Physics Capabilities of Future Atmospheric ν-Detectors

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Neutrino Oscillation Workshop

Conca Specchiulla, Otranto, Italy

September 9-16, 2012

Atmospheric Neutrinos as Source

Cosmic Ray + $A_{air} \to \pi^+ + \ldots$

$\pi^+ \to \mu^+ + \nu_\mu$

$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

➢ Provides a broad range of energy as compared to any other natural and artificial sources

➢ Provides a wide range of path-length

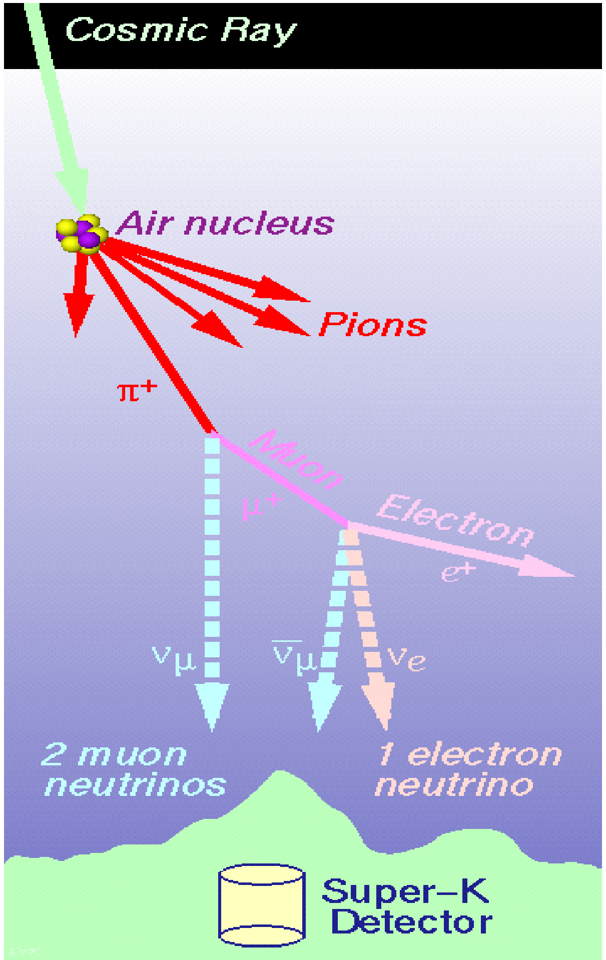
➢ Hence a broad L/E band (1 to 10^5 km/GeV).

➢ The longer baseline allow matter effects to develop

➢ Source of both neutrinos and antineutrinos

➢ Source of both ν_e and ν_μ

➢ All these for free !!



Future Detectors for Atm ν

- Magnetized Iron Detector (INO)

  ➢ 50 - 100 kT

  ➢ Muon energy measurement, direction reconstruction and charge discrimination capability

  ➢ Can determine the neutrino energy and direction through Hadron shower reconstruction

- Megaton Water Cerenkov Detector (HK, MEMPHYS)

  ➢ Large volume

  ➢ No charge ID

  ➢ Both electron and muon energy and direction measurement

- Liquid Argon TPC

  ➢ Excellent electron and muon energy and direction measurement

  ➢ Charge ID ?

- Neutrino Telescope (IceCube, PINGU)

  ➢ Huge Volume (Multi-Mton)

Physics Possibilities with Atmospheric νs

- Measurement of $|\Delta m^2_{31}|$ and $\sin^2\theta_{23}$
- Determine if $\sin^2\theta_{23}$ is maximal and if not then determination of its octant
- Determination of Mass Hierarchy or $sgn(\Delta m^2_{31})$
- CPT violation
- Sterile Neutrinos,Non Standard Interactions, Long Range Forces...,

Plan of Talk

- Determination of Mass Hierarchy and Octant in magnetized Iron Calorimeter and Liquid Argon Detectors

Physics Possibilities with Atmospheric νs

- An incomplete list of references...

Petcov (1998), Chizov, Maris, Petcov (1998), Akhmedov (1999),Akhmedov,Dighe,Lipari,Smirnov (1999),Kim (1998),Peres,Smirnov(1999),Bernabeu, Palomares-Ruiz, Perez, Petcov, (2002), Gonzalez-Garcia, Maltoni (2003), Bernabeu, Palomares-Ruiz, Petcov (2003), Peres, Smirnov (2004), Indumathi, Murthy (2004), Gandhi, Ghoshal, Goswami, Mehta, Sankar (2004), Gonzalez-Garcia, Maltoni, Smirnov (2004), Palomares-Ruiz, Petcov (2005), Choubey, Roy (2005), Fogli, Lisi, Marrone, Palazzo (2005); Huber, Maltoni, Schwetz (2005), T. Kajita (2005); E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2005), Petcov, Schwetz (2006), S. Choubey (2006); Indumathi, Murthy, Rajasekaran, Sinha (2006), E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2007), R. Gandhi, P. Ghoshal, S. Goswami, P. Mehta, S. U. Sankar and S. Shalgar (2007), E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2008), Gandhi, Ghoshal, Goswami, Sankar (2008), Mena, Mocioiu, Razzaque (2008), Peres, Smirnov (2009), Gandhi, Ghoshal, Goswami, Sankar (2009), Samanta (2006 - 10), Samanta, Smirnov (2010), Conrad, de Gouvea, Shalgar (2010), Gonzalez-Garcia, Maltoni, Salvado (2011), Barger, Gandhi, Ghoshal, Goswami, Marfatia, Prakash, Raut, Sankar (2012), Blennow, Schwetz (2012), Akhmedov, Razzaque, Smirnov (2012), ...

S. Choubey, Nu2012

India Based Neutrino Observatory Proposal

- Goal : To build an underground laboratory for science with neutrino physics as major activity
- The Detector: Magnetized Iron CALorimeter detector – (ICAL) for detection of atmospheric neutrinos in its first phase.
- Detector choice based on
  - Technological capabilities available in the country
  - Complementarity to Existing/Planned neutrino detectors in the world
  - Modularity and the possibility of phasing
  - Compactness and ease of construction
- Other Possibilities
  - Neutrinoless double beta decay, Dark Matter Experiment (DINO)..
  - Second phase end detector for a beam experiment

International participation is welcome

INO: Approval Status

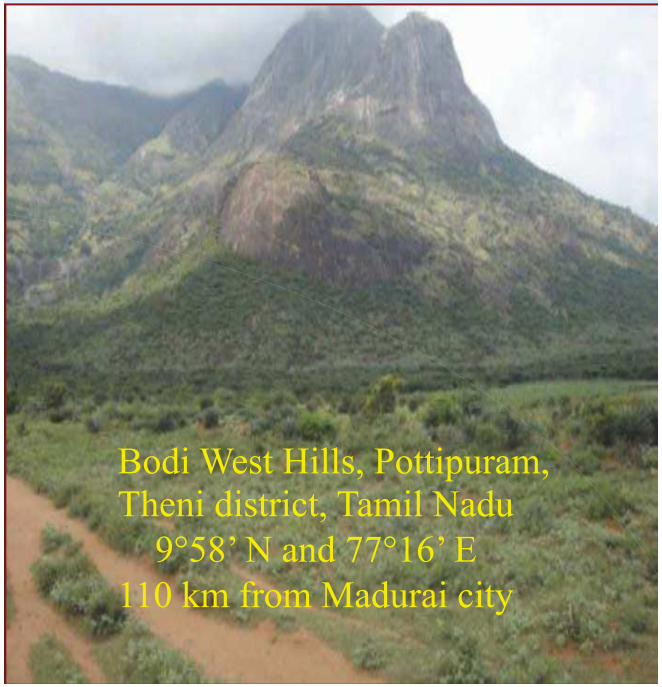
- Approvals from Indian Funding Agencies for
  - Construction of an underground Laboratory and surface facilities at Pottipuram village in South India
  - Construction of 50 kton magnetized Iron Calorimeter detector to study neutrino properties
  - Construction of INO center (The National Center for High Energy Physics) at Madurai in South India
  - Human Resource Development
  - Detector R & D

Completion of project in 6 years

N. Mondal, LP2011

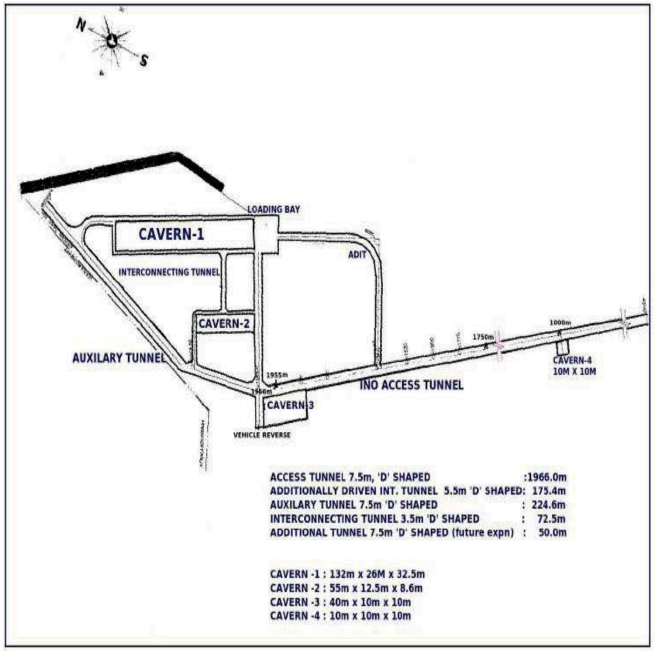
http://www.ino.tifr.res.in

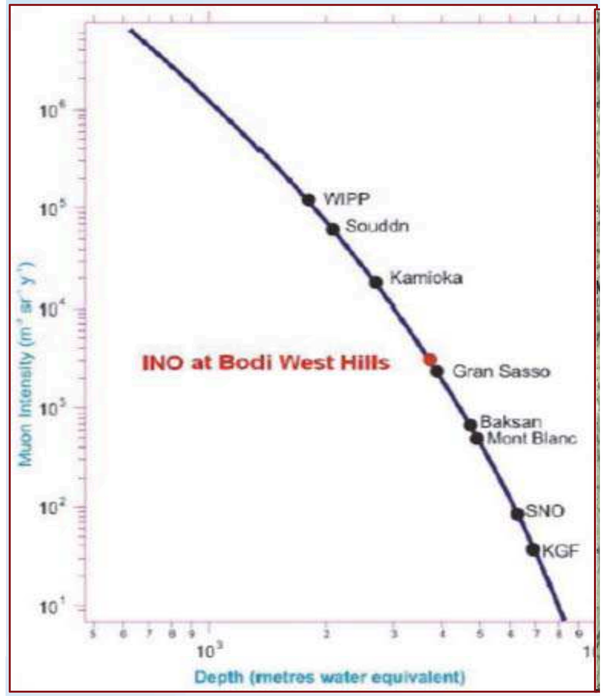
INO: Location



- Flat terrain with good access to major roads
- Low rainfall, low humidity
- Portal outside the RF boundary, surface facilities not on Forest Land, no clearing of forests required
- Environmental and Forest Clearances obtained
- 26 Hectre Land provided free of cost by state Govt.

INO: Site at a Glance

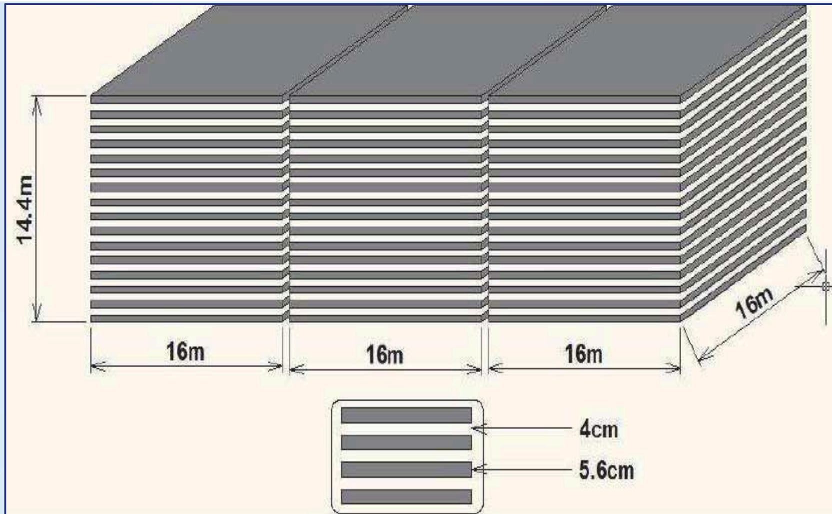


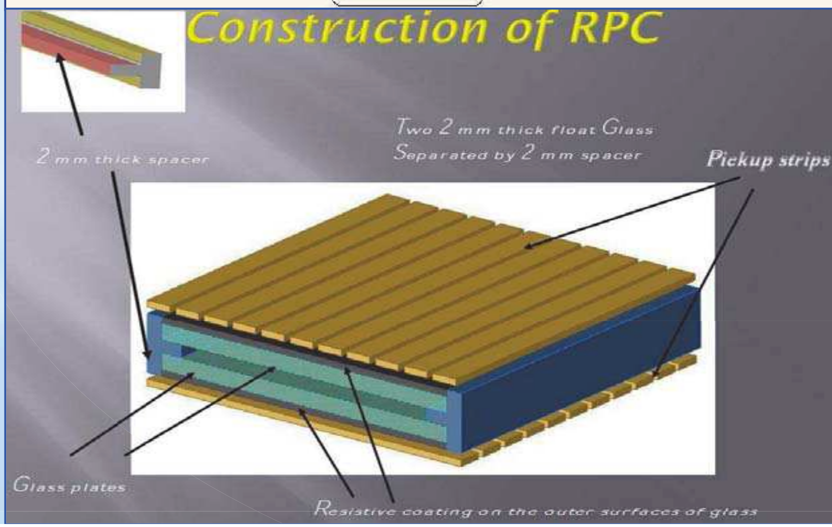


- Cavern set in Charkonite Rock under the 1589 m peak;
- Vertical cover 1289 m;
- Accessible through a 2 km tunnel
- Cavern 1 will host 50 kt ICAL (space for 100 kt);
- Other caverns for multiple experiments ($0\nu\beta\beta$, DM)

The detector: ICAL@INO

- Active Detector Element : Resistive Plate Chambers made of glass
- Iron plates Separatd by RPCs





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	$\sim$ 5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.3 Tesla
RPC	
RPC unit dimension	1.84 m $\times$ 1.84 m $\times$ 24mm
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	$\sim$ 28800
No. of electronic readout channels	3.6864×10^6

S. Agarwalla, NNN2011

Salient Feautures of the Detector

- Sensitive to muons
- Good Energy determination from
  - Track length
  - Track curvature in a magnetic field
- Directionality from tracking and ns timing resolution
- Charge identification from track curvature in magnetic field
- Hadron Shower reconstruction enables to determine the neutrino energy

Detector R&D Status

- Development of RPC

  ➢ Full size RPC's (2m X 2m) being fabricated in INO Labs

  ➢ Large scale production developed with the help of Industry

- Electronics

  ➢ Designing and Prototyping of electronics, trigger and data acquisition systems in progress

- Magnet

  ➢ Prototype magnet running at VECC Calcutta

- $8m \times 8m \times 20$ layers 800 ton engineering module is being planned

INO: Simulation Framework at a Glance

NUANCE

Neutrino Event Generation

ν_a + X -> A + B + ...

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

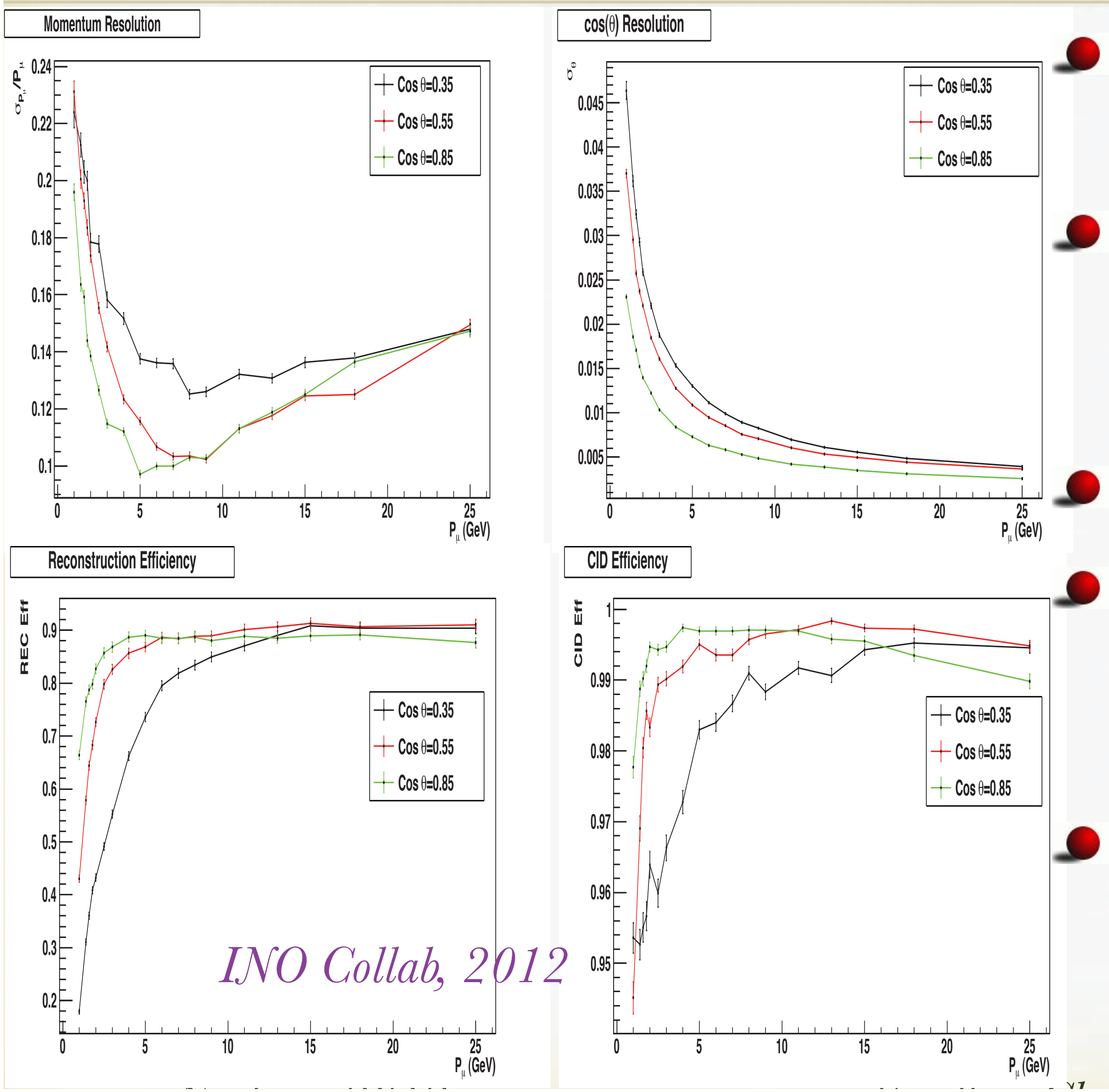
(E,p) of ν + X = (E,p) of A + B + ...

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

Output:
i) Energy & Momentum of the initial neutrino

N. Mondal, LP2011

INO: Simulation Status



- Inhomogeneous magnetic field implemented
- Muon energy and direction resolution from tracks achieved – improvements possible
- Hadron energy resolution available
- Neutrino energy and direction resolution using muon and hadron information possible
- Optimization of iron plate thickness in progress

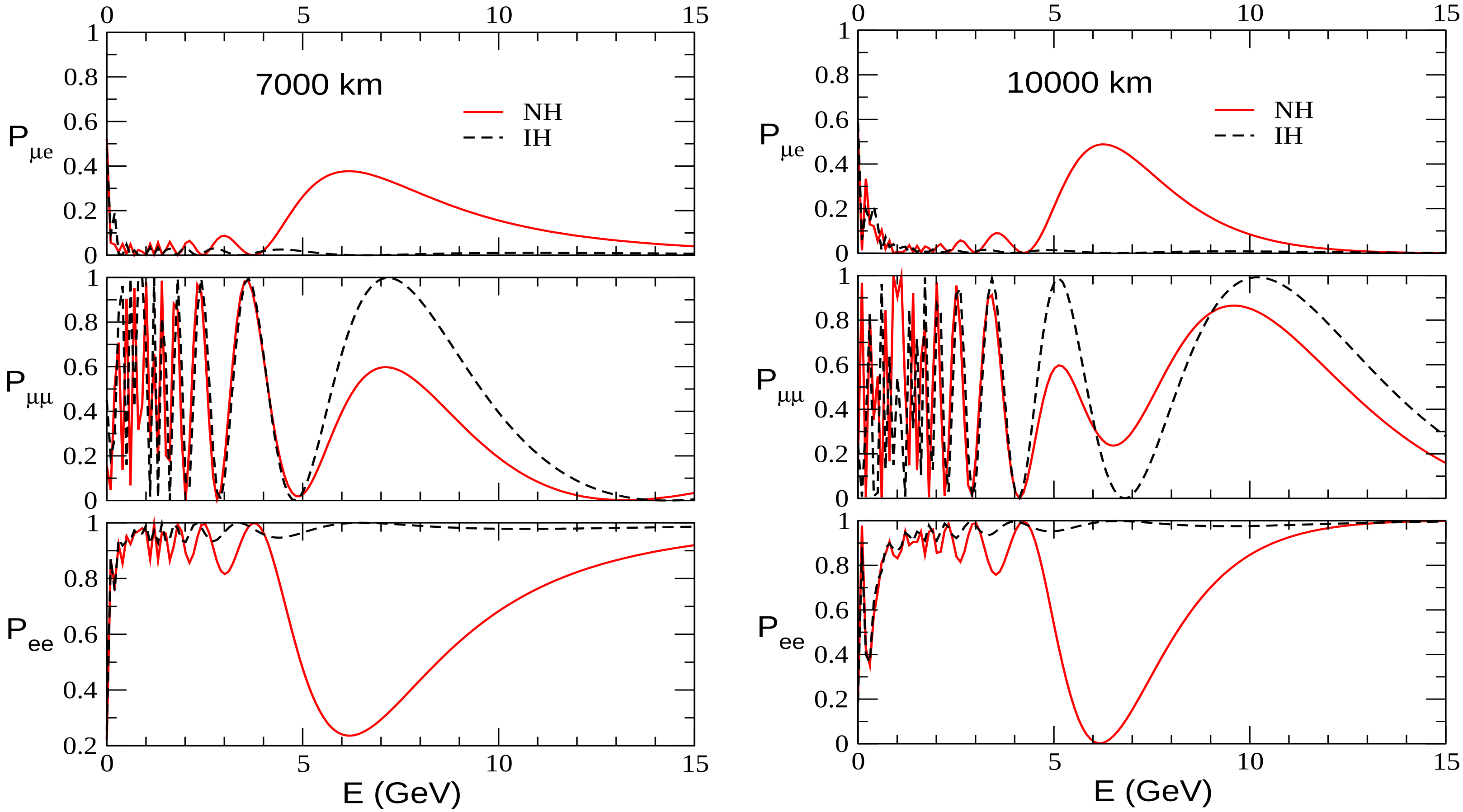
Mass Hierarchy Sensitivity

- Crux of the matter : Matter Effect

$$\tan 2\theta_{13}{}^m = \frac{\Delta m^2_{31} \sin 2\theta_{13}}{\Delta m^2_{31} \cos 2\theta_{13} \pm 2\sqrt{2} G_F n_e E}$$

- For $\Delta m^2_{\rm atm} > 0$ matter resonance in neutrinos
- For $\Delta m^2_{\rm atm} < 0$ matter resonance in anti neutrinos
- Experiments sensitive to matter effects can probe the mass hierarchy
- Matter effects for $\Delta m^2_{\rm atm}$ channel depend crucially on θ_{13}
- Thus both parameters get related
- Large measured $\theta_{13} \Longrightarrow$ good news
- Detectors with charge id that can discriminate between neutrinos and antineutrinos can be crucial

Matter effect at large baselines



- Large matter effects at long baselines in both μ and e events $\Longrightarrow$ Hierarchy Sensitvity
- ν_μ survival probability can rise or fall in matter
- Energy and angular smearing important

Atmospheric Neutrinos at INO

- Sensitive only to Muons
- Differential Number of Muons

$$\frac{d^2N_\mu}{d\Omega_m dE_m} = \frac{1}{2\pi}\int_1^{100} dE_t \int d\Omega_t R(E_t, E_m) R(\Omega_t, \Omega_m)[\Phi_\mu^d P_{\mu\mu} + \Phi_e^d P_{e\mu}]\sigma\epsilon$$

- Energy and Angular Smearing Functions

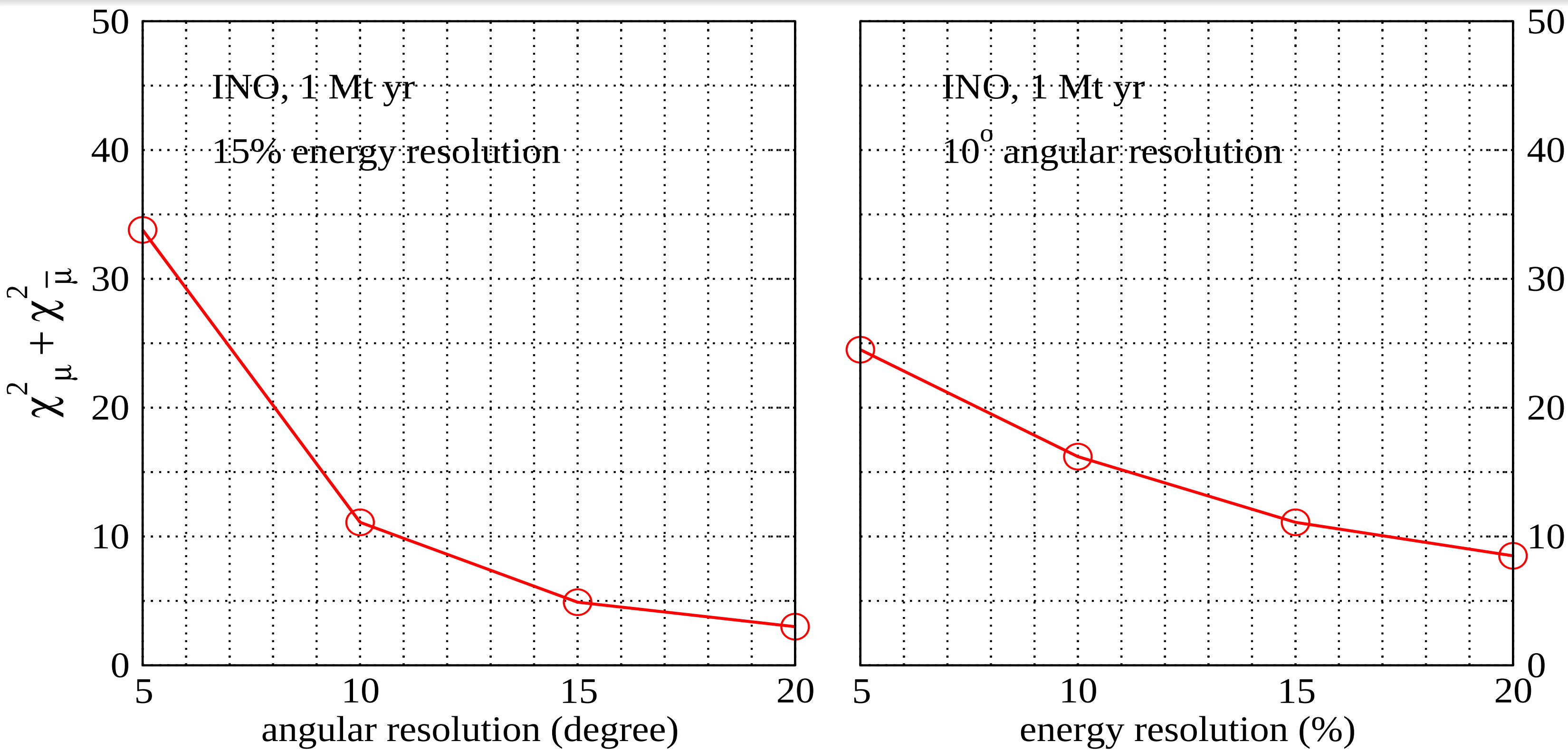
$$R(\Omega_t, \Omega_m) = N \exp\left[-\frac{(\theta_t - \theta_m)^2 + \sin^2\theta_t(\phi_t - \phi_m)^2}{2(\Delta\theta)^2}\right].$$

$$R(E_m, E_t) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(E_m - E_t)^2}{2\sigma^2}\right].$$

- Simplest Approach

  Use fixed widths for energy and angular smearing

Effect of Smearing on muon χ^2



- With increased energy or angular smearing the χ^2 for muon like events decrease.
- Effect of energy smearing is more

R. Gandhi, P. Ghoshal, S.G., P. Mehta, S. Shalgar, S. Umashankar, PRD, 2007

Also, T. Schwetz and S.T. Petcov, Nucl. Phys. B, 2006

Hierarchy Sensitivity at INO

- Events generated from NUANCE (50 kT, 10 yr exposure)
- Two sets of energy/angular resolutions:'high' $(10\%, 10^o)$ and 'low' $(15\%, 15^o)$
- Energy threshold 2 GeV, charge ID 100%, constant reconstruction efficiency 85%
- True normal hierarchy, $(\theta_{23})_{tr} = 45^o$, $\delta_{CP} = 0$, $(\sin^2 2\theta_{13})_{tr} = 0.1$, $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2, $\Delta m^2_{21} = 7.8 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.31$

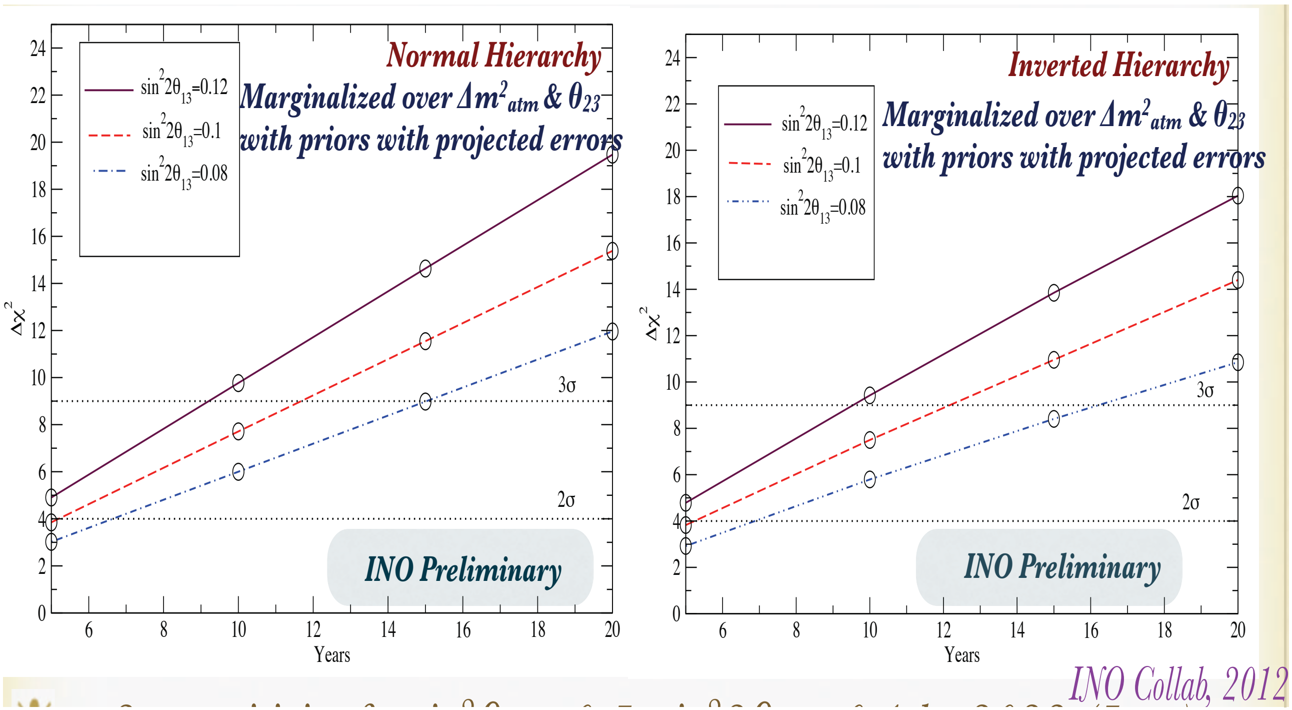
Res set	$\chi^2_{marg,no-pri}$	$\chi^2_{marg,pri}$	χ^2_{fp}
Low	1.5	3.1	4.5
High	5.4	8.2	9.7

- Using Projected priors: $\Delta m^2_{31} = 2\%$, $\sin^2\theta_{23} = 0.006$ and fixed θ_{13}
- $> 2\sigma$ to $\sim 3\sigma$ sensitivity to mass Hierarchy in 10 years

See also Blenow and Schwetz, 2010

Hierarchy Sensitivity from INO simulation

- Using 50 Kton detector and events generated from NUANCE
- Using ICAL resolutions in Muon energy and Zenith Angle
- Using efficiency and Charge-ID from ICAL simulations



True Values:

$\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.5$

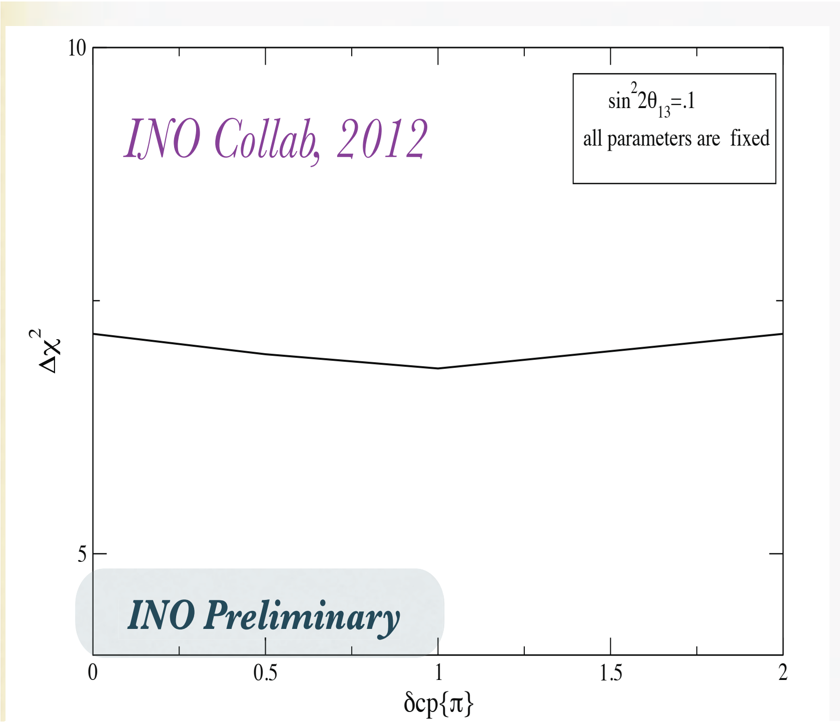
$\Delta m^2_{21} = 7.8 \times 10^{-5}$ eV^2

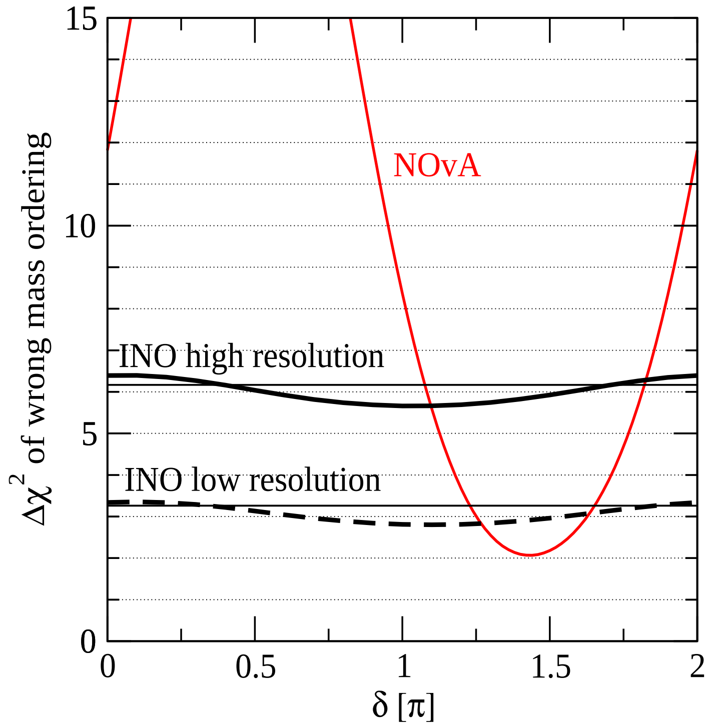
$\sin^2\theta_{12} = 0.31$

$\delta_{CP} = 0$

- For $\sin^2 2\theta_{13} = 0.1$ $\chi^2_{proj-pri} = 6.97 \sim$ 2.7 σ sensitivity in 10 years
  (*Using Projected priors:* $\Delta m^2_{31} = 2\%$, $\sin^2\theta_{23} = 0.006$ *and fixed* θ_{13})

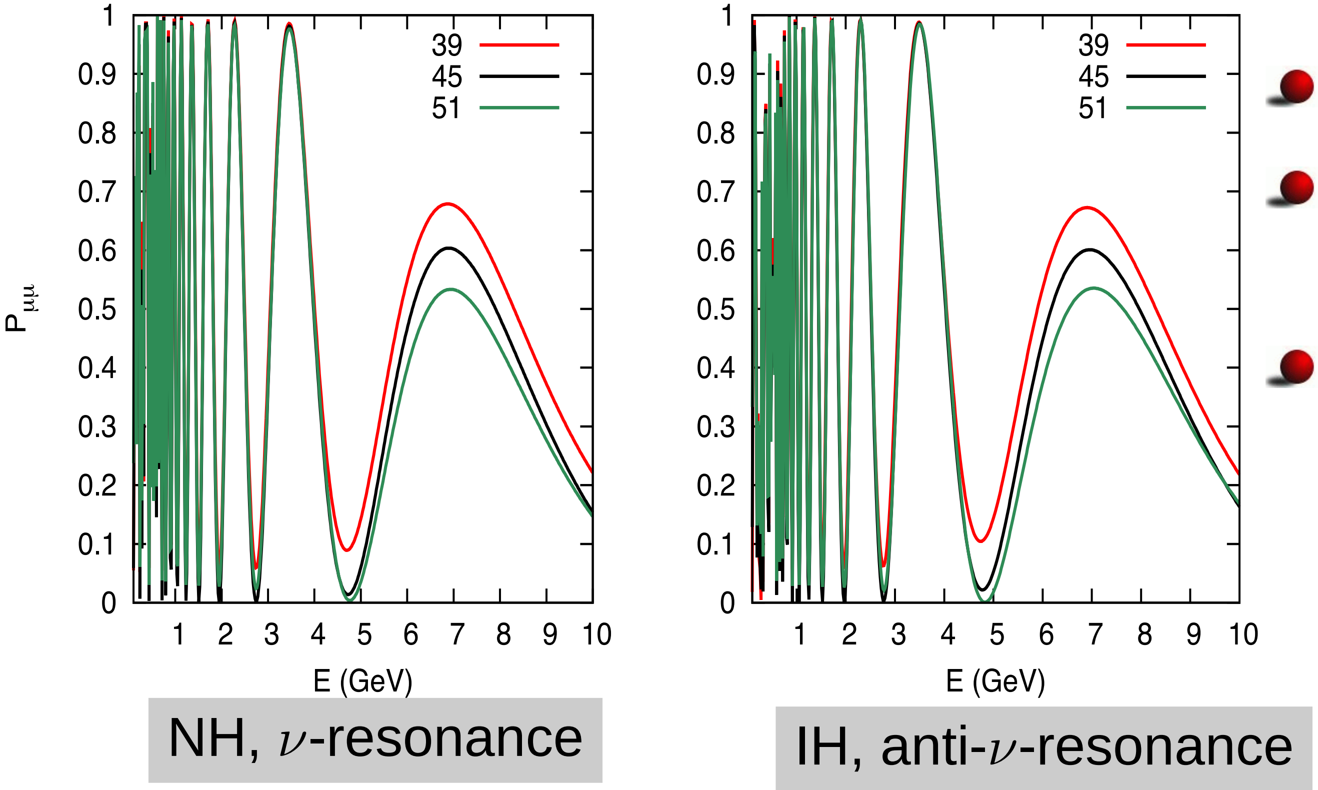
Effect of δ_{CP} on hierarchy sensitivity





- Data simulated for NH and $\delta_{CP} = 0$ and fitted for IH with varying δ_{CP}
- MH sensitivity with atmospheric neutrinos almost independent of δ_{CP}
- Complementarity with LBL experiments

Octant sensitivity in $P_{\mu\mu}$



- $D \equiv 1/2 - \sin^2\theta_{23}$
- |D| gives the deviation of $\sin^2\theta_{23}$
- sgn(D) gives the octant of $\sin^2\theta_{23}$

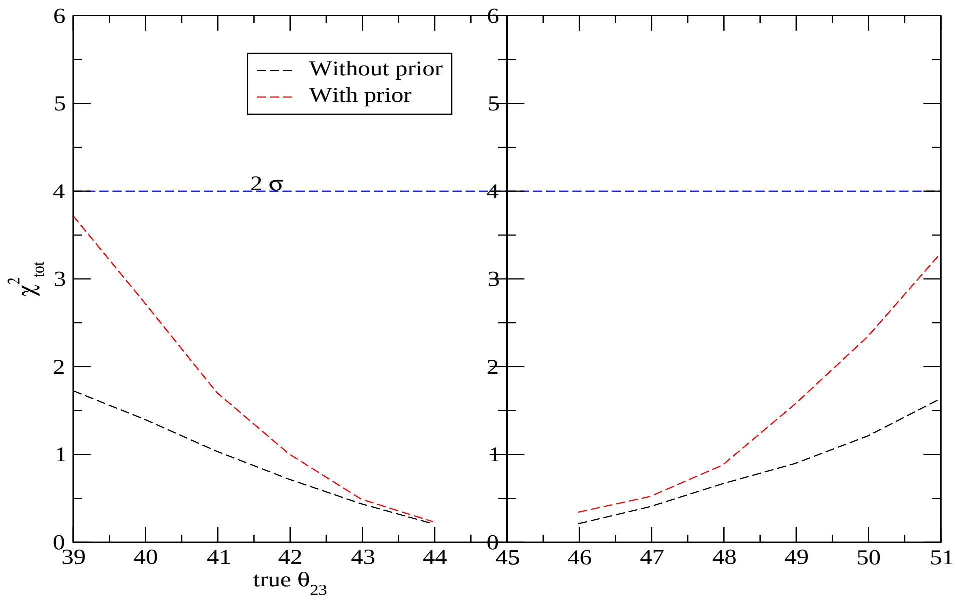
- $$\mathrm{P}^{\mathrm{m}}_{\mu\mu} \sim \sin^4\theta_{23}\sin^2 2\theta^{\mathrm{m}}_{13}\sin^2(1.27\Delta^{\mathrm{m}}_{31}\mathrm{L/E})$$
- Octant sensitvity from the $\sin^4\theta_{23}$ term

S.Choubey. and P. Roy hep-ph/0509197

Indumathi,Murthy, Rajasekaran,Sinha hep-ph/0603264

Octant Sensitivity at INO

- Events generated from NUANCE (50 kT, 10 yr exposure)
- Results for 'high' $(10\%, 10^o)$ resolutions
- Energy threshold 2 GeV, charge ID 100%, reconstruction efficiency 85%



True Parameters

Normal Hierarchy

$(\theta_{23})_{tr} = 45^o$,

$\delta_{CP} = 0$,

$(\sin^2 2\theta_{13})_{tr} = 0.1$,

$\Delta m^2_{21} = 7.8 \times 10^{-5}$ eV^2

$\sin^2\theta_{12} = 0.31$

- $< 2\sigma$ sensitvity for $|\theta_{23} - \pi/4| > 5^\circ$
- Analysis using INO simulation code in progress

Magentized Liquid-Ar TPC

- 50-100 Kton Magnetized LiqAr detector –
- Energy threshold 1 GeV
- Sensitive to both muons and electrons
- 100% CID for muons and 20% for electrons in the energy range 1-5 GeV
- $\sigma_{E_e} = \sigma_{E_\mu}$ = 0.01; $\sigma_{E_{had}}$ = $\sqrt{(0.15)^2/E_{had} + (0.03)^2}$
- σ_{E_ν} = $\sqrt{(\sigma_{E_l})^2 + (0.15)^2/(yE_\nu) + (0.03)^2}$;
  $y \rightarrow$ average rapidity = 0.45
- σ_{θ_e} = $1.72°$; σ_{θ_μ} = $\sigma_{\theta_{had}}$ = $2.29°$; $\sigma_{\theta_{\nu e}}$ = $2.8°$; $\sigma_{\theta_{\nu\mu}}$ = $3.2°$

Barger,Gandhi,Ghosal,Goswami,Marfatia,Prakash,Raut,Umashankar, Phys. Rev.Lett., 2012

Hierarchy and Octant with electron events

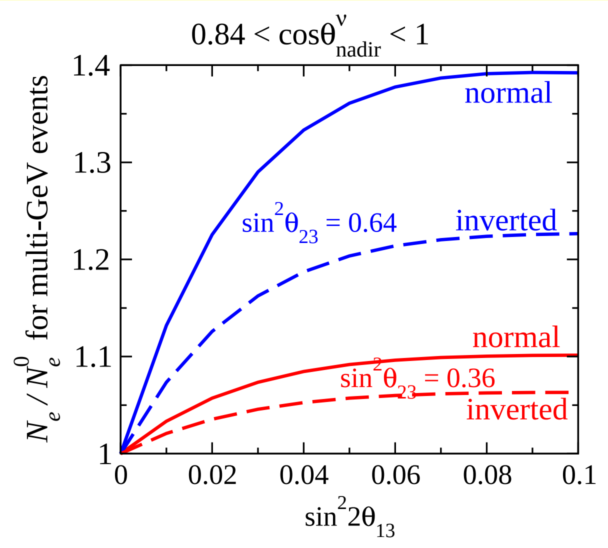
excess of electron-like events:

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \qquad \theta_{13}\text{-effects}$$

$$+ \ (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \qquad \Delta m_{21}^2\text{-effects}$$

$$- \ 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A_{ee}^* A_{\mu e}) \qquad \text{interference: } \delta_{\mathrm{CP}}$$

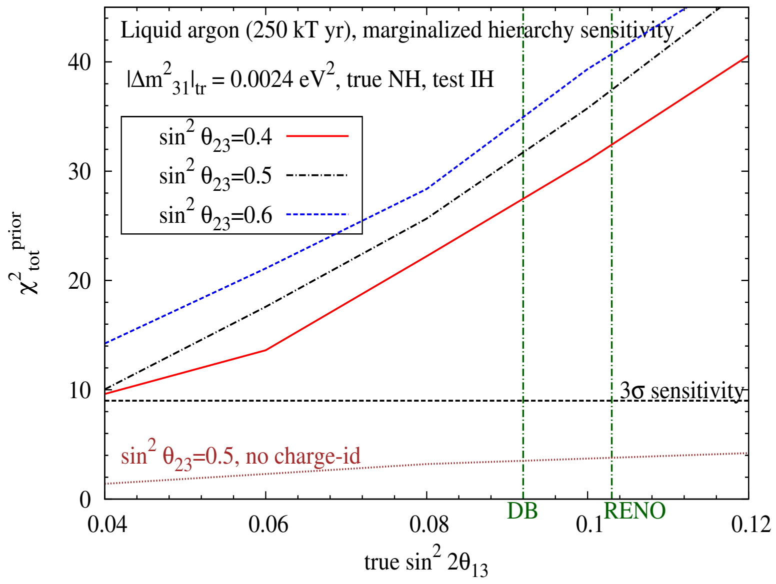
$$r = \frac{F_\mu^0}{F_e^0} \rightarrow \text{the flux ratio}$$

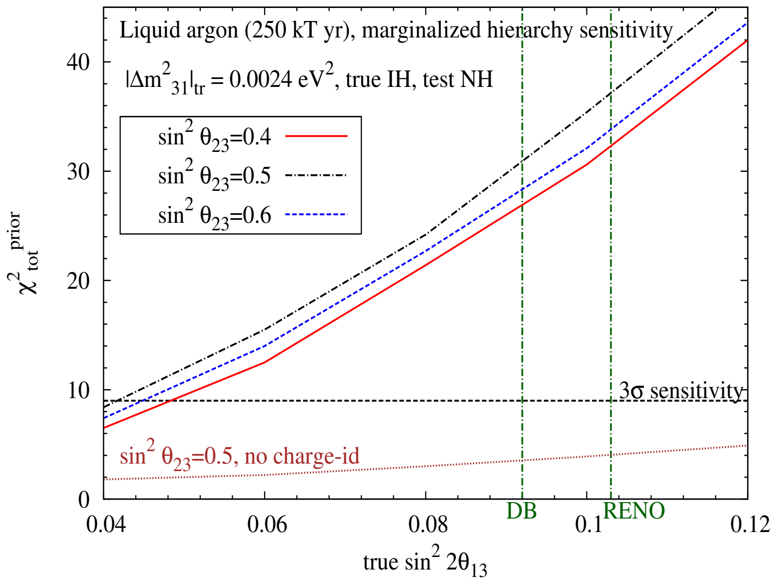


Bernabeu, Palomares-Ruiz, Petcov, hep-ph/0305152

- Resonant matter effect in $P_{2\nu}(\Delta m_{31}^2, \theta_{13})$ for multi-GeV neutrinos .
- NH – neutrinos   IH - antineutrinos
- All three terms important for sub-GeV neutrinos
- Sensitivity to both Hierarchy and Octant

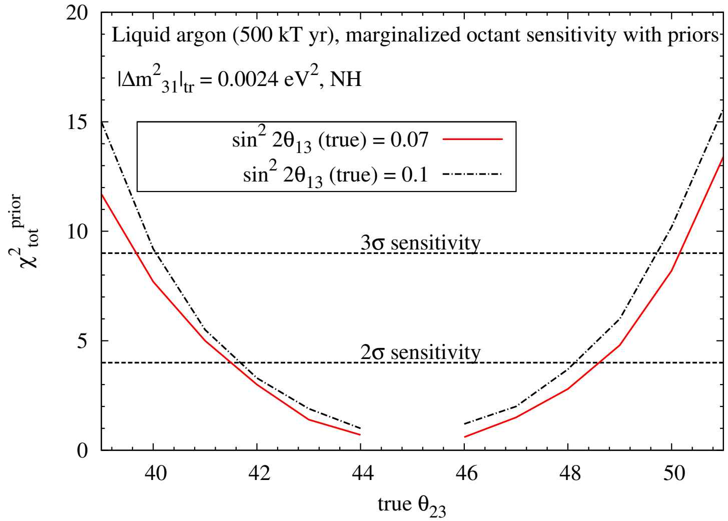
Hierarchy Sensitivity using LiqAr TPC

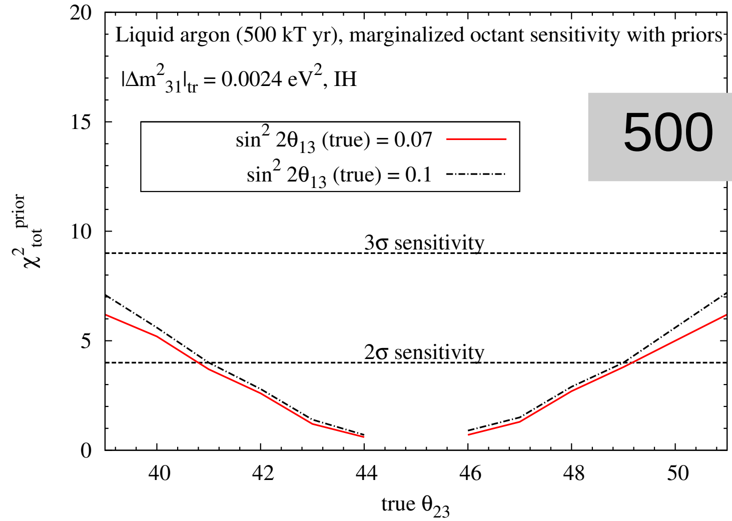




- $\chi^2 = \chi^2_\mu + \chi^2_{\bar\mu} + (\chi^2_e + \chi^2_{\bar e})_{1-5GeV} + (\chi^2_{e+\bar e})_{5-10GeV} + \chi^2_{prior}$
- True values of undisplayed Parameters: $(|\Delta m^2_{31}|) = 2.4 \times 10^{-3}$ eV^2, $(\delta_{CP}) = 0$, $\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2, $\theta_{12} = 34^\circ$
- Marginalized over all parameters
- $> 5\sigma$ sensitivity for $\sin^2 2\theta_{13} = 0.1$ and $\sin^2\theta_{23} = 0.5$
- Drastic drop in sensitivity if no CID is assumed.

Octant Sensitivity using LiqAr TPC





500 Ktyr exposure

- NH : 2σ discrimination for $|\theta_{23} - \pi/4| > 3.5°$ ($\sin^2 2\theta_{23} < 0.985$).
  3σ Discrimination for $|\theta_{23} - \pi/4| > 5°$
- IH : 2σ Discrimination for $|\theta_{23} - \pi/4| > 4°$ ($\sin^2 2\theta_{23} < 0.985$).

NH

θ_{23}	χ^2_{cid}	χ^2_{no-cid}
39°	15	12.5
42°	3.3	2.8

- Not having CID does not affect the results so drastically.

IH

θ_{23}	χ^2_{cid}	χ^2_{no-cid}
39°	7.1	5.1
43°	2.8	1.2

Conclusion

- In view of large θ_{13} determination of of mass hierarchy and octant using matter effect in atmospheric neutrinos look very promising
- INO a strong contender because of the possibility of magnetization and charge identification
- $\sim 3\sigma$ sensitvity to mass hierarchy in 10 years for 50 kton detector
- Hierarchy sensitivity from atmospheric neutrinos independent of δ_{CP}
- Complimentary information to Long Baseline Experiments..
- INO R&D going on full swing
- Liquid Argon detectors with charge-id provides excellent hierarchy sensitivity $> 5\sigma$ for 250 ktyrs
- Non-Magnetized LArTPC would necessarily need larger volume/exposure
- Other possibilities ..CPT violation, Sterile Neutrinos,NSI, ...

Acknowledgements

- INO collaboration

Ahmadabad: *Physical Research Lab.*
Aligarh: *Aligarh Muslim University*
Allahabad: *HRI*
Calicut : *University of Calicut*
Chandigarh: *Panjab University*
Chennai : *IIT, Madras IMSc*
Delhi : *University of Delhi*
Guwahati : *IIT, Guwahati*
Hawaii (USA) : *University of Hawaii*
Indore: *IIT, Indore*
Jammu : *University of Jammu*
Kalpakkam : *IGCAR*
Kolkata : *Ramakrishna Mission Vivekananda University, SINP, VECC , University of Calcutta*
Lucknow : *Lucknow University*
Madurai : *American College*
Mumbai : *BARC*
Mumbai : *IIT, Bombay TIFR*
Mysore : *University of Mysore*
Sambalpur : *Sambalpur University;*
Srinagar : *University of Kashmir*
Varanasi : *Banaras Hindu University*

Special Thanks : Animesh Chatterjee, Sandhya Choubey,Anushree Ghosh, Pomita Ghoshal, Sushant Raut, Nita Sinha, Tarak Thakore

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						

N. Mondal, LP2011

Background

- A preliminary study using a GEANT based simulation of cosmic ray muon background in INO shows that these are unlikely to mimic the signal

Indumathi and Murthy, hep-ph/0407336

- NC background: the 6 cm thickness of the iron plates is sufficient to absorb any pions and kaons in the $1-10$ GeV range before they can decay.
- Oscillated ν_τ induced muons softer in energy and can be eliminated by suitable energy cuts

Agarwalla, Raychaudhuri, Samanta, hep-ph/0505015