic parameter and b as the residual resolution.

M.M. Devi et al., JINST, 2014

ennow, Coloma, Huber, Schwetz, 1311.182

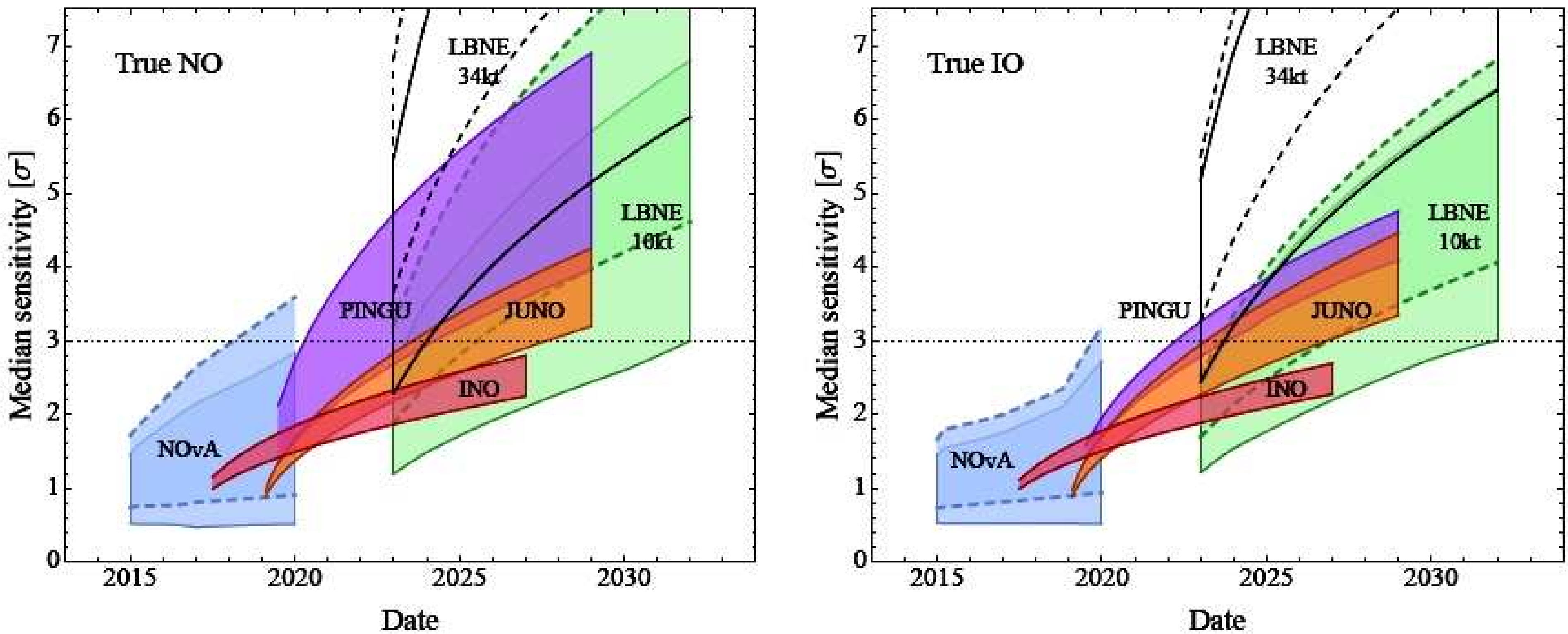


FIG. 12: The left (right) panel shows the median sensitivity in number of sigmas for rejecting the IC (NO) if the NO (IO) is true for different facilities as a function of the date. The width of the bands correspond to different true values of the CP phase δ for NOνA and LBNE, different true values of θ_{23} between 40° and 50° for INO and PINGU, and energy resolution between $3\%\sqrt{1 \text{ MeV}/E}$ and $3.5\%\sqrt{1 \text{ MeV}/E}$ for JUNO. For the long baseline experiments, the bands with solid (dashed) contours correspond to a true value for θ_{23} of 40° (50°). In all cases, octant degeneracies are fully searched for.