VietNus 2012: Towards CP Violation in Neutrino Oscillations
Qui Nhon, December 2012

India-based Neutrino Observatory (INO)

…an indirect boost to CP sensitivity

Sushant Raut
Physical Research Laboratory (PRL), Ahmedabad

for the INO Collaboration

Outline

- Motivation: INO ←→ CP Violation
  - Requirements for measuring CP
- INO: Details
  - Physics aims
  - Detector and simulations
  - Current status
- INO: Physics potential
  - Precision measurements
  - Mass hierarchy measurement
  - Octant measurement
  - Towards CP measurement?
- Summary

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Q: Why should we discuss atmospheric neutrinos at a workshop on CP Violation?

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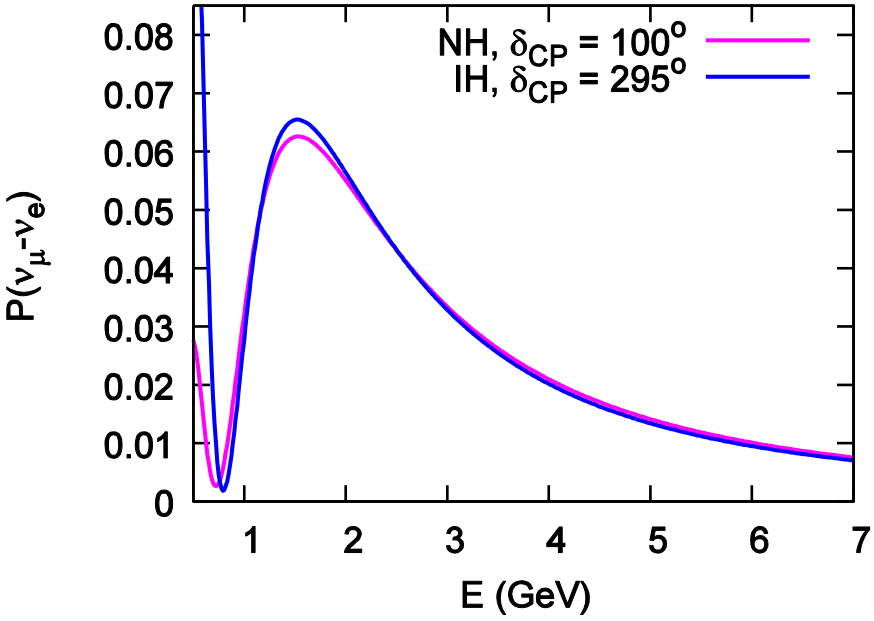
- Currently unknown oscillation parameters:
  - Mass hierarchy
  - δ_{CP}
  - Octant of θ_{23}

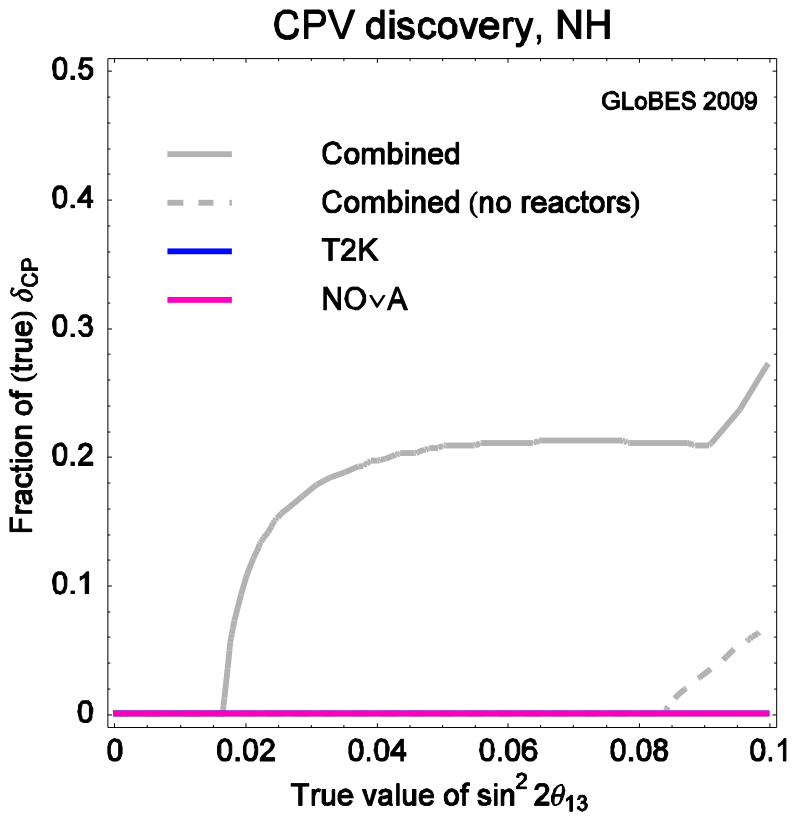
- Hierarchy-δ_{CP} degeneracy:

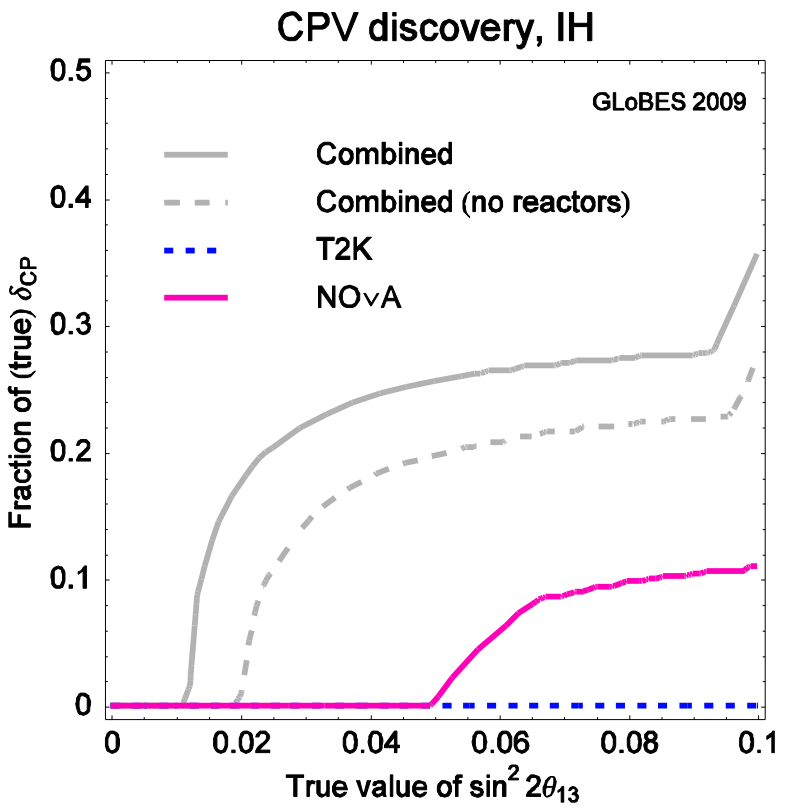
  $P(NH, \delta_{CP}) = P(IH, \delta_{CP}')$



Towards CPV discovery

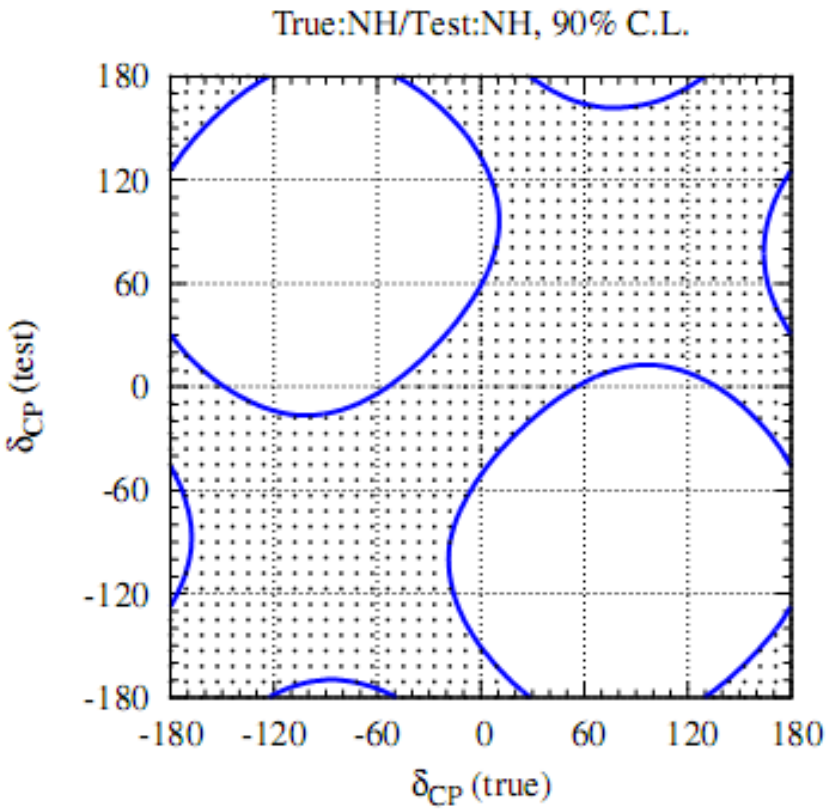
Q: What can we say about δ_{CP}, using data from existing/upcoming long baseline facilities?

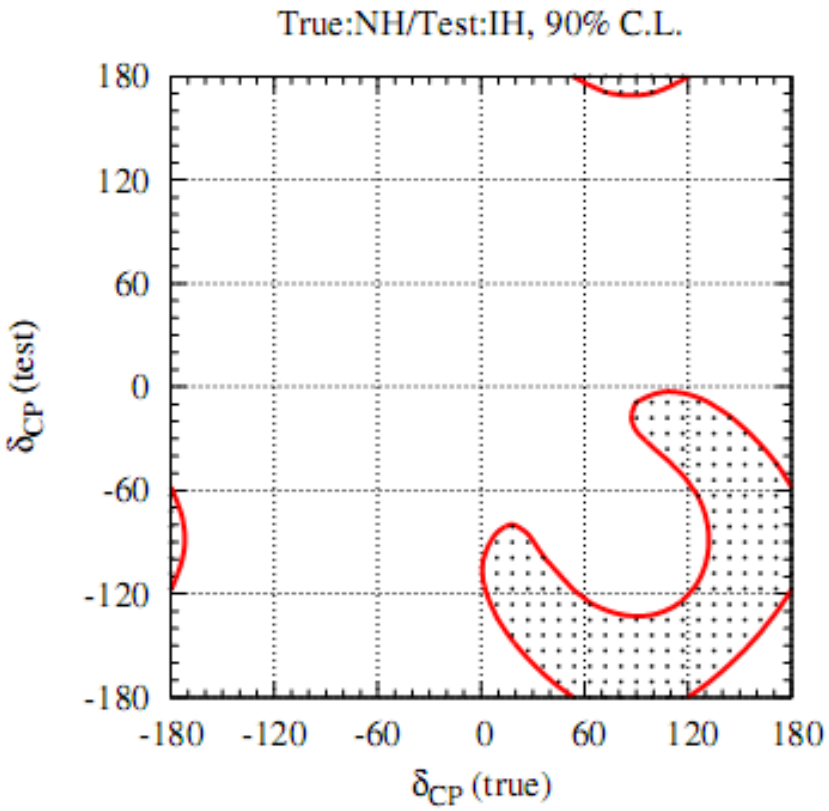




Huber, Lindner, Schwetz, Winter: 0907.1896

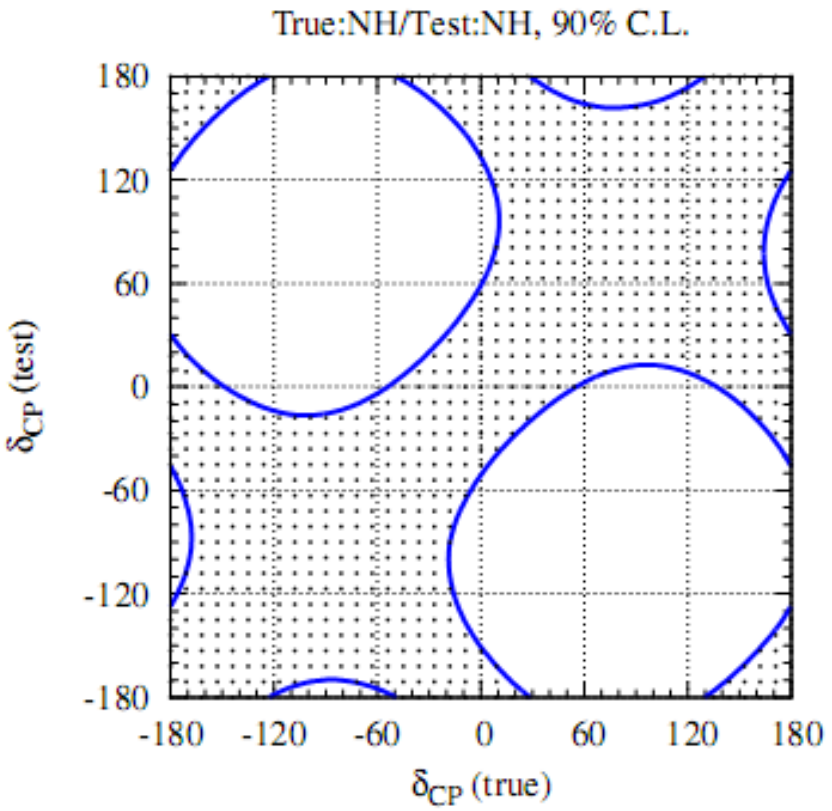
Measuring δ_{CP}

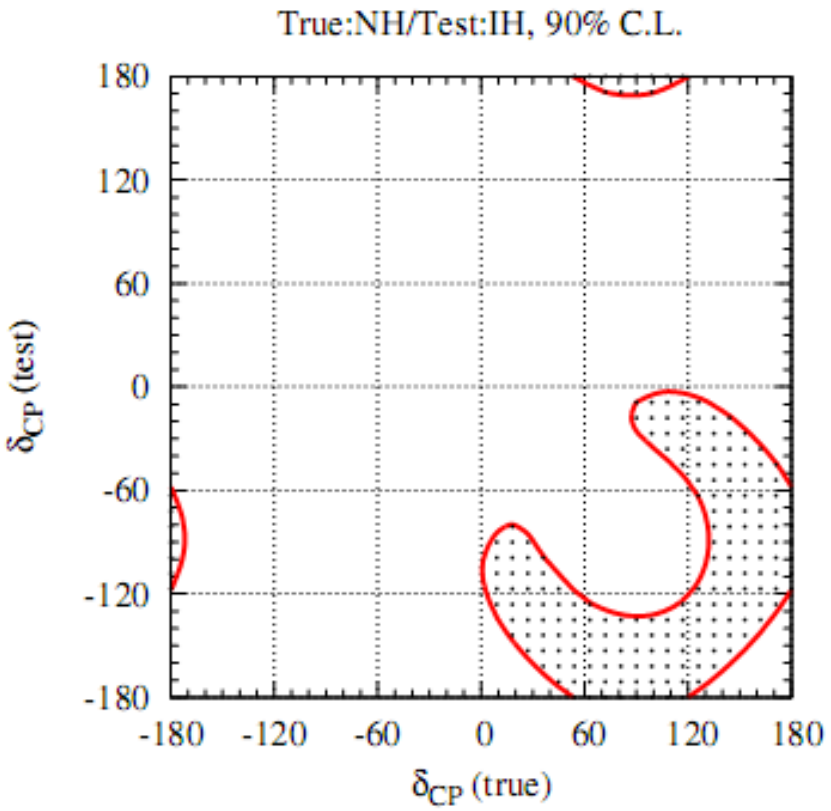




Prakash, SR, Uma Sankar: 1201.6485

Measuring δ_{CP}



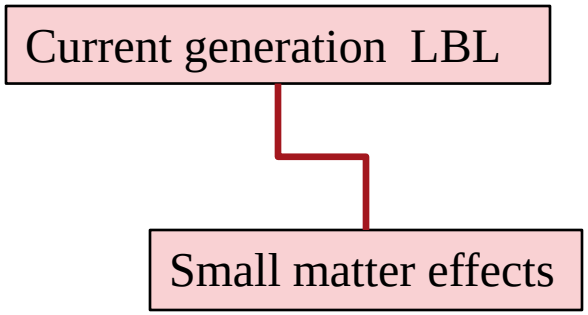


Prakash, SR, Uma Sankar: 1201.6485

Need to know the hierarchy first, in order to measure δ_{CP}!

Lifting the hierarchy-δ_{CP} degeneracy

(with current/upcoming facilities)



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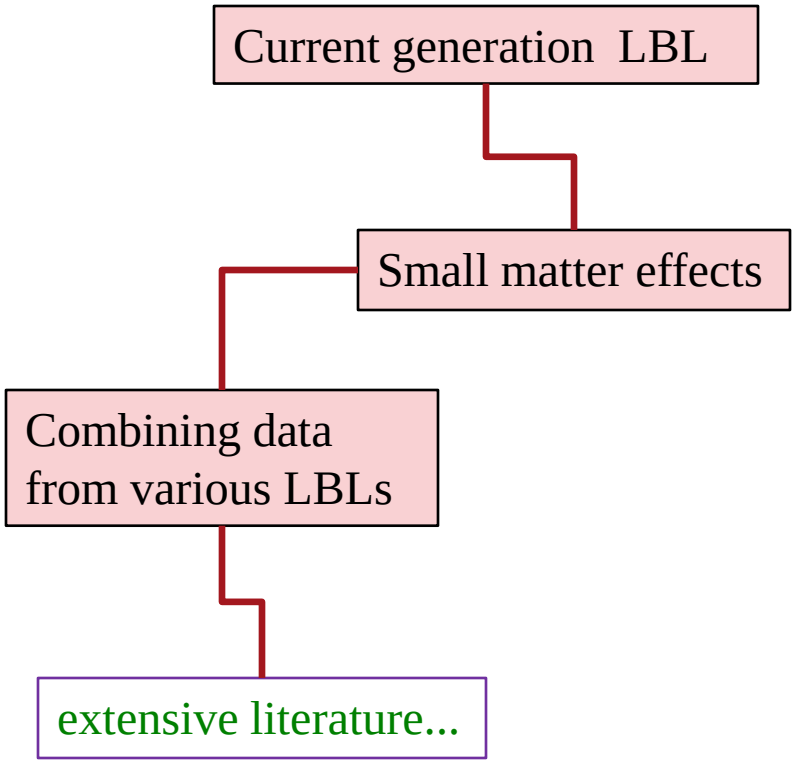

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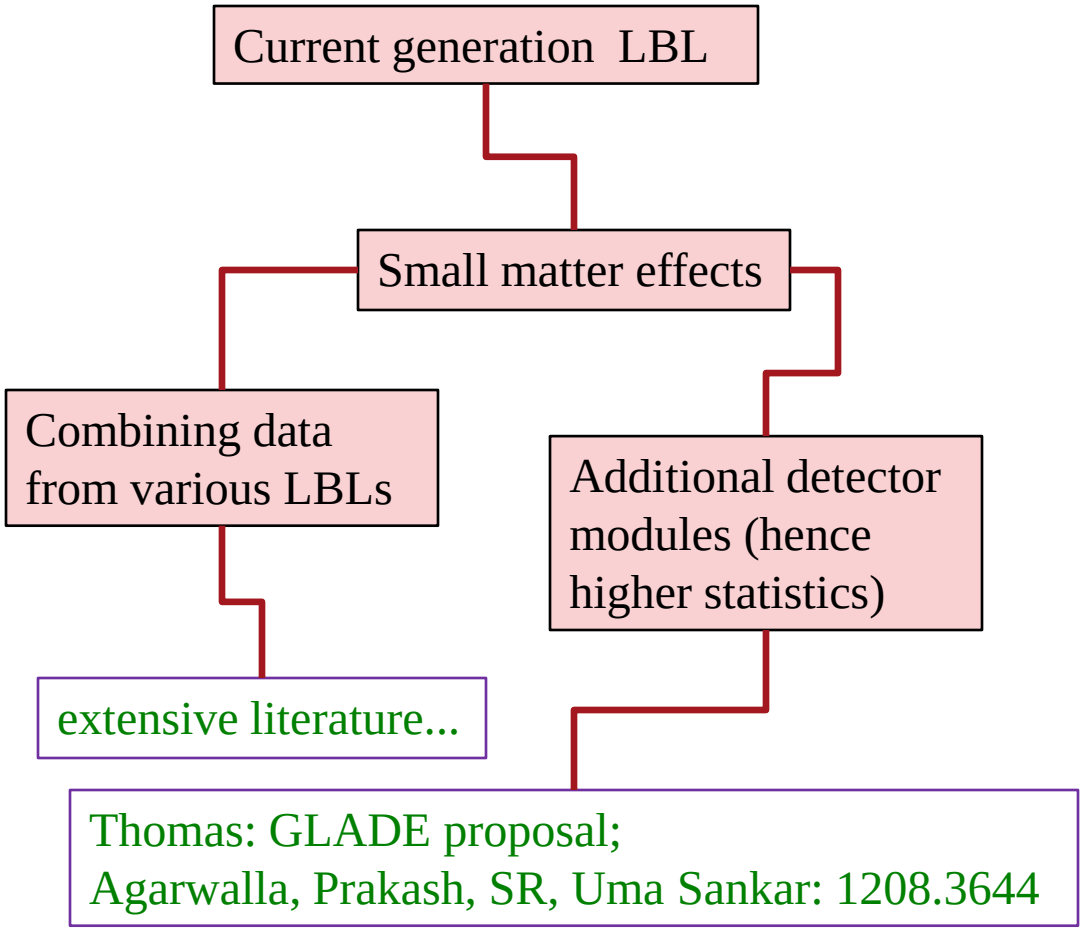

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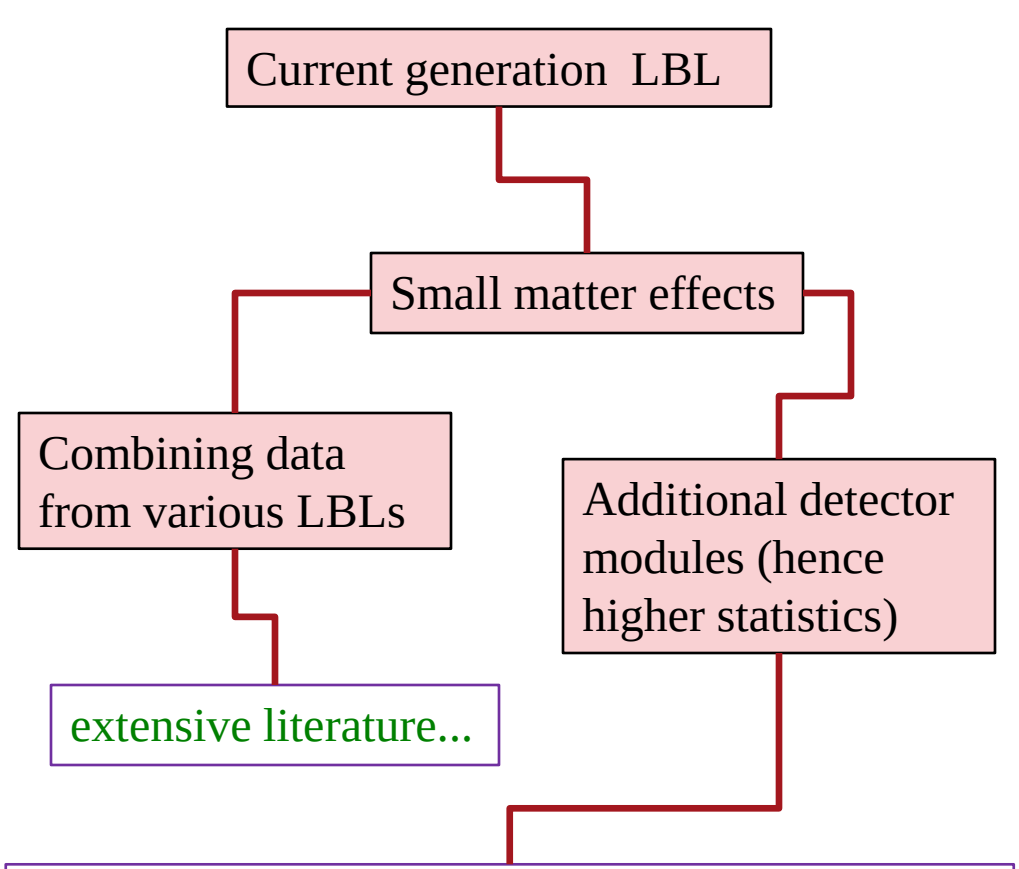

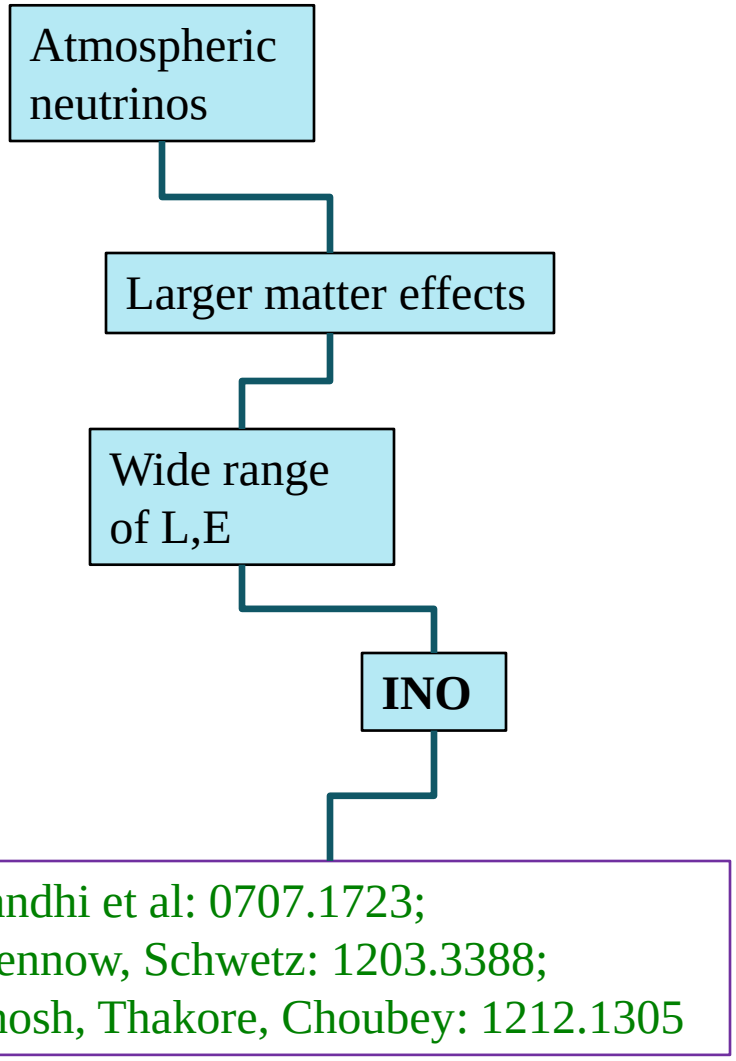

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INO:
India-based Neutrino Observatory

- **Ahmedabad**: Physical Research Lab
- **Aligarh**: Aligarh Muslim Univ
- **Allahabad**: Harish-Chandra Research Inst
- **Calicut**: Univ of Calicut
- **Chandigarh**: Panjab Univ
- **Chennai**: IIT Madras, Inst of Mathematical Sciences
- **Delhi**: Univ of Delhi
- **Guwahati**: IIT Guwahati
- **Hawaii**: Univ of Hawaii
- **Indore**: IIT Indore
- **Jammu**: Univ of Jammu
- **Kalpakkam**: Indira Gandhi Centre for Atomic Research
- **Kolkata**: Ramakrishna Mission Vivekananda Univ, Saha Inst of Nuclear Physics, Variable Energy Cyclotron Centre, Univ of Calcutta
- **Lucknow**: Lucknow Univ
- **Madurai**: American College
- **Mumbai**: Bhabha Atomic Research Centre, IIT Bombay, Tata Inst of Fundamental Research
- **Mysore**: Univ of Mysore
- **Sambalpur**: Sambalpur Univ
- **Srinagar**: Univ of Kashmir
- **Varanasi**: Banaras Hindu Univ

Collaborators are welcome!

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

Physics Aims of INO

- Detection of atmospheric neutrinos: wide range of L,E
- Iron Calorimeter (ICAL) with charge-id (magnetization), for nu-antinu separation

- Precision measurement of atmospheric parameters
- Mass hierarchy determination

- NSI, CPT violation, NDBD, ultra high energy muons, etc.

- Stage I: Atmospheric neutrino observatory
- Stage II: Detector for a future long baseline experiment??

Location of INO

Bodi West Hills, Pottipuram village, Theni district, Tamil Nadu state
(9º 58’ N, 77º 16’ E)

120 km west of Madurai town

The INO site

- Vertical cover :1289 m; all-round cover: ~1000 m

- Four caverns: Accessible through a 2 km tunnel
- Cavern 1: 50 kt ICAL (space for 100 kt)
- Caverns 2-4: Available for other experiments: NDBD, DM, etc.

- Underground cavern and tunnel, small surface lab at Pottipuram (outside the reserve forest boundary)

Construction updates

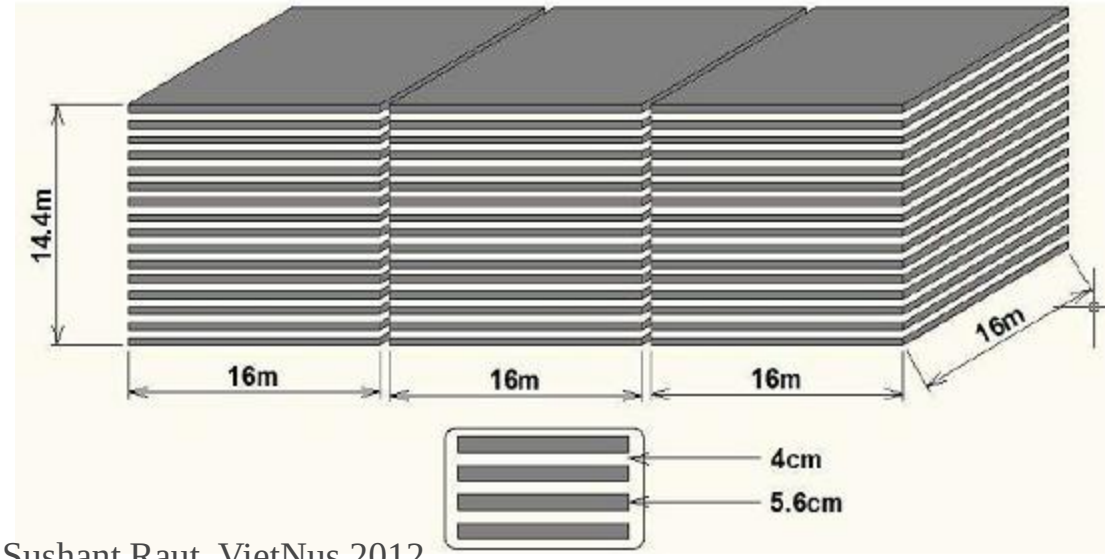
- INO project approved ‘in principle’ by Indian funding agencies
- Environment and forest clearance obtained
- Tendering for site preparation in progress
- Pre-project works (approach roads, water supply, electricity connections) have begun

Detector factsheet

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	1.3 Tesla
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 (97,505m^2)
No. of readout strips	3,686,400

The ICAL Detector

- Iron plates (target mass) separated by glass RPCs (active detector): 150 layers
- Magnetization: Charge-id through bending of muons
- Directionality through tracking and timing (1 ns resolution)

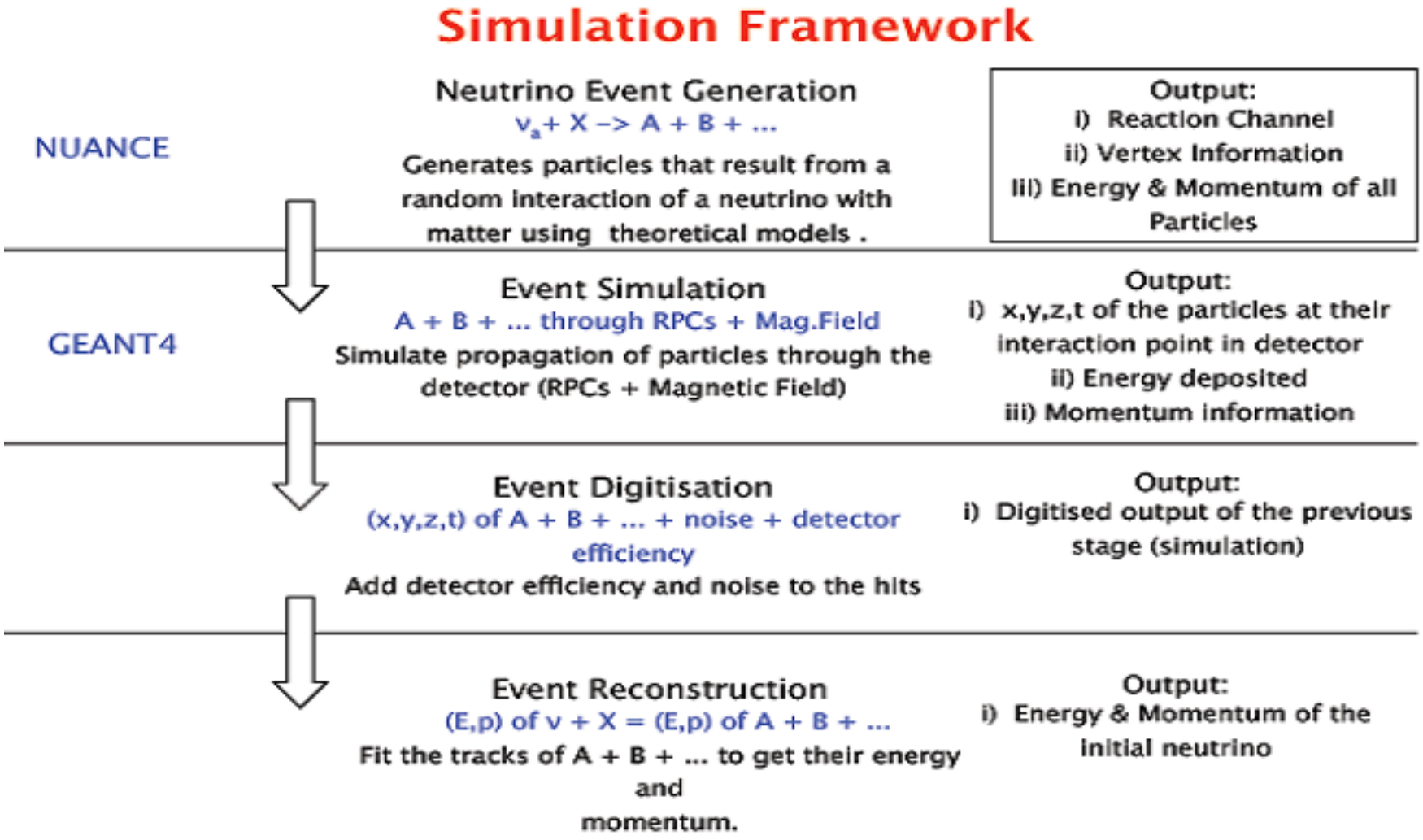


- Modular structure, for ease of construction and modification
- Front end electronics chip developed at BARC Electronics Division

Detector updates

- Timing resolution, noise, tracking, etc of RPC being tested with cosmic muons
- RPC R&D almost complete. 2m x 2m RPCs being fabricated by the industry. 40 kt prototype tested in Kolkata. Both glass and bakelite RPCs tested.
- Electronics: Design and prototyping going on, ASIC front end being tested in RPC lab
- Magnetization: Prototype magnet running at VECC

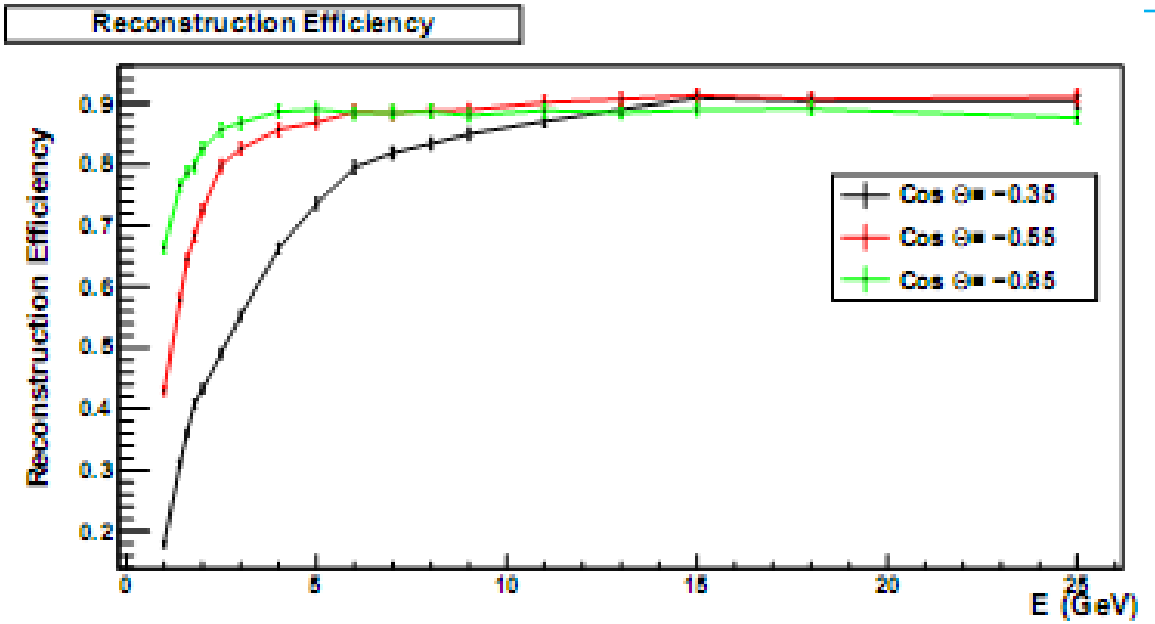
Simulation framework

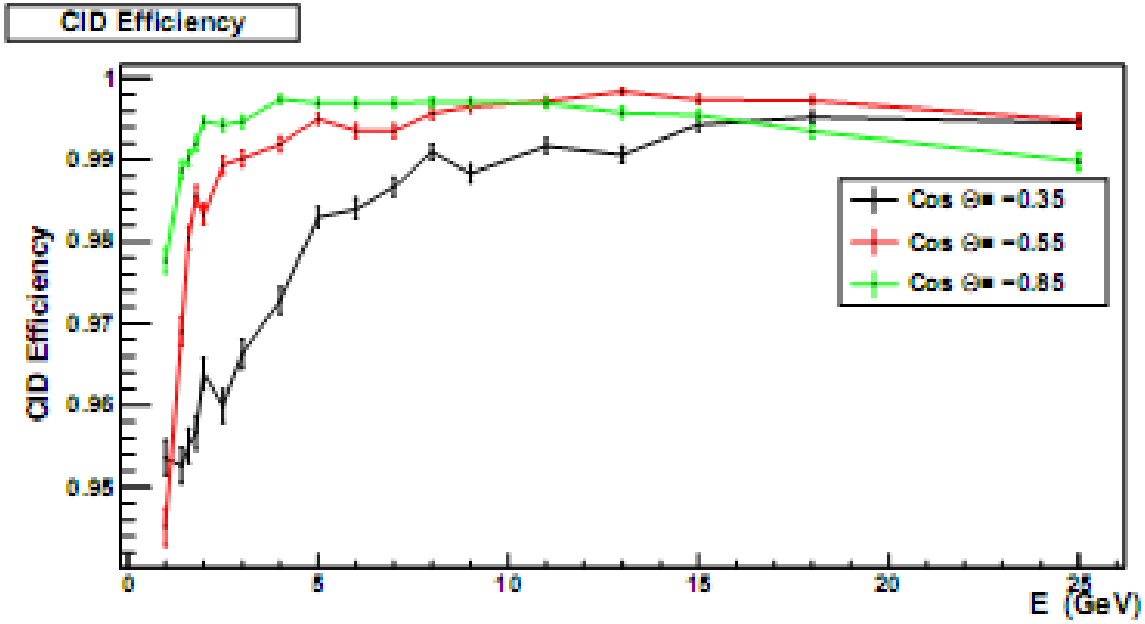


Simulation Updates

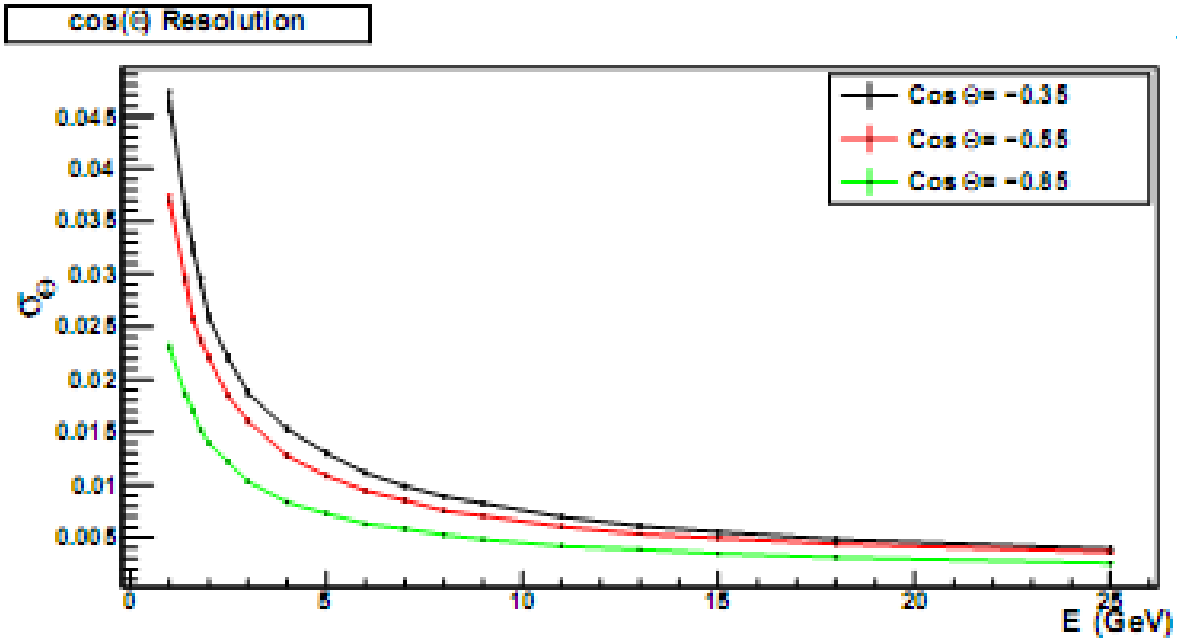
- Inhomogenous magnetic field map implemented
- Muon reconstruction: Energy and direction resolutions available, but efforts are on to improve them
- Hadron reconstruction: Energy resolutions available
- Neutrino energy resolution using muon and hadron momenta

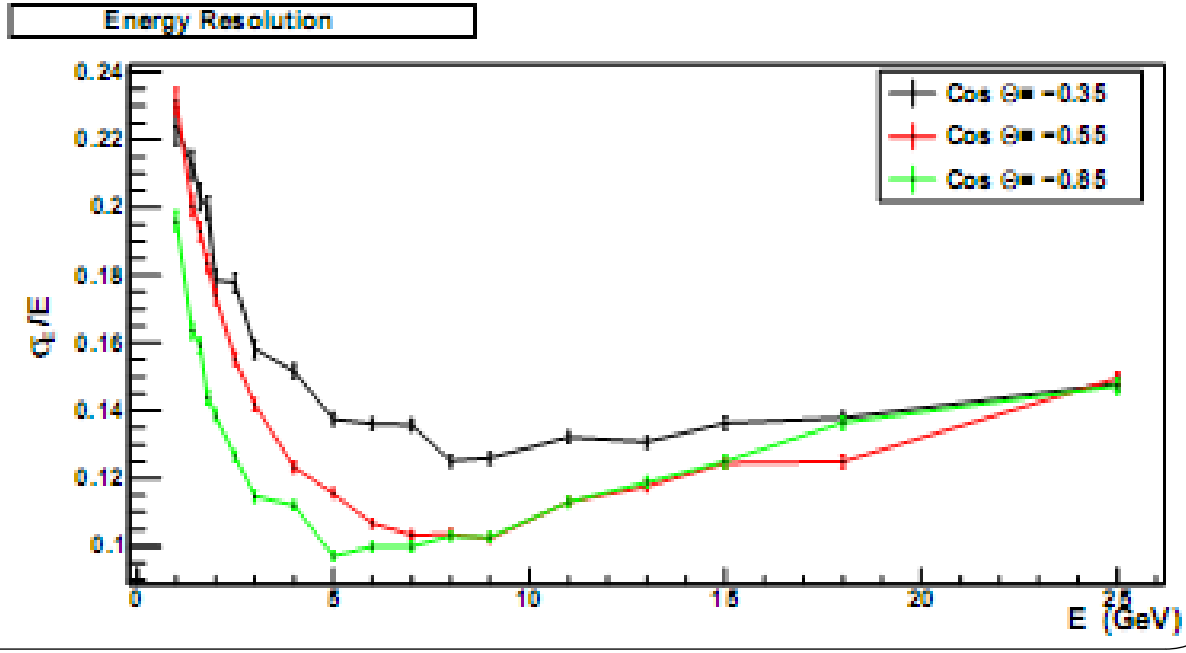
Detector efficiency





Detector resolution





More work required

- Detector effects
  - Improving sensitivity to electrons
  - Improving angular resolution of neutrinos by more precise direction reconstruction for hadrons
  - Lowering the energy threshold
  - Improving resolution/efficiency for horizontal events
- Other systematic effects:
  - Flux normalization uncertainty
  - Flux tilt uncertainty
  - Cross-section uncertainty

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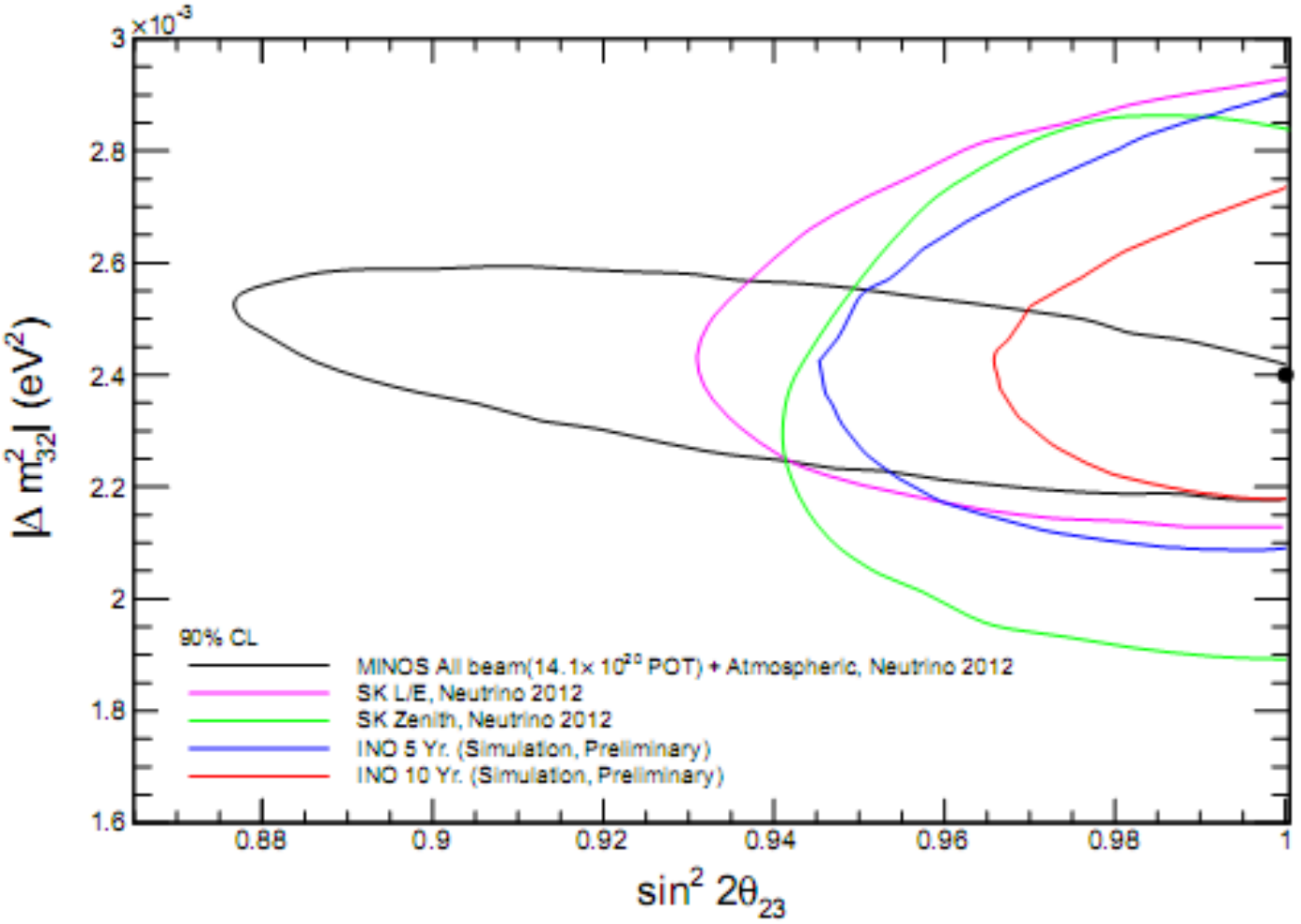
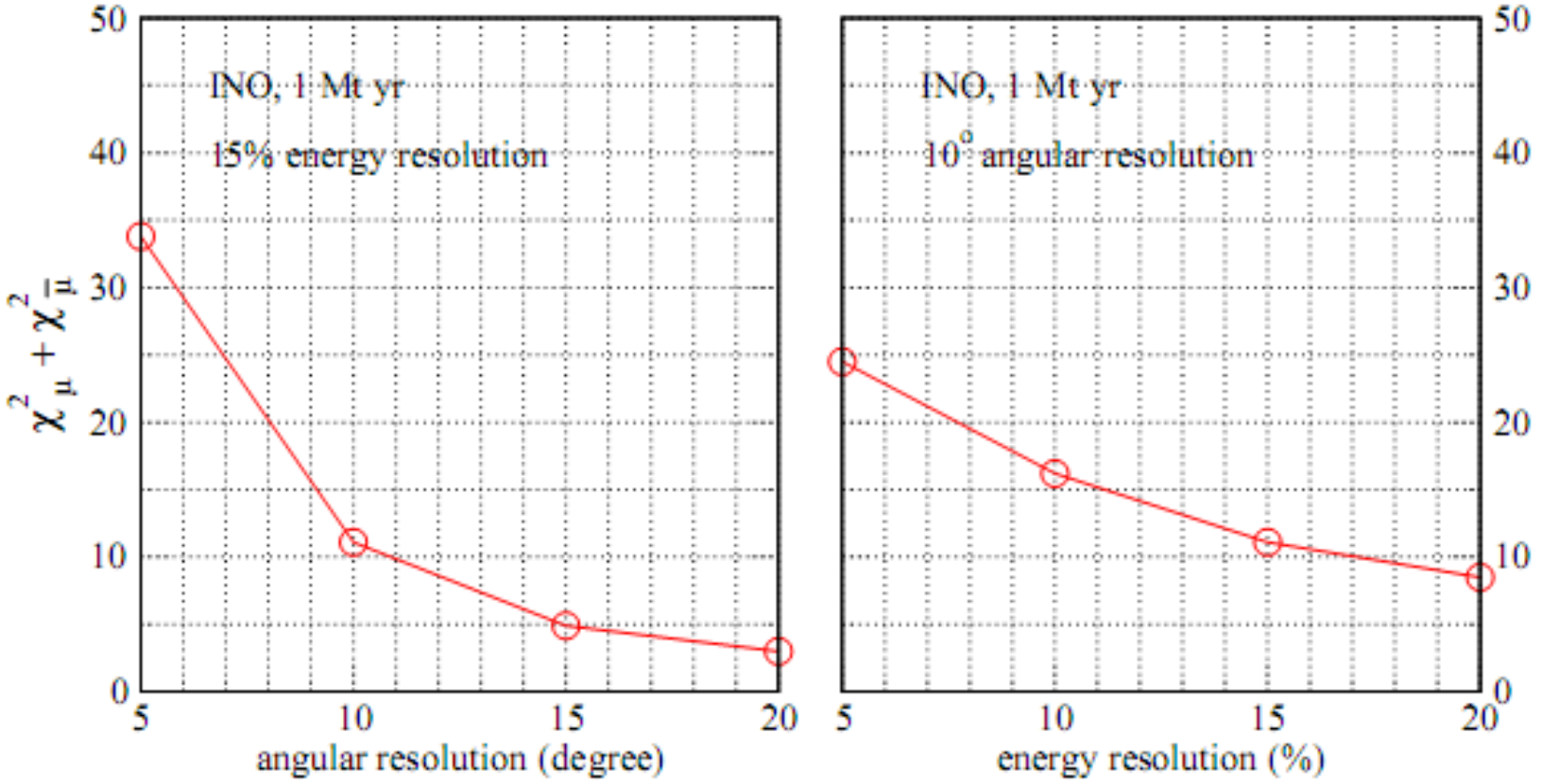
Precision measurements



(with projected priors on atmospheric parameters)

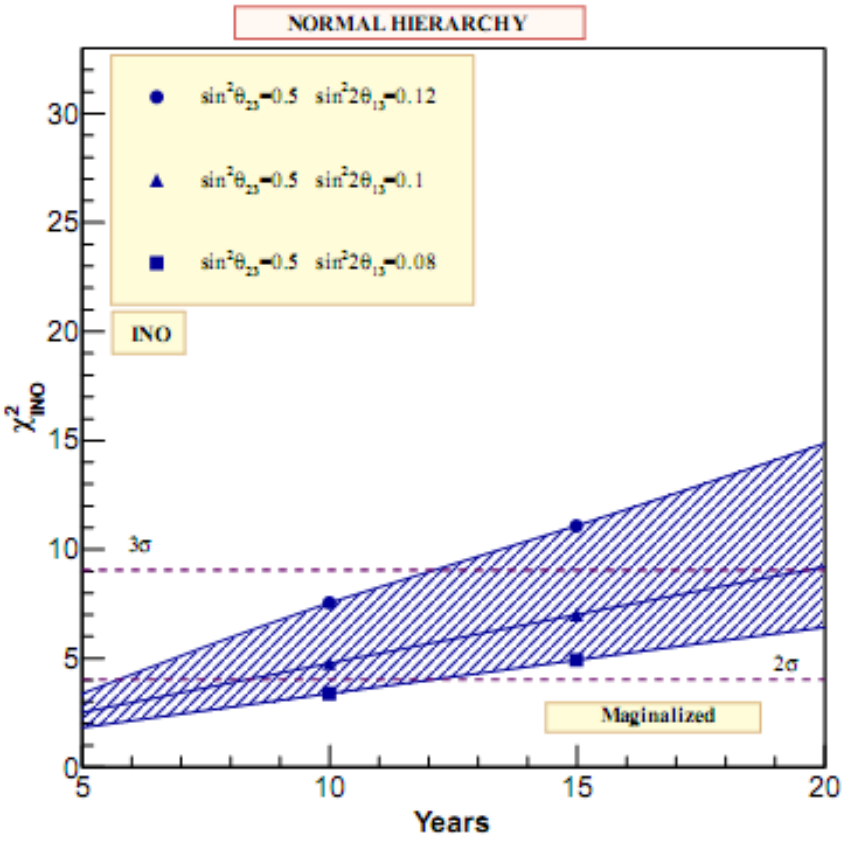
Mass hierarchy determination

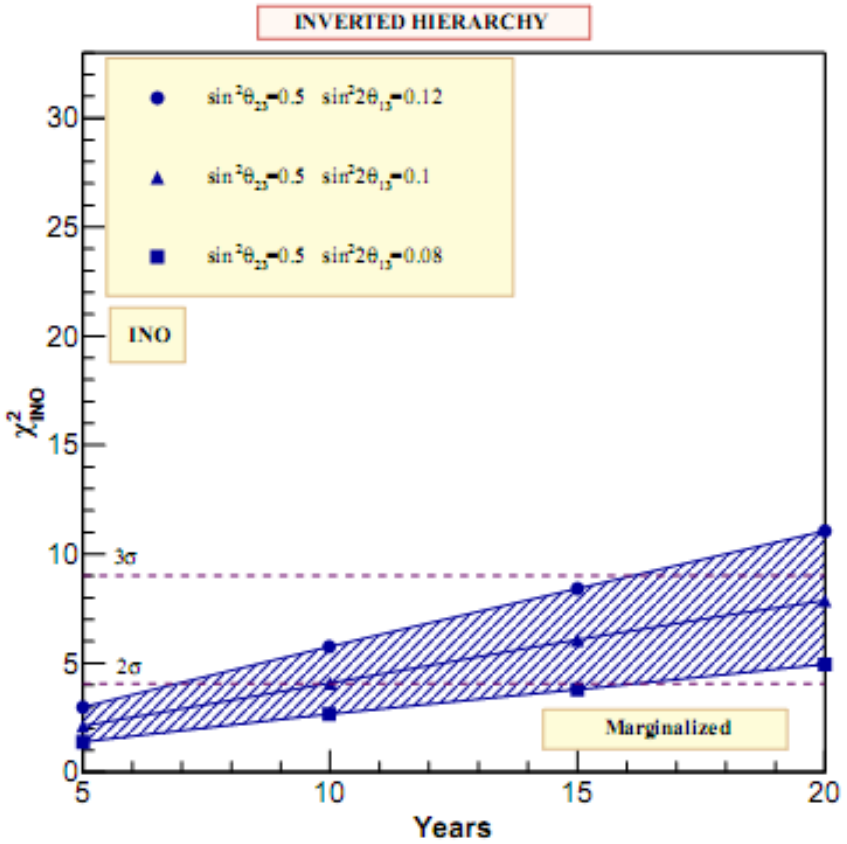
- Impact of resolutions



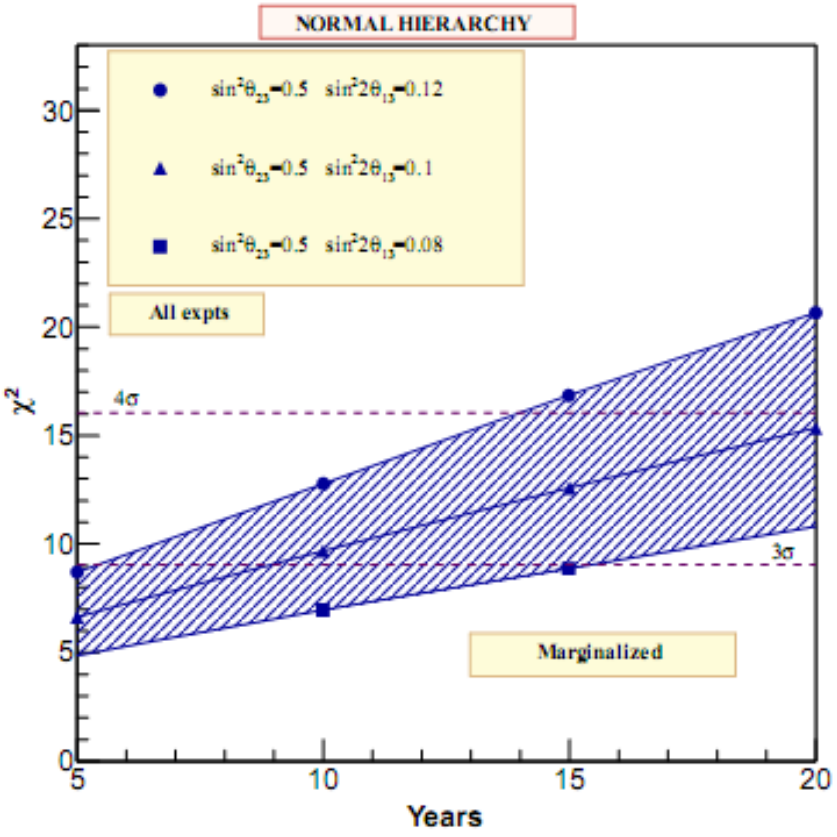
Gandhi et al: 0707.1723;
Also see
Petcov, Schwetz: hep-ph/0511277

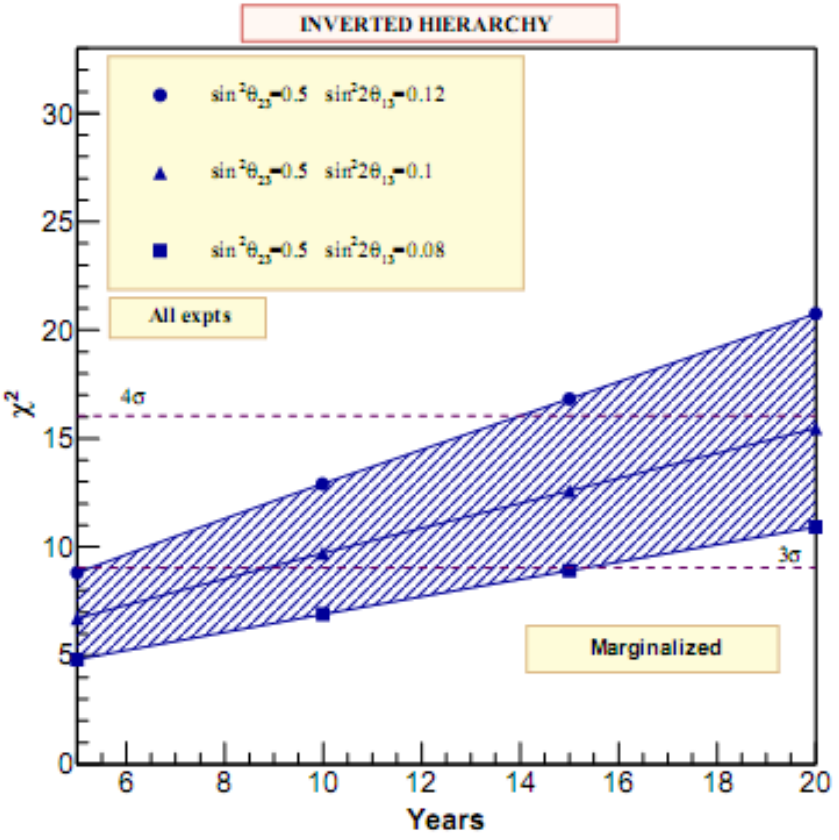
Mass hierarchy timeline: INO





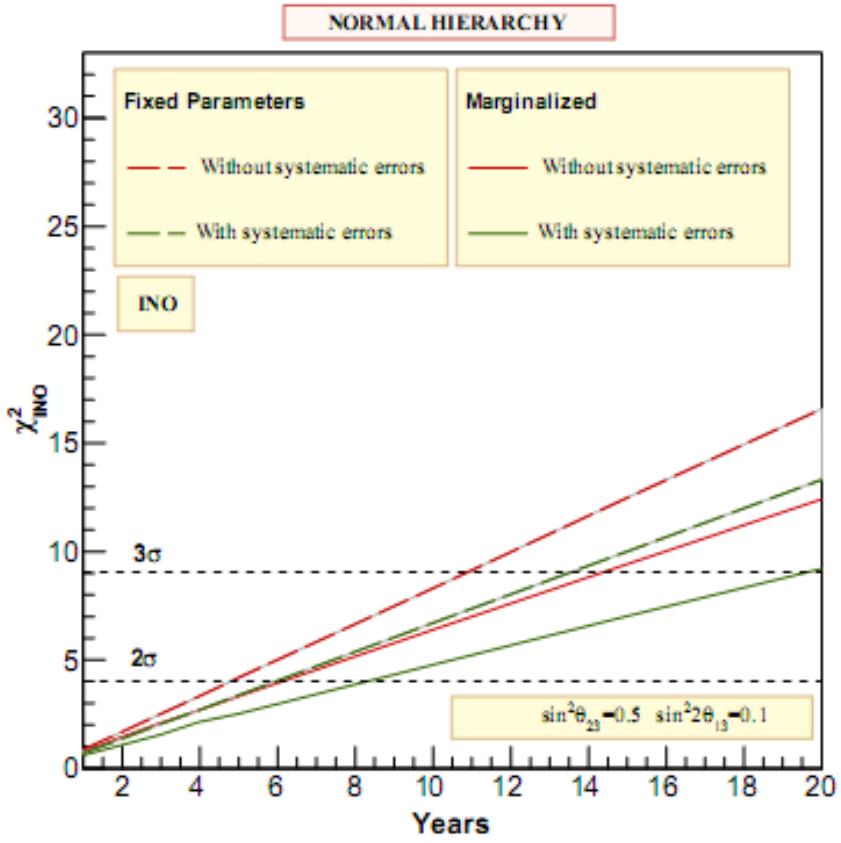
Mass hierarchy timeline: INO+others

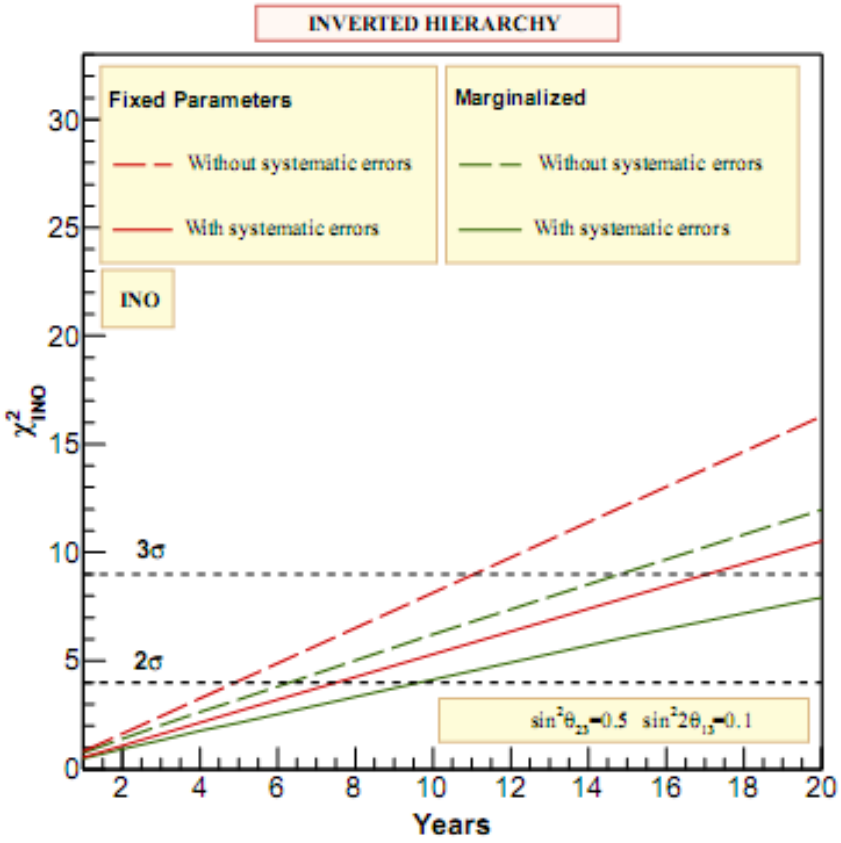




Mass hierarchy determination

- Impact of systematics and priors

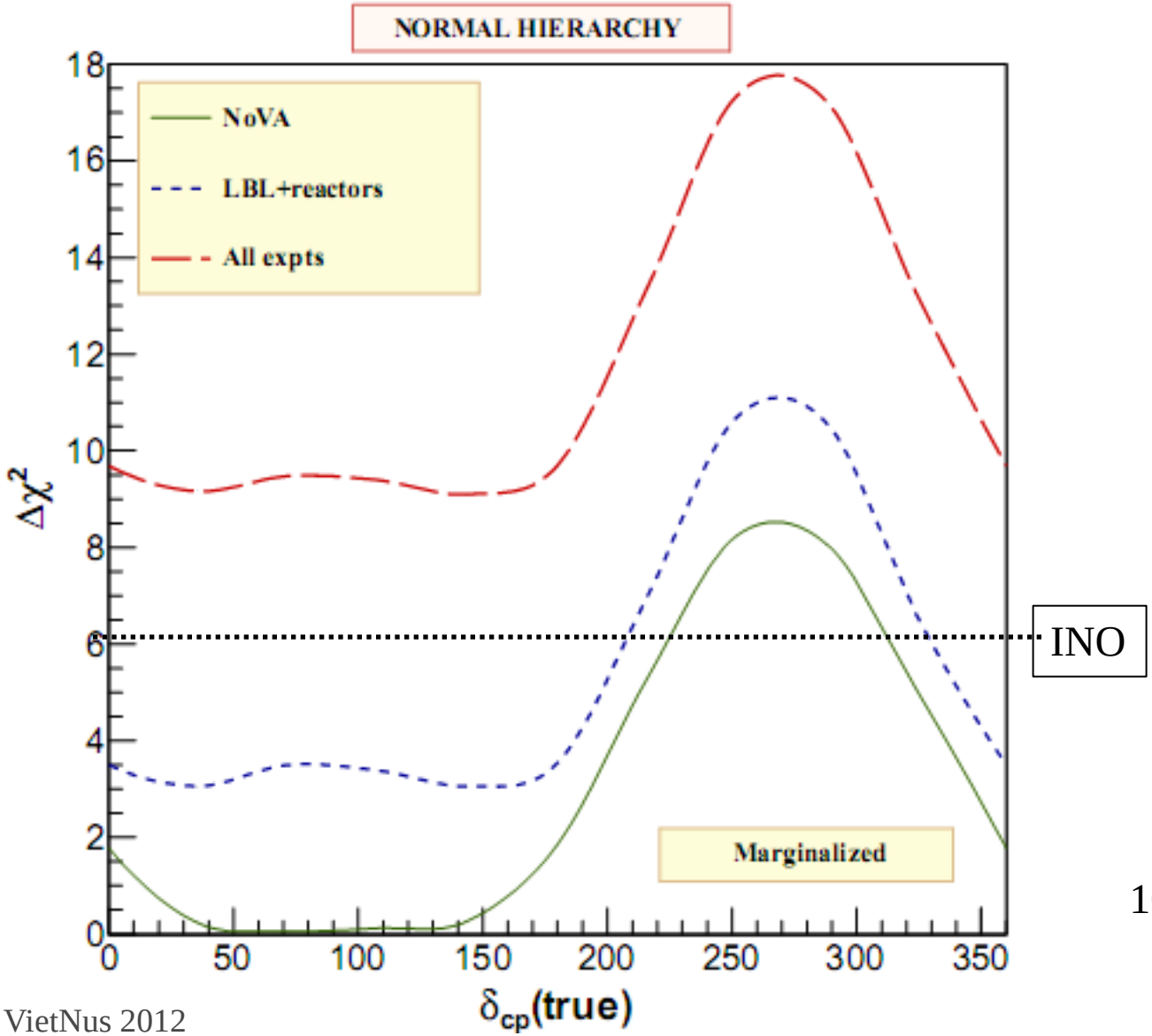




20-30% drop in sensitivity due to systematics

Further 20-30% drop due to parameter uncertainties

Comparison & Combination



INO

10 years data

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Q: Why should we discuss atmospheric neutrinos at a workshop on CP Violation?

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- Measuring δ_{CP} requires knowledge of the hierarchy
- With current LBL experiments, hierarchy sensitivity depends significantly on the value of δ_{CP}
- Atmospheric neutrino experiments (in particular INO) can determine hierarchy independently of δ_{CP}
- Combining with other experiments improves the sensitivity

Summary: INO Experiment

- Land acquired, civil construction to start soon
- RPC testing going on
- Improvements expected in energy and angular resolutions through simulations
- Data taking expected to start around 2017.

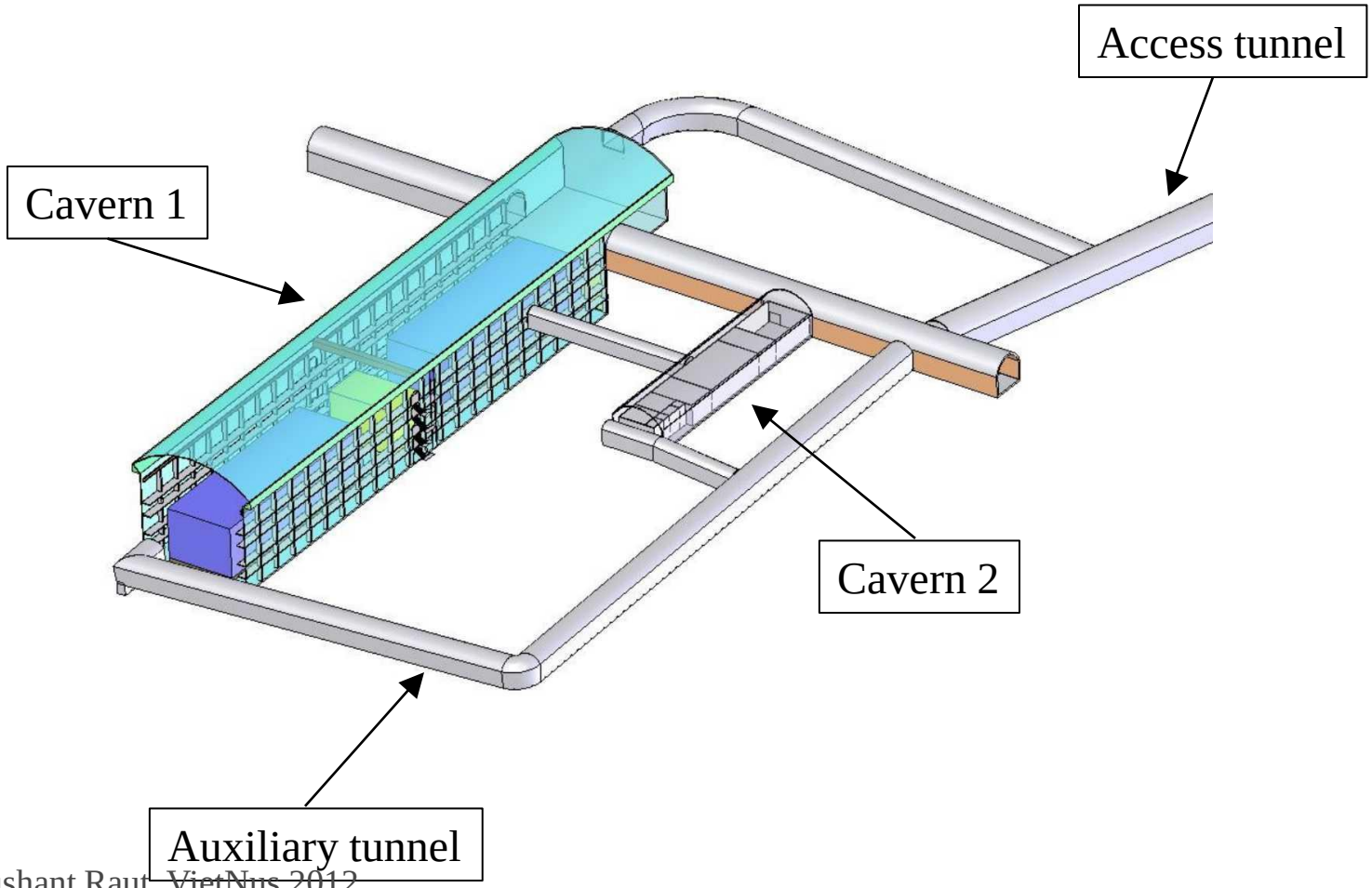
THANK YOU

Thanks to Sandhya Choubey, Brajesh Choudhary, Amol Dighe, Anushree Ghosh, Pomita Ghoshal, Srubabati Goswami, Naba Mondal, M.V.N.Murthy and Tarak Thakore for their inputs.

BACKUP SLIDES

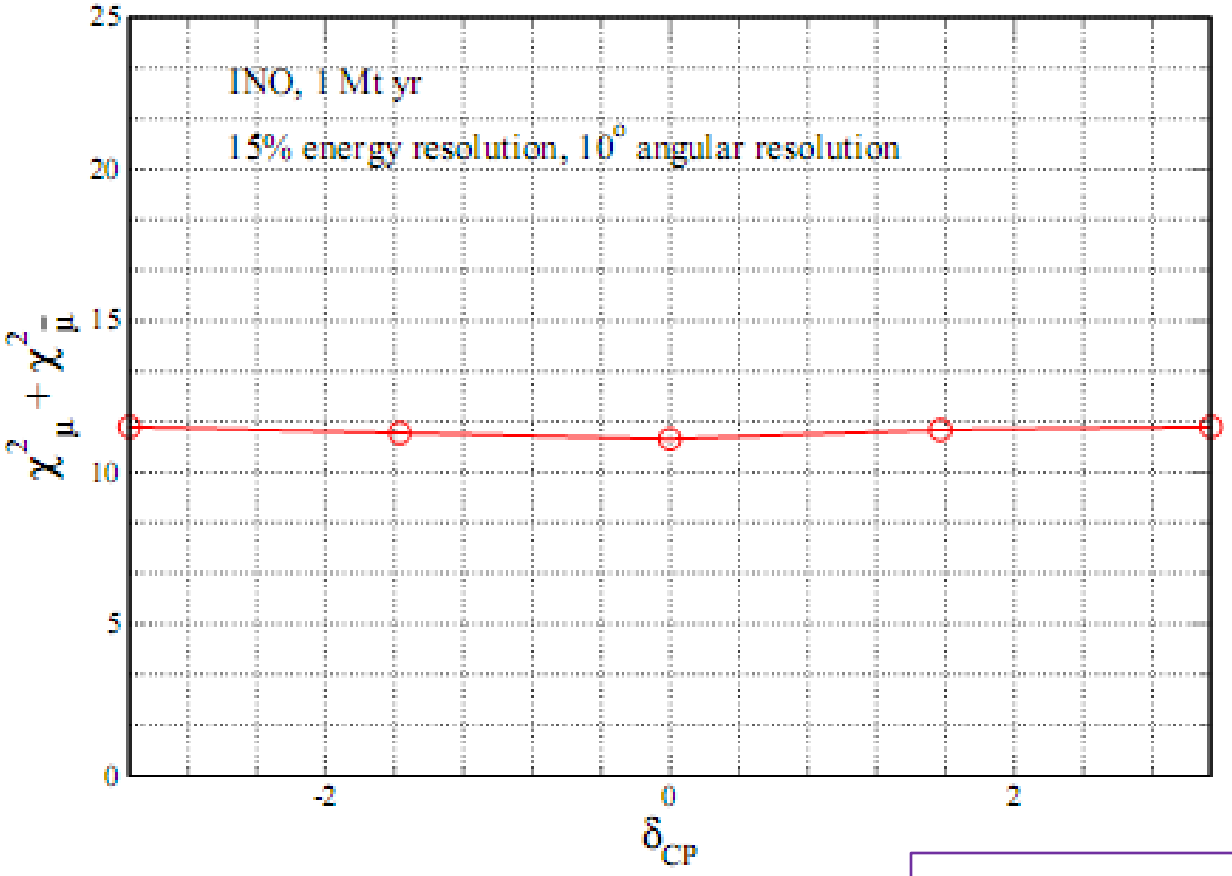
Atmospheric neutrino flux at Theni

INO Cavern



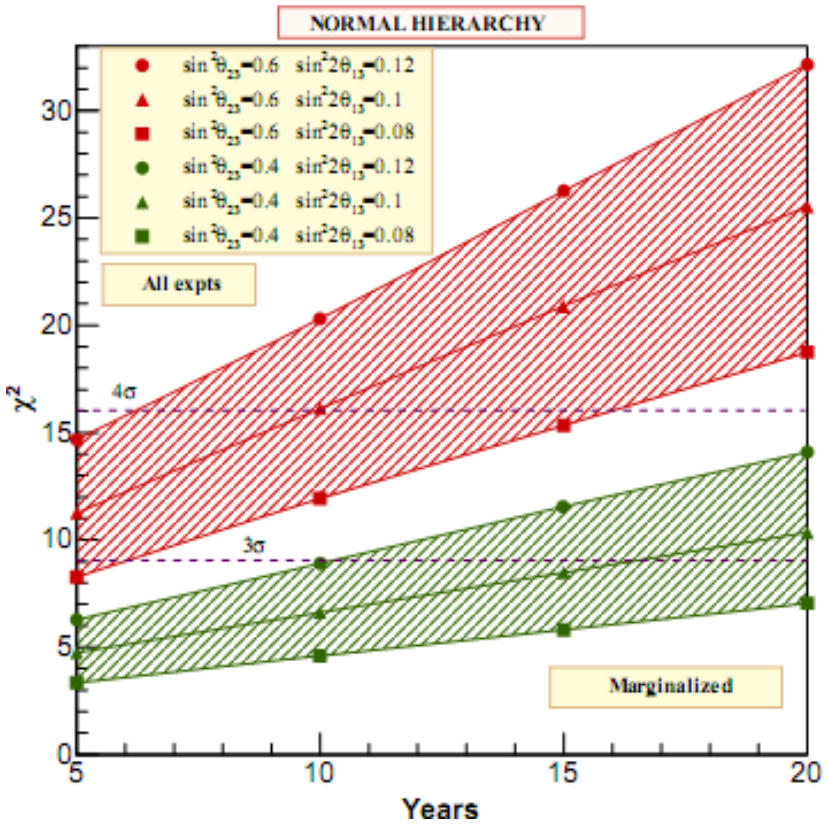
Mass hierarchy determination

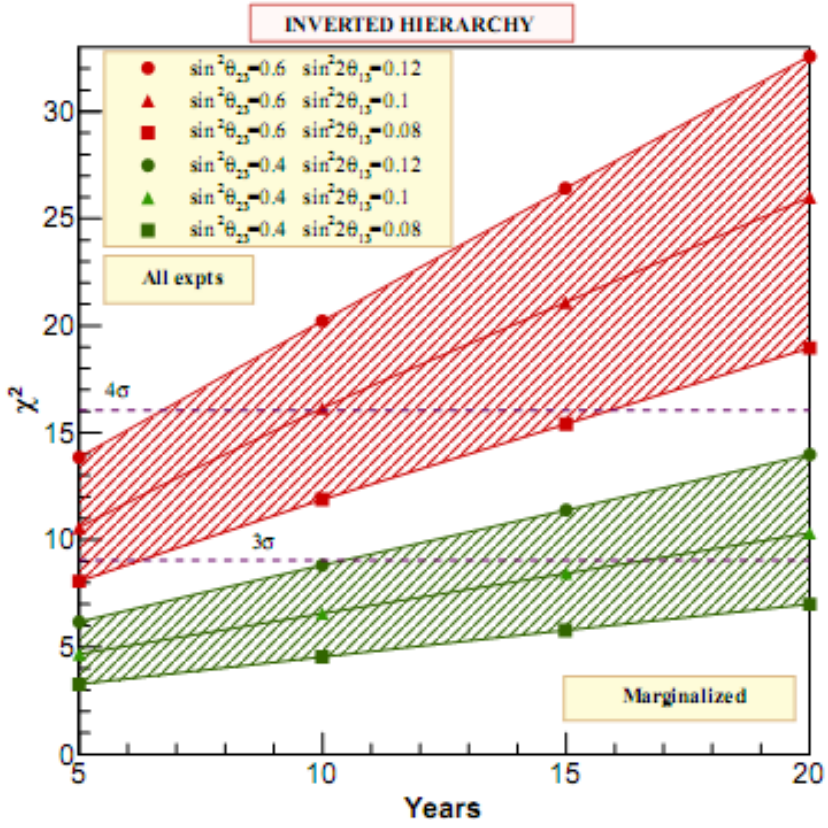
- Impact of δ_{CP}



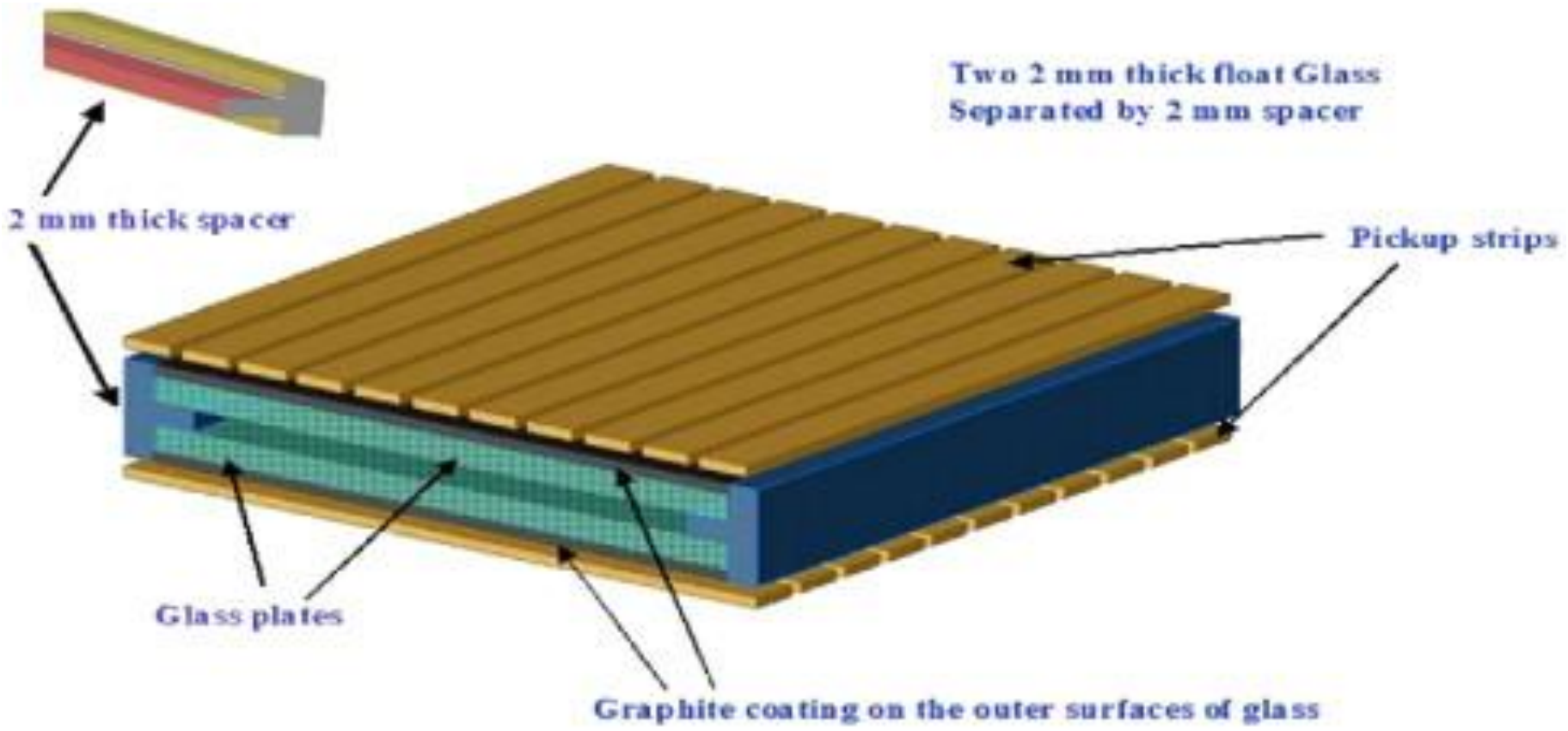
Gandhi et al: 0707.1723

Mass hierarchy timeline: INO+others



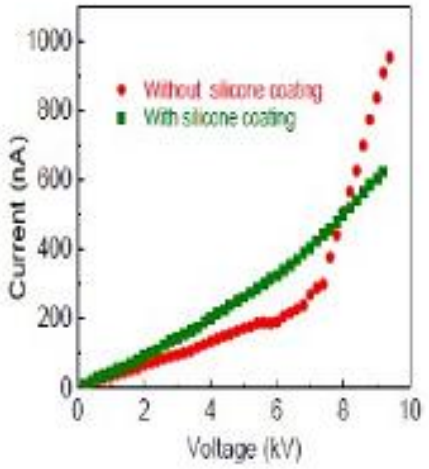


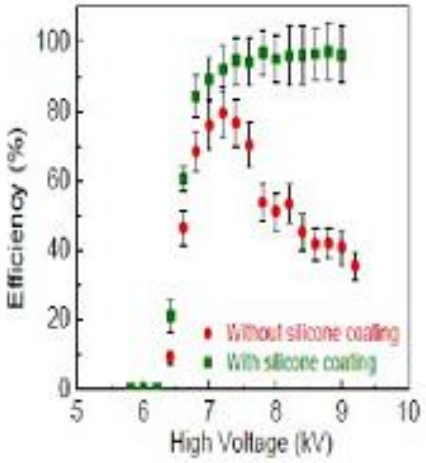
RPC

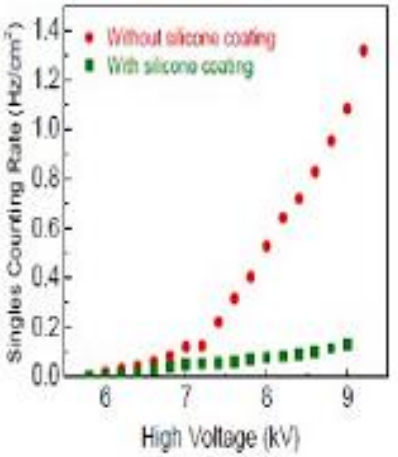

Two 2 mm thick float Glass
Separated by 2 mm spacer
2 mm thick spacer
Pickup strips
Glass plates
Graphite coating on the outer surfaces of glass

Bakelite RPC R&D

- SINP and VECC groups in Kolkata developing bakelite RPCs in streamer mode
- Inner surface of bakelite coated with PDMS (silicone) to make the surface smooth
- Efficiency plateau over 96% obtained with reduced noise rate and long term stability
- INO-ICAL being modular, can use both, glass and/or bakelite RPCs



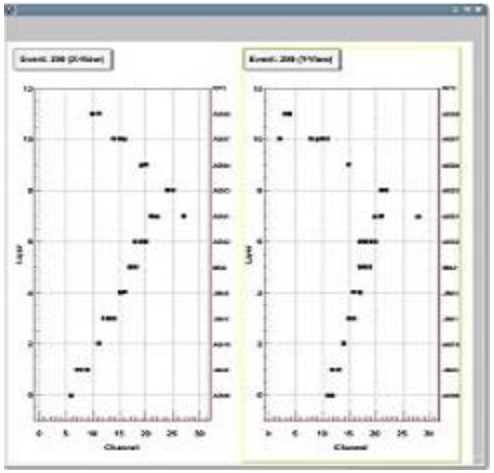


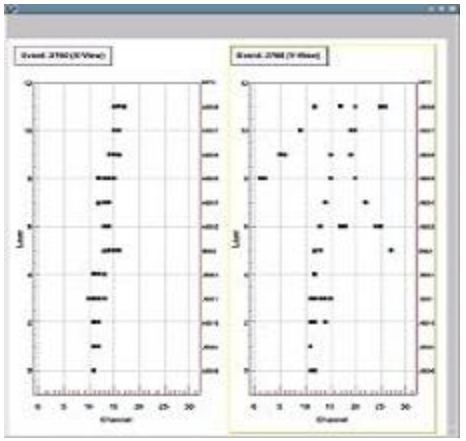


Dighe: NuFact 2012

Testing RPCs using cosmic rays

- Timing resolution
- Pulse height resolution
- Tracking capability for muons and hadrons
- Noise rate





INO Timeline

SN	Description of work	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
	Civil work at Pottipuram						
1	Land acquisition and pre-project work						
2	Architectural and Engineering consultancy						
3	Tendering and award of contracts						
4	Mining of access portal						
5	Excavation of tunnel						
6	Excavation of caverns						
7	Installation of services, cranes, lifts etc.						
8	Civil work for magnet support bed						
9	Surface facilities						
	Magnet						
10	Procurement of steel plates						
11	Machining job for steel plates						
12	Transportation of machined plates at site						
13	Procurement of copper coils						
14	Assembly/erection of magnet (3 modules)						
	RPC						
15	Finalization of all design details, tendering						
16	Procurement of components						
17	Fabrication and assembly of 30000 pcs						
18	Transportation to site and tests						
19	Procurement of electronics, gas handling						
20	Installation and commissioning						