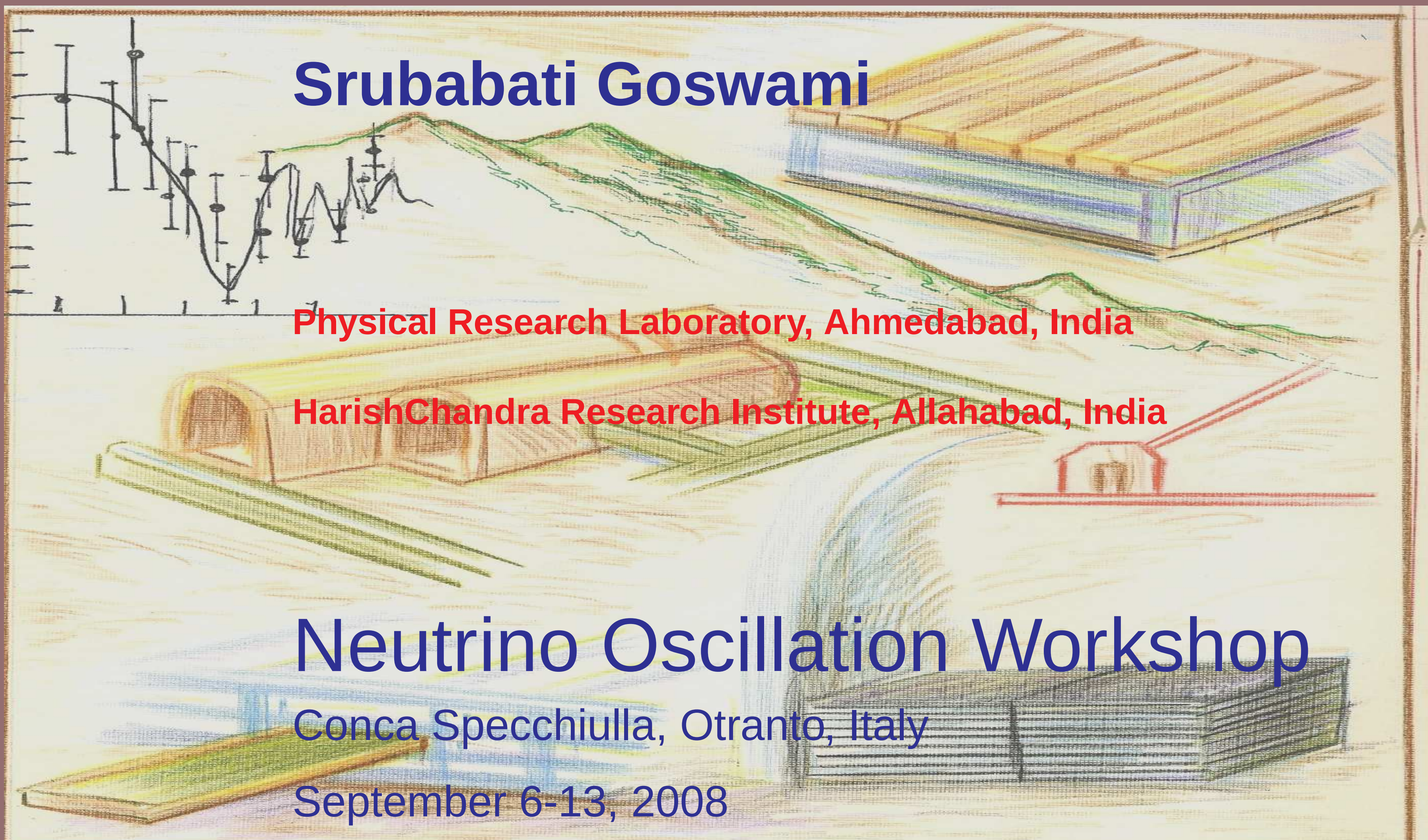
INO/2005/01
Interim Project Report
Volume I

Physics Program of
INDIA-BASED NEUTRINO OBSERVATORY



Srubabati Goswami

Physical Research Laboratory, Ahmedabad, India

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Neutrino Oscillation Workshop

Conca Specchiulla, Otranto, Italy

September 6-13, 2008

I N O

India Based Neutrino Observatory Proposal

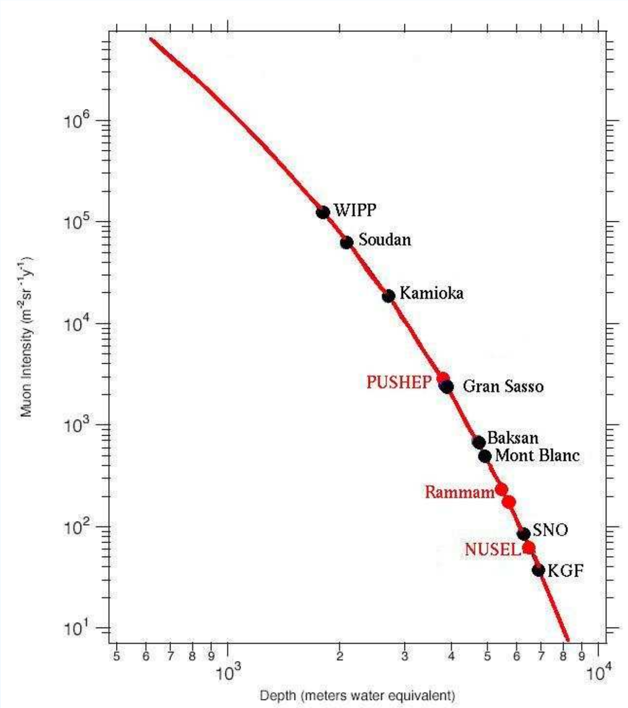
- Goal : To build an underground laboratory for science with neutrino physics as major activity
- The Detector: A large mass detector with charge identification capability. The collaboration zeroed on magnetized Iron CALorimeter detector (ICAL)
- Detector choice based on
  - Technological capabilities available in the country
  - Existing/Planned other neutrino detectors in the world
  - Modularity and the possibility of phasing
  - Compactness and ease of construction

R & D Activities

- Phase-I
  - Physics Studies
  - Detector R & D
  - Site Finalisation and Clearences
  - Human Resource Development
  - Construction of the underground lab and ICAL detector
- Phase-II
  - Physics with Atmospheric Neutrinos
- Phase-III
  - Physics with Beams

Site

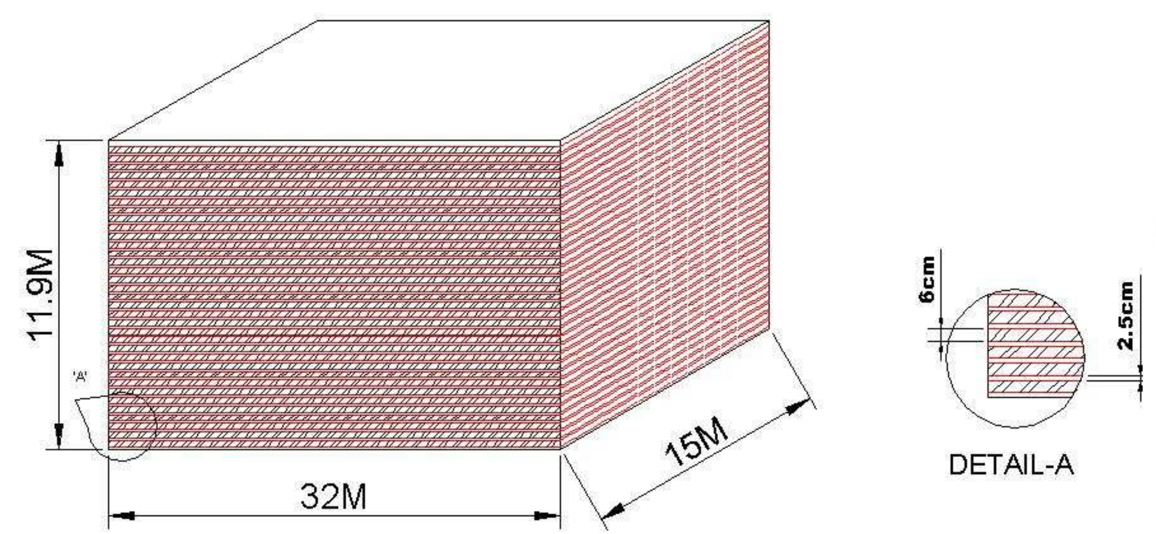
- PUSHEP at South India has been recommended as the preferred site for the underground lab

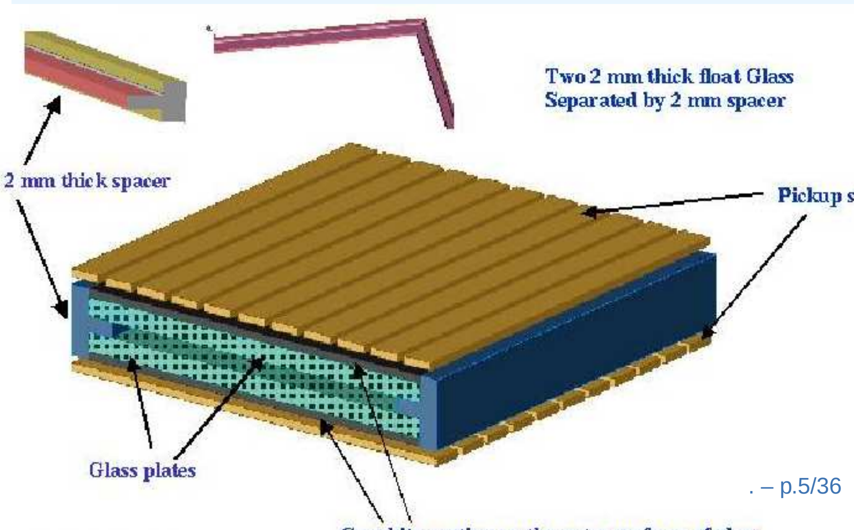


The detector

- Magnetised iron calorimeter
- Modular structure - 3 modules
- Module dimension 16m $\times$ 16m $\times$ 12m
- Detector: 48 m $\times$ 16m $\times$ 12m
- 140 horizontal iron layers interspersed with Glass RPC
- Iron Plate thickness 6 cm
- Gap for RPC trays 2.5 cm

- Sensitive to muons
- Energy determination from
  - Track length
  - Track curvature in a magnetic field
- Direction of parent neutrino from the track
- Charge identification from track curvature in magentic field



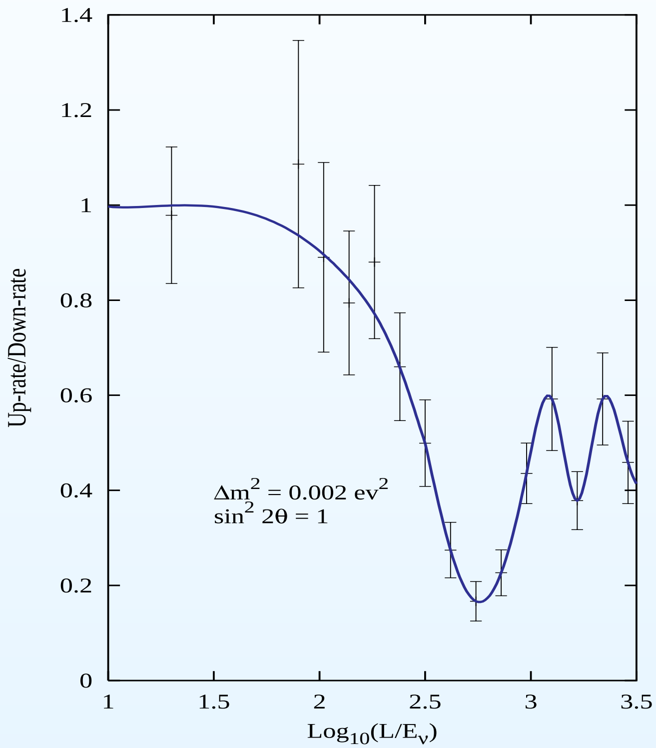


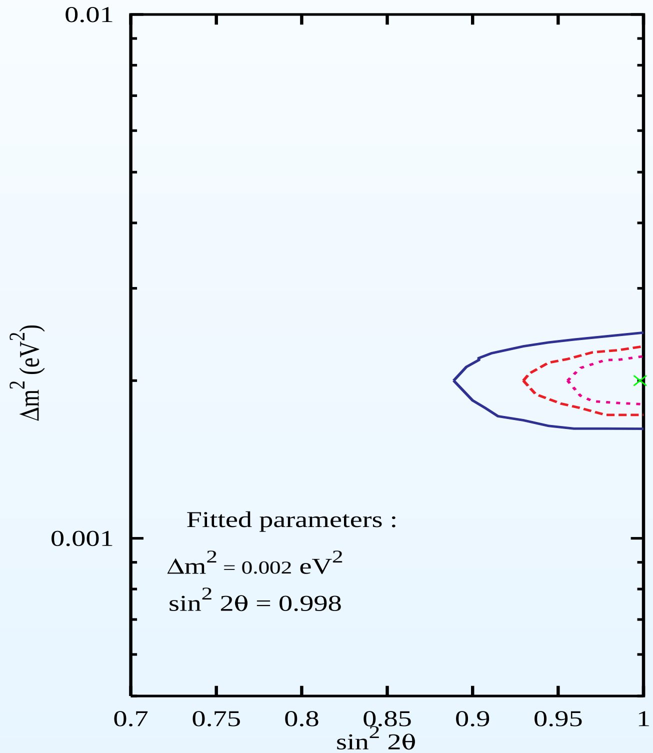
Physics Goals for INO

- First phase – measurement of atmospheric neutrino flux
  - Reconfirmation of the first oscillation dip as a function of L/E
  - Improved precision of oscillation parameters
  - Determination of the octant of θ_{23}
  - Matter effects and determination of sign of Δm^2_{31}
  - Probing CPT violation, Lorentz violation
  - Discrimination between $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_s$
  - Constraining long range leptonic forces
  - 1-100 TeV cosmic muon flux measurement
- Second Phase – end detector for beta beams, neutrino factory
  - hierarchy, θ_{13}, CP violation
- Other possibilities
  - Search for $0\nu 2\beta$ in ^{124}Sn via cryogenic bolometer (feasibility ongoing)

Atmospheric Neutrinos and INO

- Observation of fall and rise of up/down ν_μ events





- Increased precision of Δm^2_{atm}

Comparison with Long Baseline Experiments

- 3σ spread ($|\Delta m^2{}_{31}|$ = 2×10^{-3} eV^2, $\sin^2\theta_{23} = 0.5$).

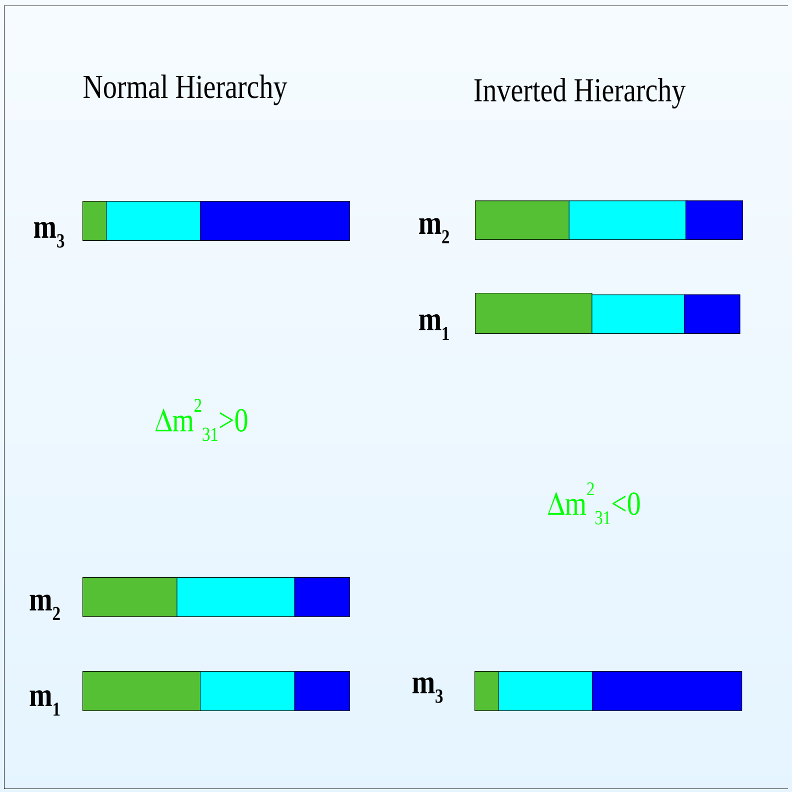
	$\vert\Delta m^2{}_{31}\vert$	$\sin^2\theta_{23}$
current	29%	33%
MINOS+CNGS	13%	39%
T2K	6%	23%
Nova	13%	43%
INO, 50 kton, 5 years	10%	30%

M. Lindner, hep-ph/0503101

Table refers to the older NOνA proposal; the revised March 2005 NOνA proposal is expected to be competitive with T2K.

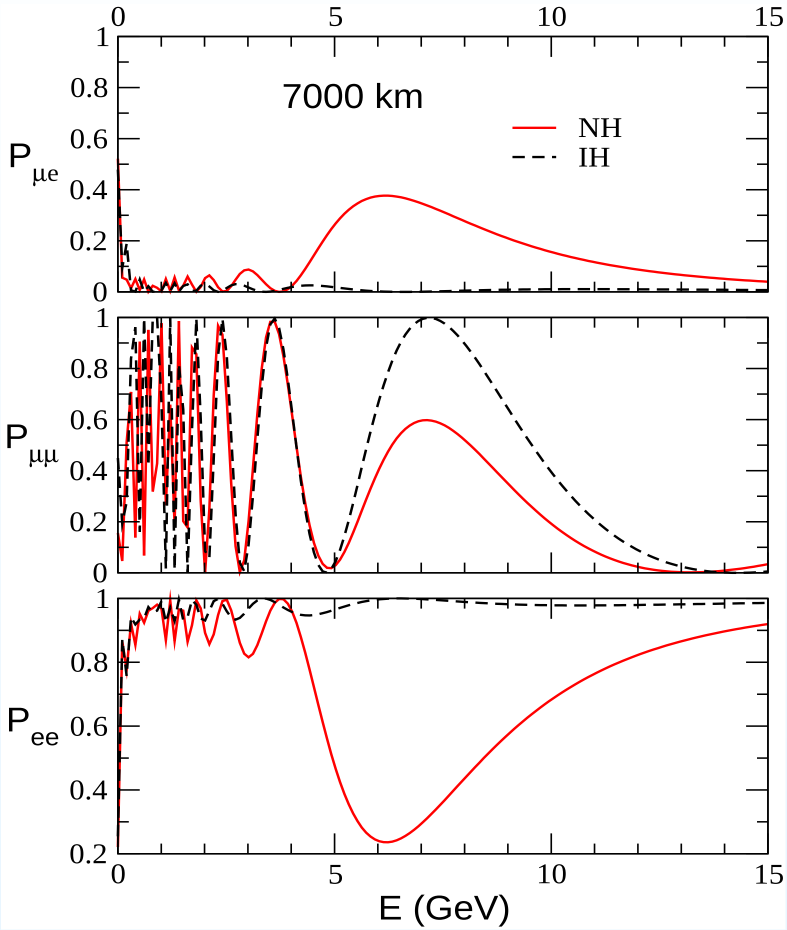
Ambiguity in Mass Hierarchy

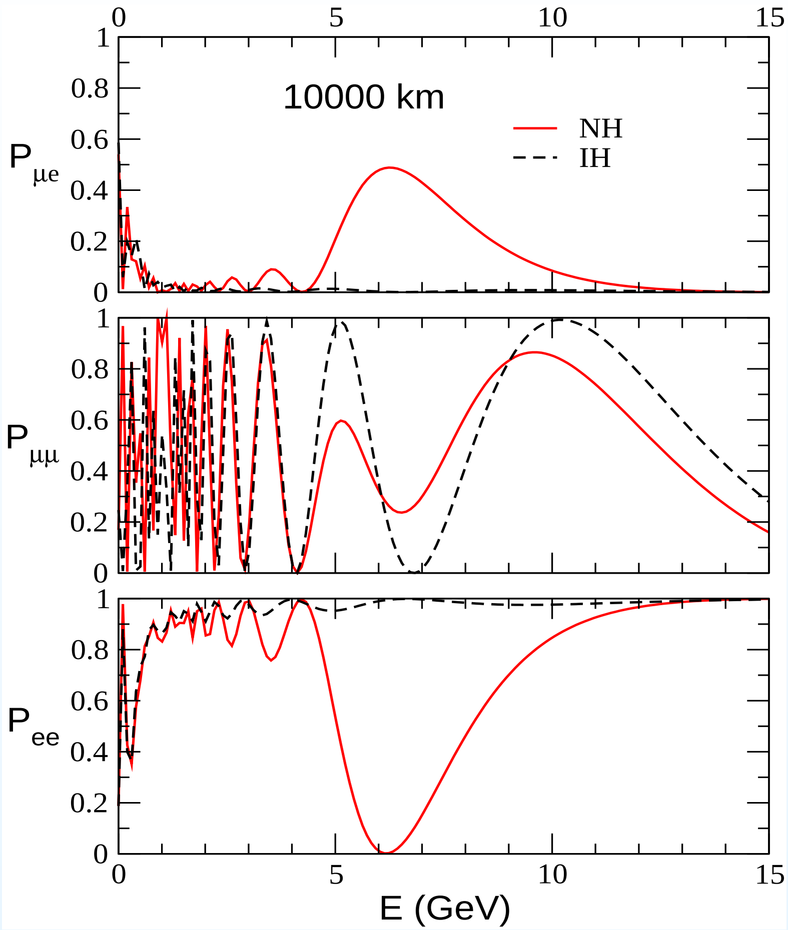
- $$\tan 2\theta_{13}{}^{m} = \frac{\Delta m^2_{31} \sin 2\theta_{13}}{\Delta m^2_{31} \cos 2\theta_{13} \pm 2\sqrt{2} G_F n_e E}$$



- 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

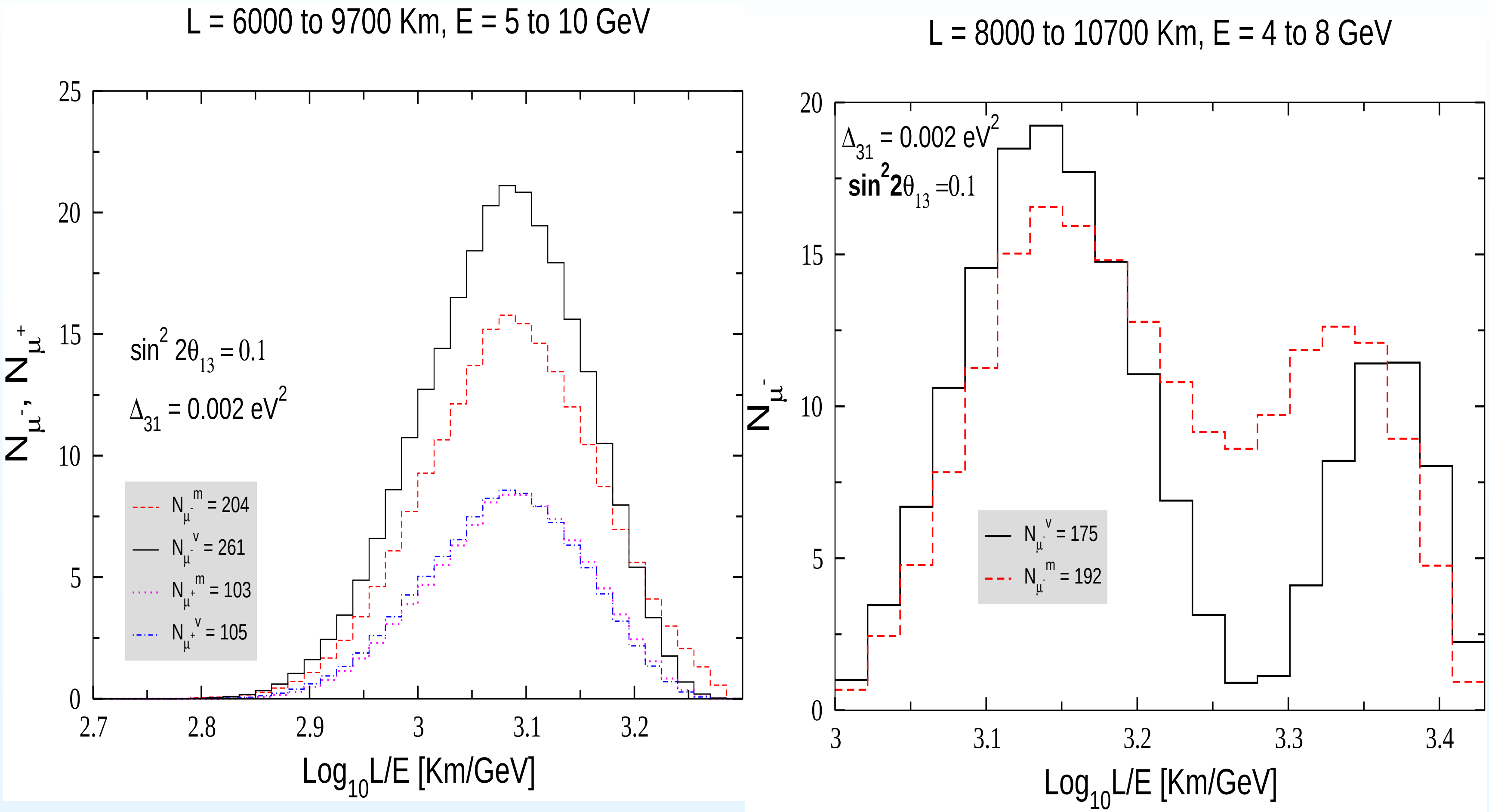
Matter effect at large baselines





- Large matter effects at long baselines
- For $\Delta m^2_{\rm atm} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} = 0.1$ and the PREM profile $\rho_{av} = 4.13$ gm/cc, $E_{res} \simeq 7.5$ GeV
- ν_μ survival probability can rise or fall in matter

Hierarchy Sensitivity in Atmospheric ν events



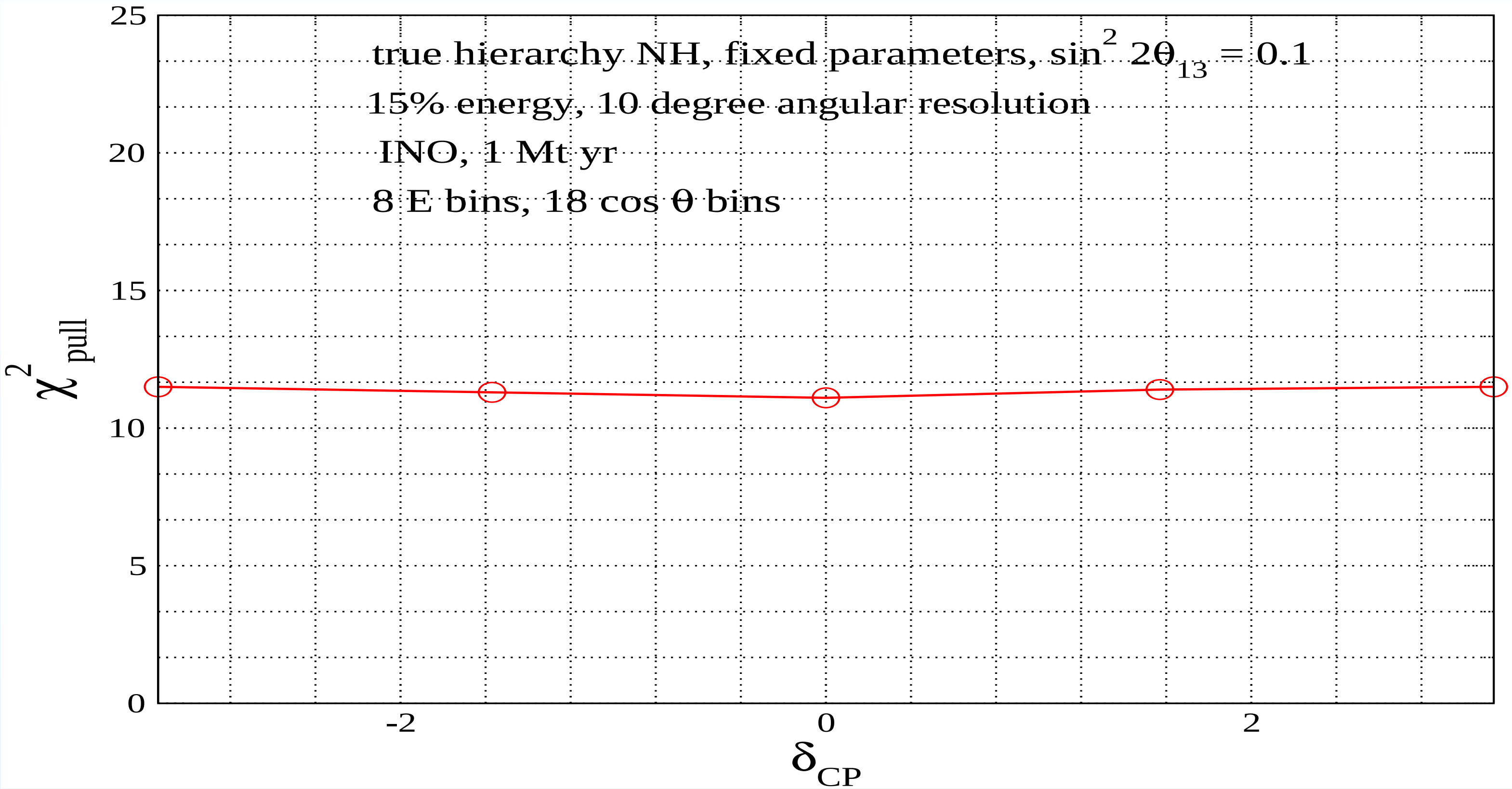
- For $\Delta m^2_{31} > 0$ matter effect in ν_μ and $(\mathrm{N}^{\mathrm{mat}}_{\mu-} \neq \mathrm{N}^{\mathrm{vac}}_{\mu-})$
- $(\mathrm{N}^{\mathrm{mat}}_{\mu+} \approx \mathrm{N}^{\mathrm{vac}}_{\mu+})$

R. Gandhi, P. Ghoshal, S.G., P. Mehta, S. Umashanakr, PRD, 2005

Analysis of Hierarchy Sensitivity in INO

- Exposure: 100 Kt $\times$ 10 yr $=$ 1000 Kt yr
- Muon event number: $(\phi_\mu \times P_{\mu\mu} + \phi_e \times P_{e\mu}) \times \sigma_{CC} \times \epsilon$
- Detection efficiency: 87%
- Charge i.d. of muons 100%
- 3-dimensional Honda fluxes
- Range studied for matter effects: E $=$ 2 to 10 GeV, $\cos\theta_z =$ -0.1 to -1.0
- Muon threshold: 1 GeV
- Detector resolution of $10^o, 15\%$
- Energy and $\cos\theta_z$ range divided into 8 $\times$ 18 = 144 bins
- Oscillation parameters uncertainties are taken care of by Marginalizatio

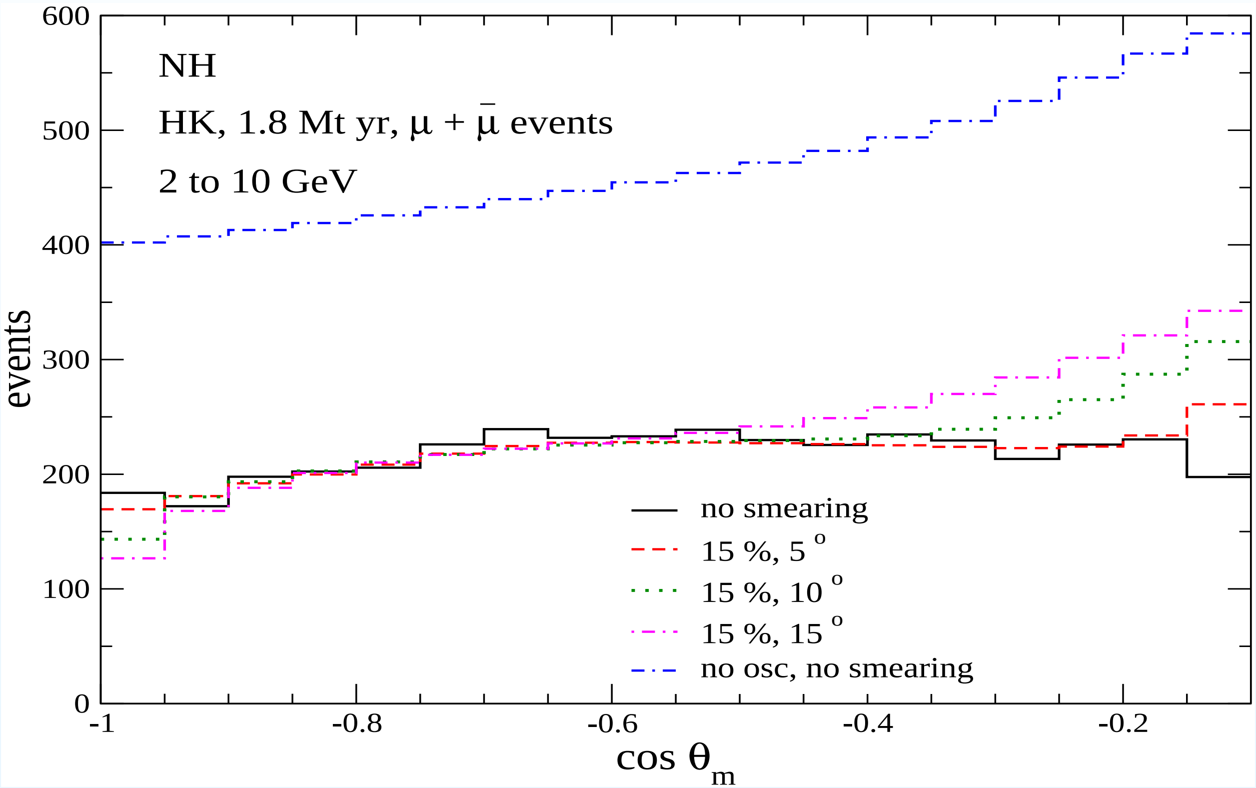
Effect of δ_{CP} on χ^2



- Effect of δ_{CP} on Muon χ^2 insignificant
- Problem of δ_{CP} degeneracy less

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

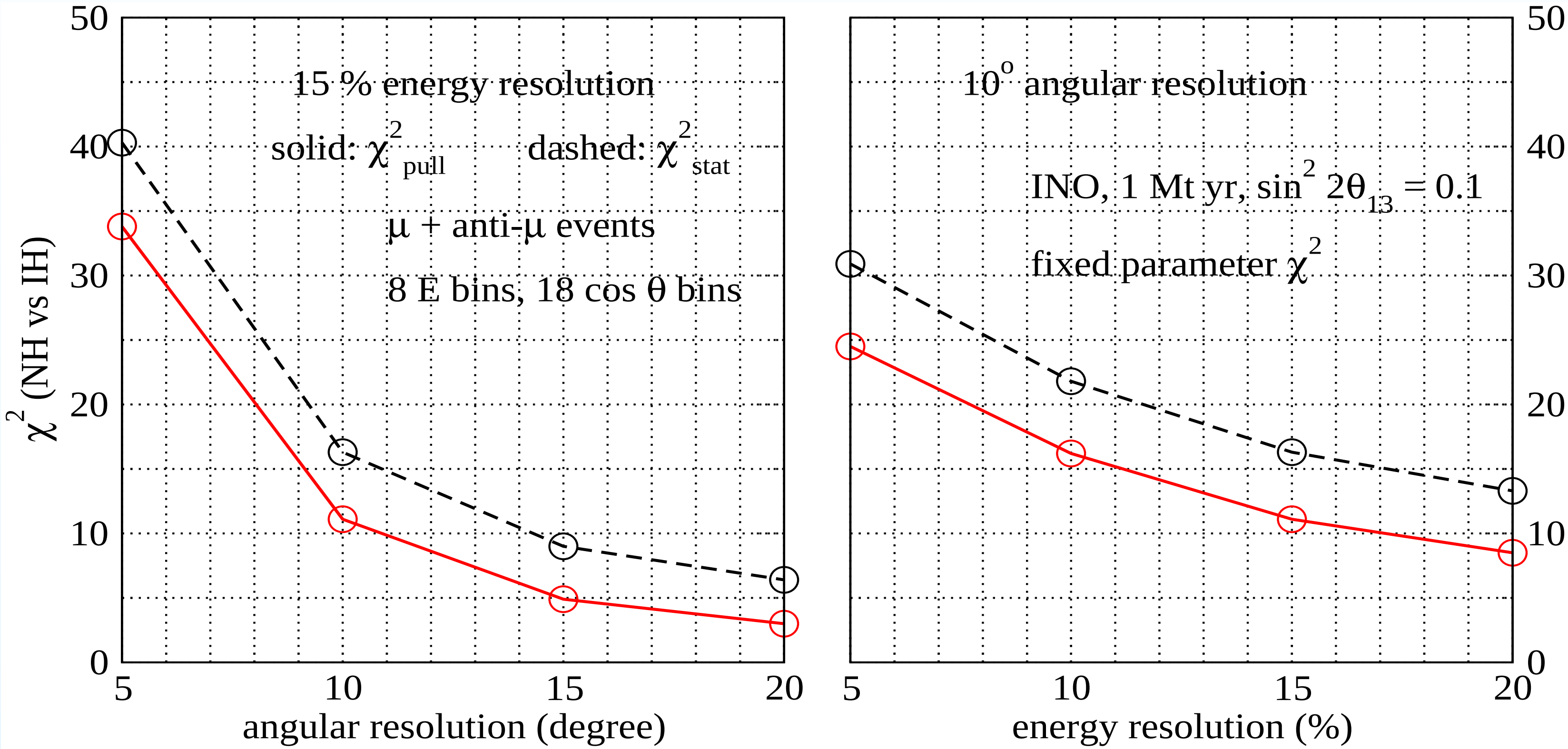
Effect of Smearing on Atmospheric ν Events



- With increased width of smearing the event distribution tends to no oscillation distribution

Effect of Smearing on χ^2

- Effect of smearing on muon-χ^2 in INO

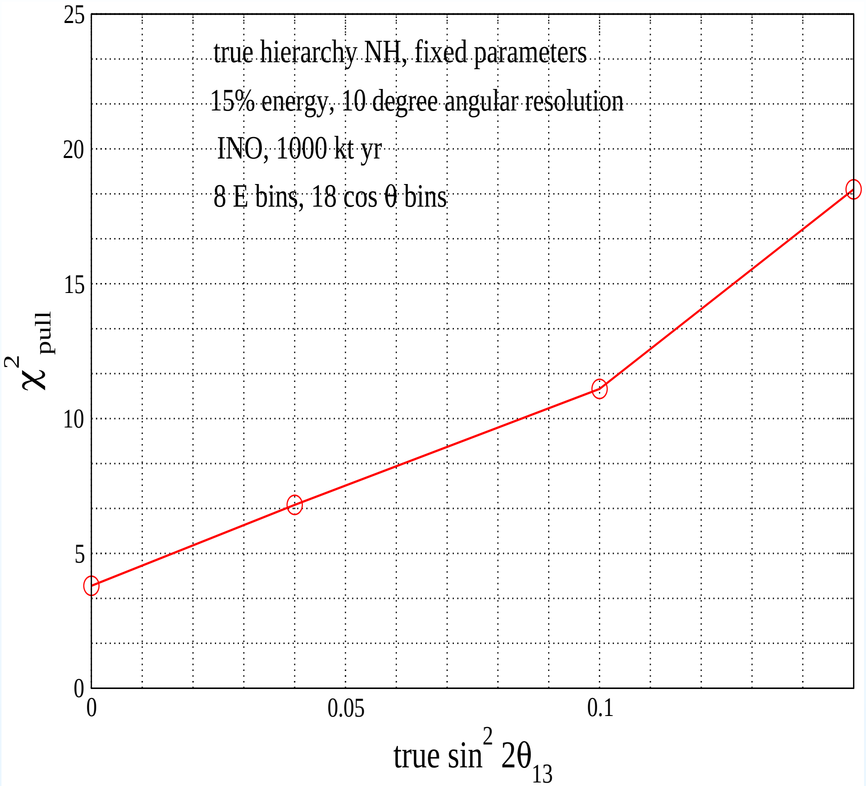


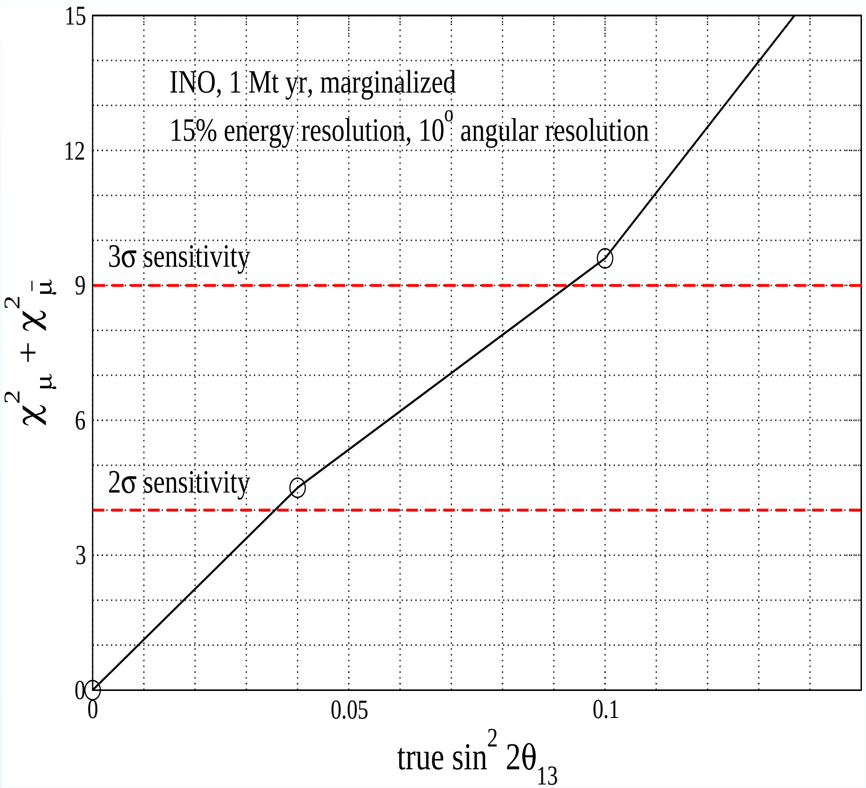
- With increased energy or angular smearing the χ^2 for muon like events decrease.

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

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

Results





- Hierarchy sensitivity reduces with marginalization

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

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

A. Samanta, 2006

D. Indumathi and M.V.N. Murhty, PRD, 2005

Hierarchy Sensitivity: comparative study

- INO: 1 Mtyear (100 kT $\times$ 10 years)
  $\chi^2 = \chi^2_\mu + \chi^2_{\bar{\mu}}$
- HyperKamiokande : 1.8 Mtyear (544 kT $\times$ 3.3 years)
  $\chi^2 = \chi^2_{\mu+\bar{\mu}} + \chi^2_{e+\bar{e}}$
- LiqAr : 1 Mtyear (100 kT $\times$ 10 years)
  $\chi^2 = \chi^2_\mu + \chi^2_{\bar{\mu}} + (\chi^2_e + \chi^2_{\bar{e}})_{1-5GeV} + (\chi^2_{e+\bar{e}})_{5-10GeV}$

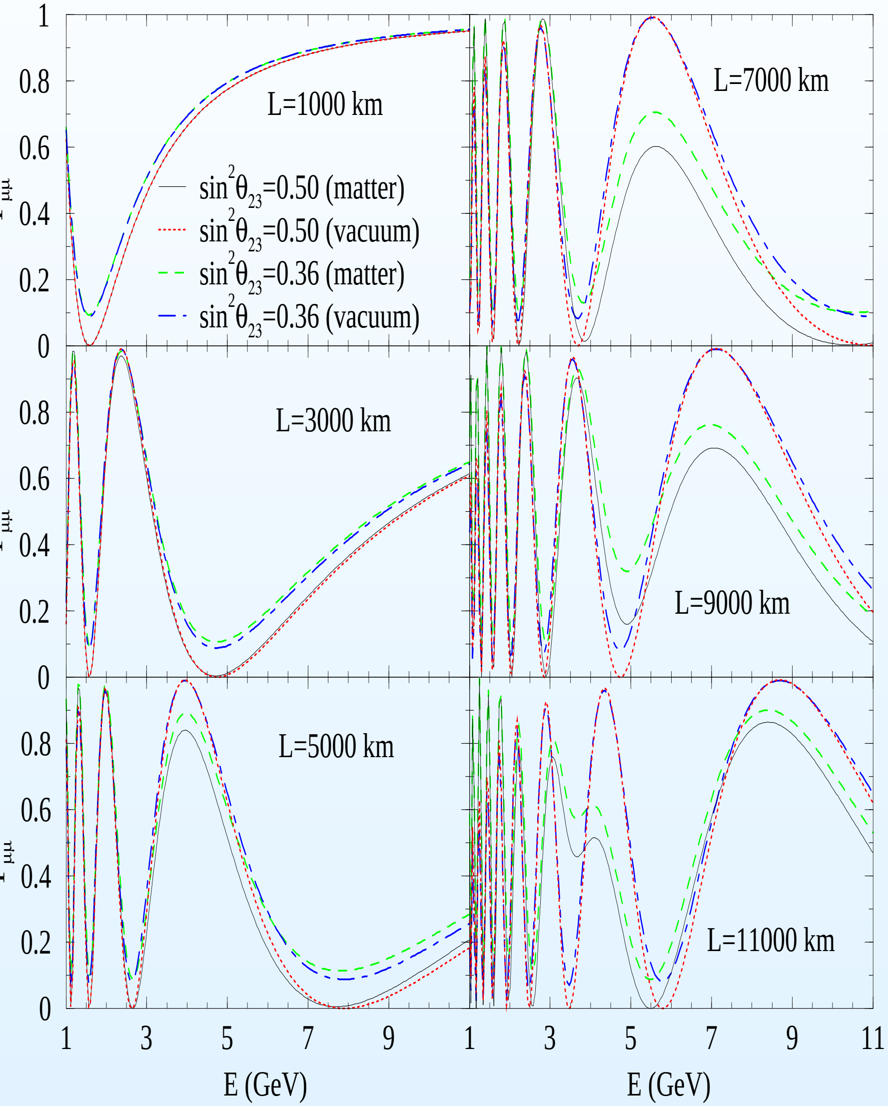
$\sin^2 2\theta_{13}$	$HK\chi^2$	$INO\chi^2$	LiqAr χ^2
0.04	3.6	4.5	13.8
0.1	5.9	9.6	27.5
0.15	7.1	16.9	

- LiqAr type detector has lower energy thresold,better energy smearing and partial charge identification of electrons
  (Gandhi,Ghoshal,Goswami.,Umashankar,arXiv:0807.2759)

Deviation of $\sin^2\theta_{23}$ from maximal value

- $D \equiv 1/2 - \sin^2\theta_{23}$
- |D| gives the deviation of $\sin^2\theta_{23}$
- sgn(D) gives the octant of $\sin^2\theta_{23}$
- Current 3σ limits:
  - $|D| < 0.16$ at 3σ from the SK data
  - No robust information on sgn(D)

Can Earth matter effects determine $|D|$?



$$P^m_{\mu\mu} = 1 - P^{m\ 1}_{\mu\mu} - P^{m\ 2}_{\mu\mu} - P^{m\ 3}_{\mu\mu}$$

$$P^{m\ 1}_{\mu\mu} = {c^2_{13}}^m \sin^2 2\theta_{23} \sin^2 [1.27(\Delta^m_{32})L/2E]$$

$$P^{m\ 2}_{\mu\mu} = {s^2_{13}}^m \sin^2 2\theta_{23} \sin^2 [1.27(\Delta^m_{21})L/2E]$$

$$P^{m\ 3}_{\mu\mu} = \sin^4 \theta_{23} \sin^2 2\theta^m_{13} \sin^2 (1.27\Delta^m_{31} L/E)$$

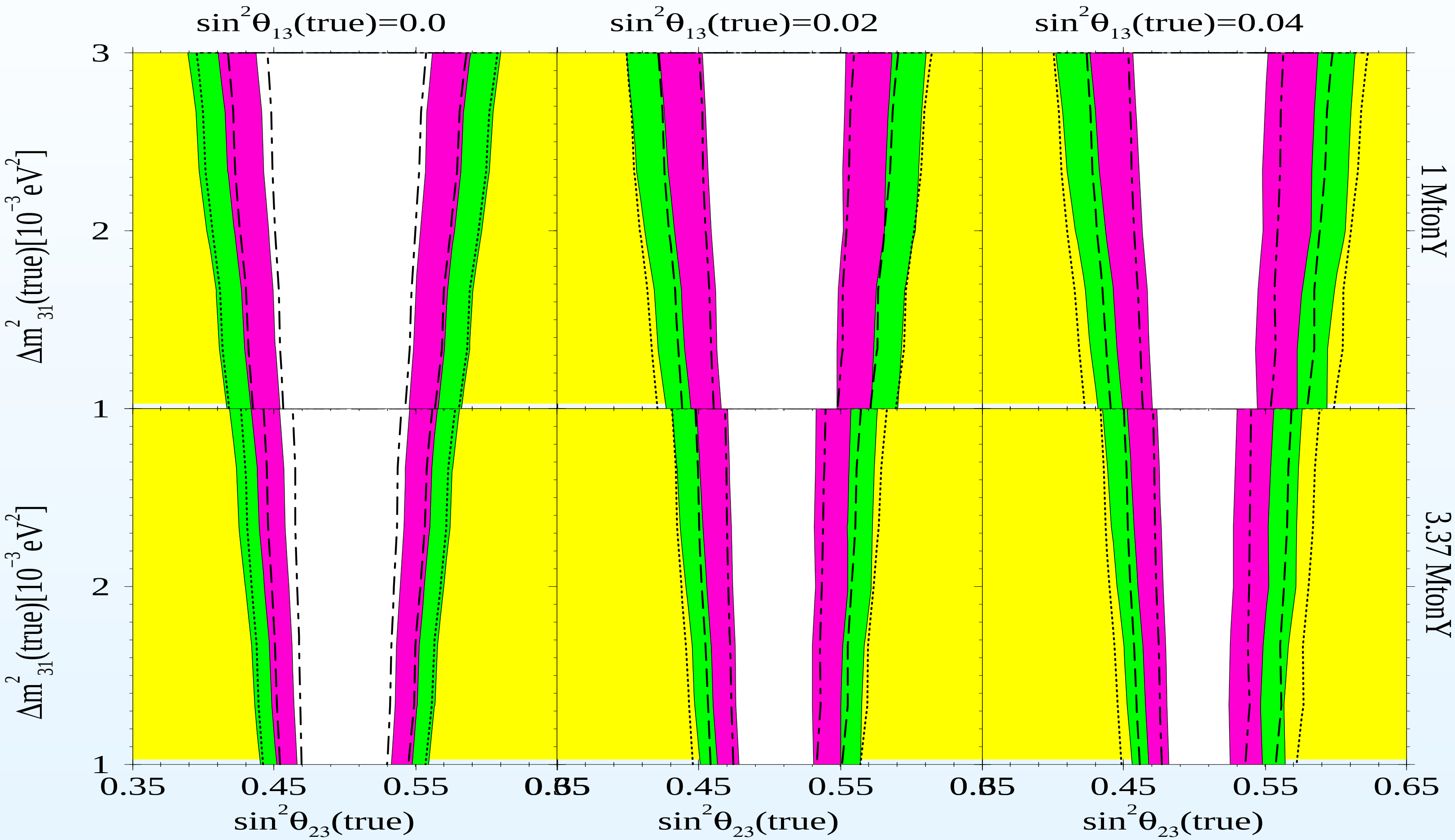
- Dependence on θ_{23} in the form $\sin^4 \theta_{23}$
- Octant sensitivity ?

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

Also Indumathi et al. hep-ph/0603264

Can Earth matter effects determine $|D|$?

- Using atmospheric neutrinos in INO



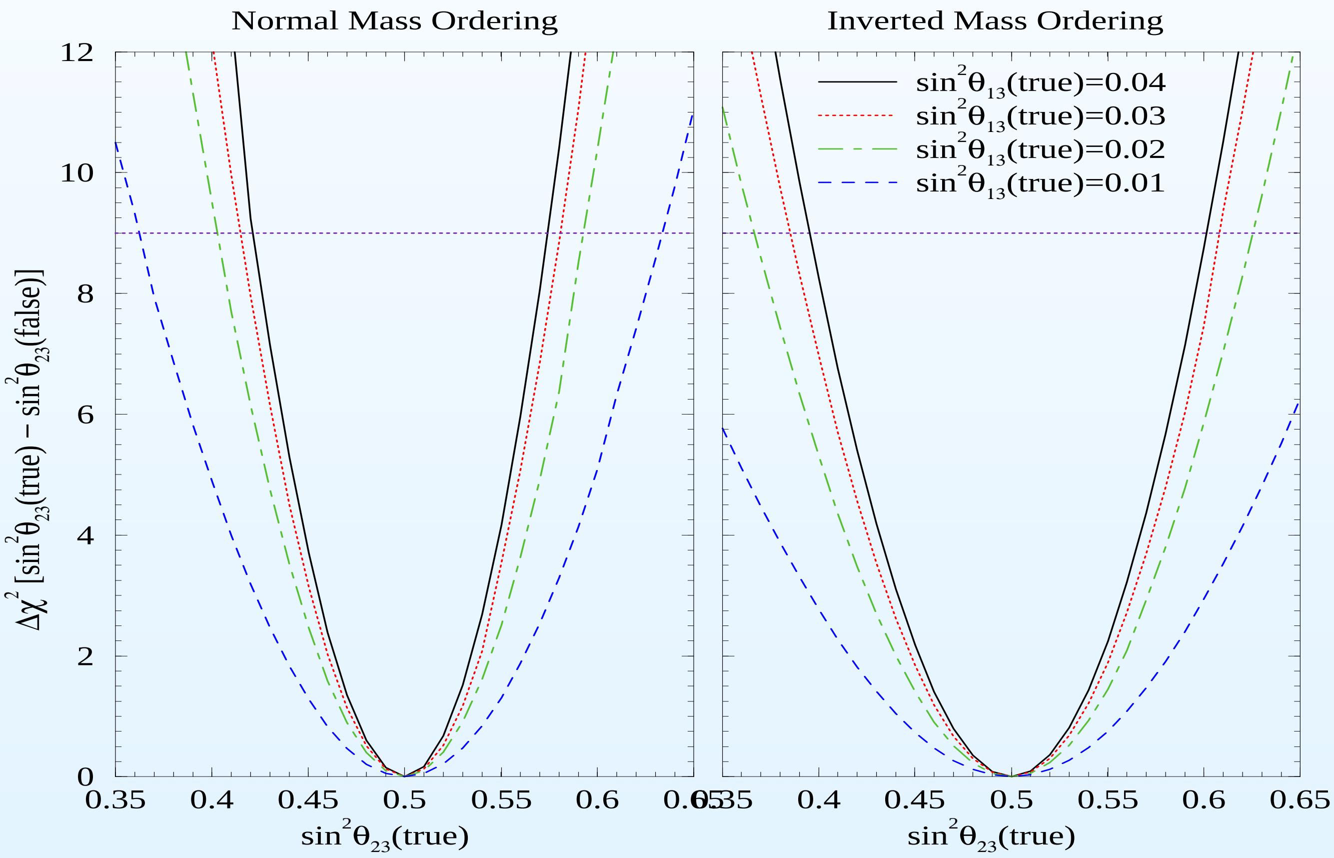
- $|D|$ can be measured to $\sim 17\%(20\%)$ at 3σ for $s^2_{13} = 0.04(0.00)$ with 1 MtonY exposure and 50% detector efficiency

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

Resolving the octant ambiguity in INO

- Using atmospheric neutrinos in INO
- For every non-maximal $\sin^2\theta_{23}$(true) there exists a $\sin^2\theta_{23}$(false)

$$\sin^2\theta_{23}(\text{false}) = 1 - \sin^2\theta_{23}(\text{true})$$



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

Comparing the Octant Sensitivity of Experiments

- Long baseline experiments
  No octant sensitivity
  - LBL+atmospheric   Huber et al hep-ph/0501037
  - LBL accelerator + reactor   Minakata et al hep-ph/0601258
- Atmospheric neutrinos in water Cerenkov detectors
  $\sin^2\theta_{23}$(false) can be excluded at 3σ if:

$$\sin^2\theta_{23}(\text{true}) < 0.36 \text{ or } > 0.62$$

Gonzalez-Garcia et al, hep-ph/0408170

- Atmospheric neutrinos in large magnetized iron detectors
  $\sin^2\theta_{23}$(false) can be excluded at 3σ if:

$$\sin^2\theta_{23}(\text{true}) < 0.36 \text{ or } > 0.63 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.01,$$

$$\sin^2\theta_{23}(\text{true}) < 0.40 \text{ or } > 0.59 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.02,$$

$$\sin^2\theta_{23}(\text{true}) < 0.41 \text{ or } > 0.58 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.03,$$

$$\sin^2\theta_{23}(\text{true}) < 0.42 \text{ or } > 0.57 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.04.$$

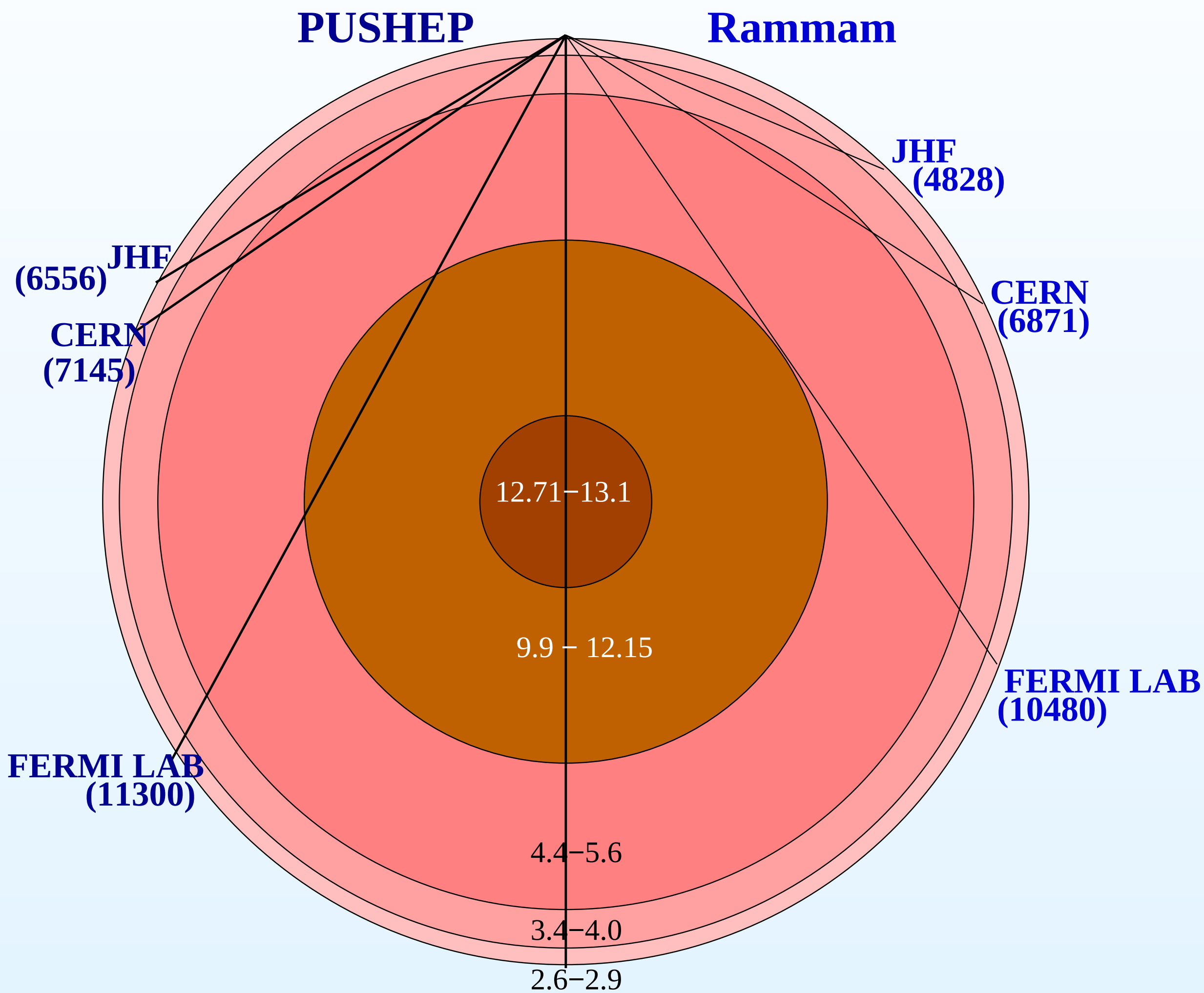
S.Choubey. and P. Roy hep-ph/0509197

Detector and Physics Simulation

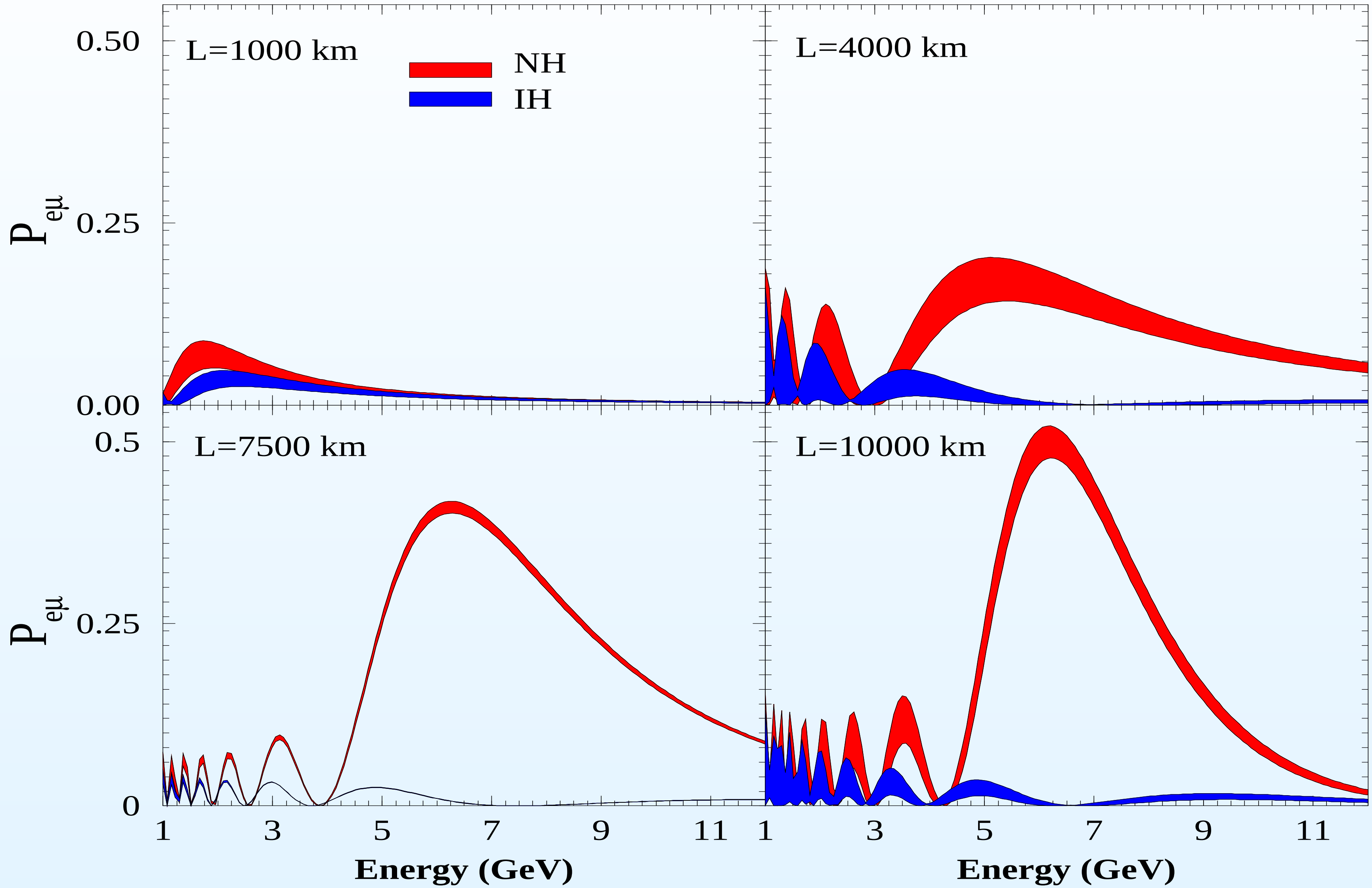
- Simulation studies with atmospheric neutrinos are in progress at many collaborating Institutions

- Nuance Event Generator
    - Generates of atmospheric neutrino events inside the INO detector
- GEANT Monte Carlo Package
    - Simulates the detector response for the neutrino events
- Event Reconstruction
    - Fits the raw data to extract neutrino energy and direction
- Physics Performance
    - Analysis of reconstructed events to extract physics.

INO as a long baseline detector

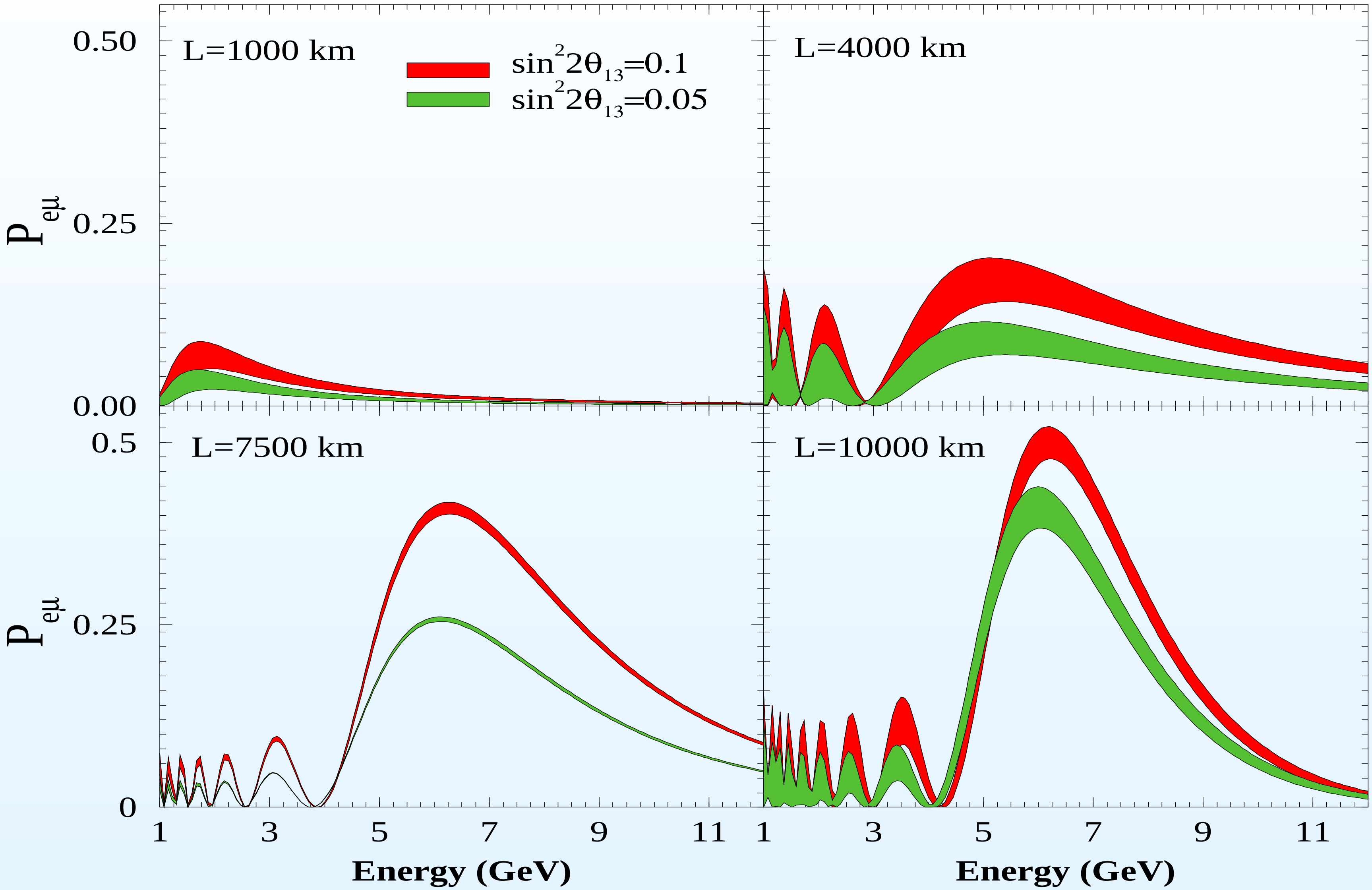


$P_{e\mu}$ for NH and IH at different baselines



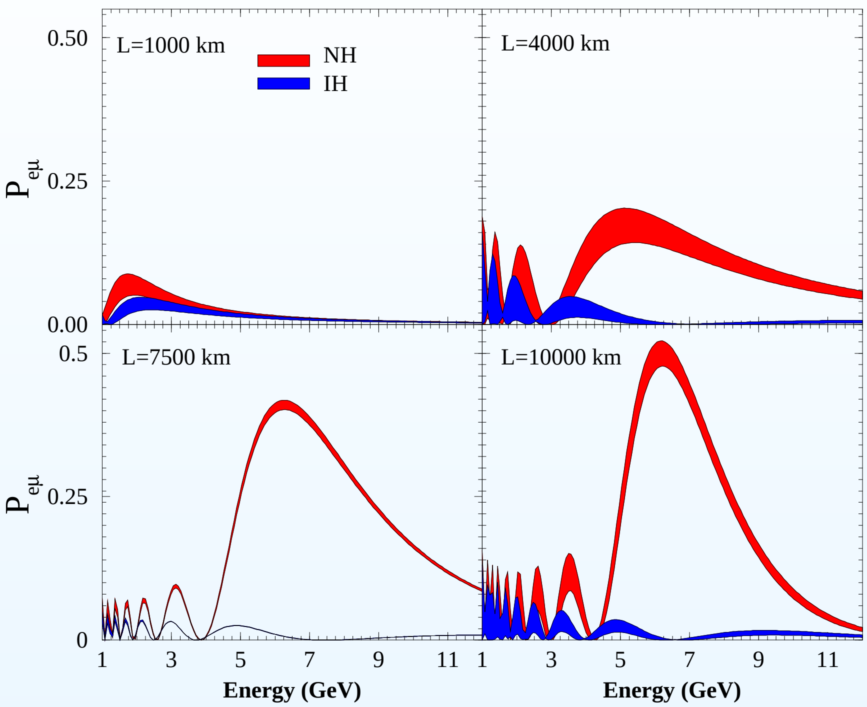
Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

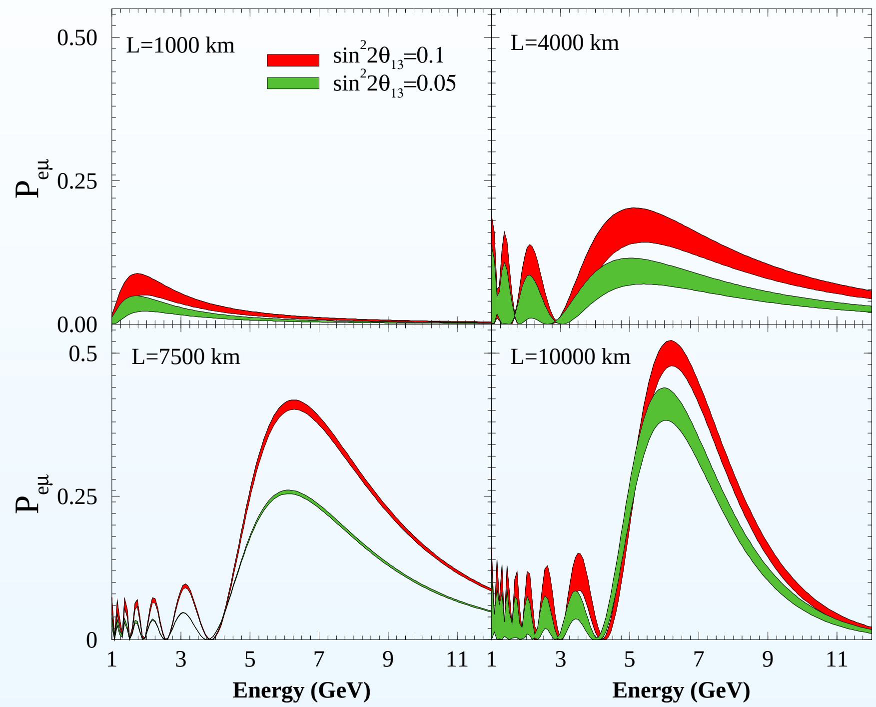
$P_{e\mu}$ for two values of θ_{13} at different baselines



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

The Magic baseline





Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

- At $\sim$ 7500 km δ_{CP} dependence negligible
- $(\delta_{CP}, \theta_{13})$ and $(\delta_{CP}, sgn(\Delta m^2_{\rm atm}))$ degeneracies vanish
- Clean measurement of $sgn(\Delta m^2_{\rm atm})$ θ_{13}

The Magic baseline

$$
\begin{aligned}
P_{e\mu} \quad & \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& \pm\ \alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta_{CP}\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& +\ \alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\delta_{CP}\cos\Delta\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& +\ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

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& +\ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

- If $\sin(\hat{A}\Delta) \simeq 0 \Rightarrow P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$

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$$

- If $\sin(\hat{A}\Delta)\simeq 0 \Rightarrow P_{e\mu}\simeq\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$
- $\sin(\hat{A}\Delta)\simeq 0 \Rightarrow L_{magic}\simeq 7690\text{ km}$

Barger, Marfatia, Whisnant, hep-ph/0112119

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198

The Magical Reach of INO

- CERN to INO distance = 7152 km

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- RAL to INO distance = 7653 km

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INO is wonderfully close to magic baseline

CERN-INO Magical Beta-Beam Experiment

- CERN-INO distance is equal to 7152 km

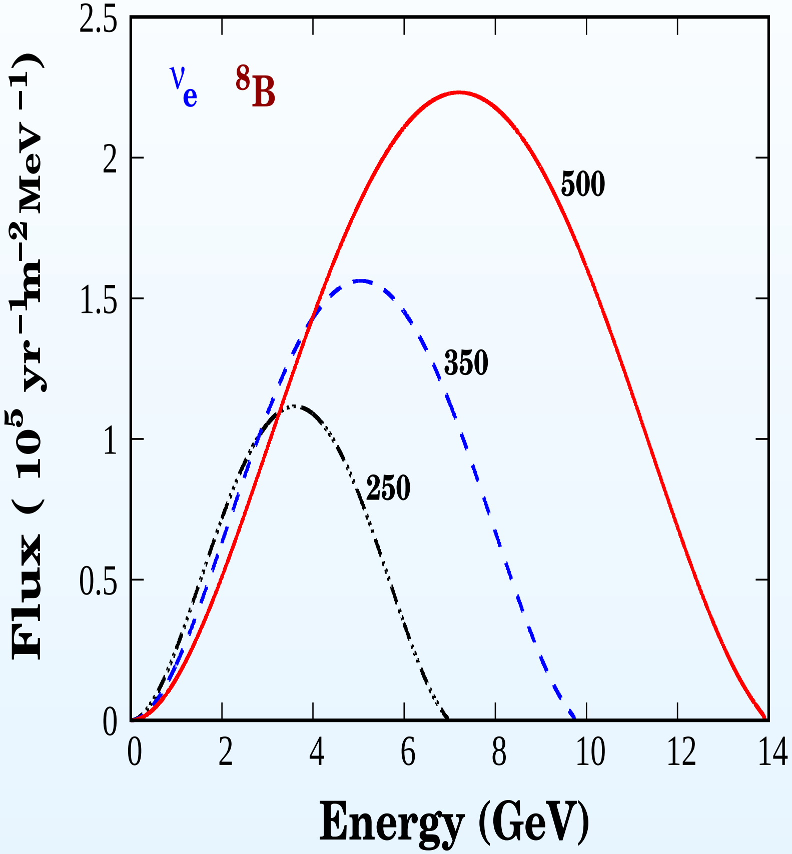
CERN-INO Magical Beta-Beam Experiment

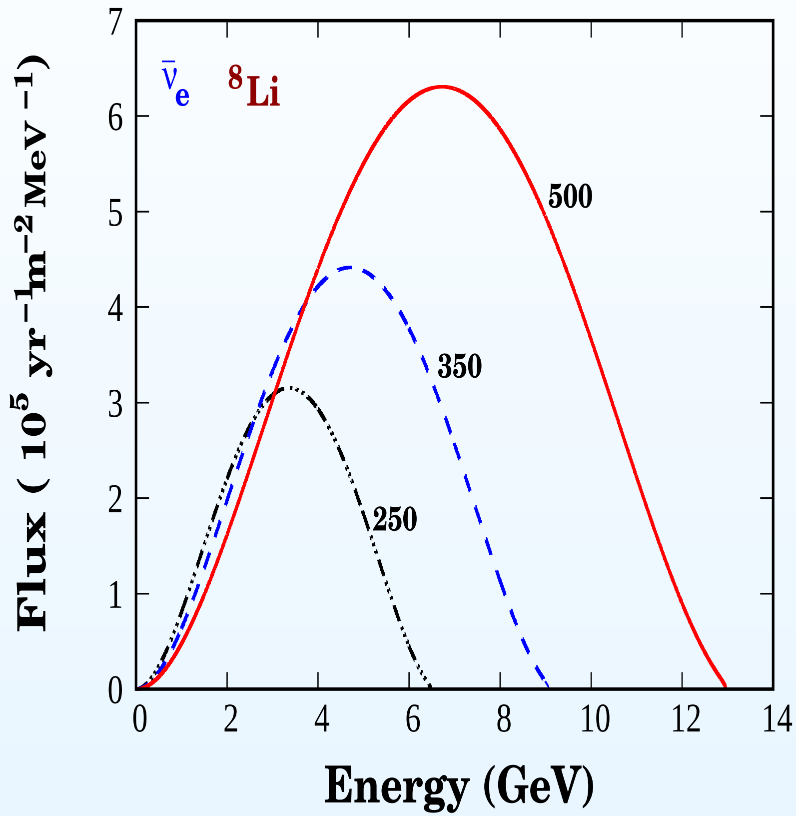
- CERN-INO distance is equal to 7152 km
- A golden channel ($P_{e\mu}$) experiment at magic baseline using a β beam as source of ν_e and INO as the end detector
- Beta beam spectrum depends on the end point energy of the beta unstable ion and Lorentz boost γ
- The standard Beta-Beam ions ^{18}Ne and ^{6}He would require very large gamma

Agarwalla, Raychaudhuri,Samanata, PLB, 2005

CERN-INO Magical Beta-Beam Experiment

- CERN-INO distance is equal to 7152 km





Agarwalla, SC, Raychaudhuri, hep-ph/0610333

- Alternative ions ^8B and ^8Li have large end-point energy and hence “harder” spectra.
- Flux peaks at $E \simeq 6$ GeV for $\gamma = 350 - 500$

Conditions For Maximum Matter effect

- Large Distance $\Rightarrow$ Large Matter effects

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- Resonance energy

$$E_{res} = \frac{|\Delta m^2_{\rm atm}| \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

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- Maximal oscillations when $\sin^2 2\theta_{13}^m \simeq 1$ and $\sin^2(\frac{(\Delta m^2_{\rm atm})^m L}{4E}) \simeq 1$ simultaneously

Gandhi,Ghoshal,Goswami,Mehta,Umashanakar , hep-ph/0408361

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- Maximal oscillations when $\sin^2 2\theta^m_{13} \simeq 1$ and $\sin^2(\frac{(\Delta m^2_{\rm atm})^m L}{4E}) \simeq 1$ simultaneously

Gandhi,Ghoshal,Goswami,Mehta,Umashanakar , hep-ph/0408361

- At the magic baseline, largest oscillations come when $E \simeq 6$ GeV

Conditions For Maximum Matter effect

- Large Distance $\Rightarrow$ Large Matter effects
- Resonance energy

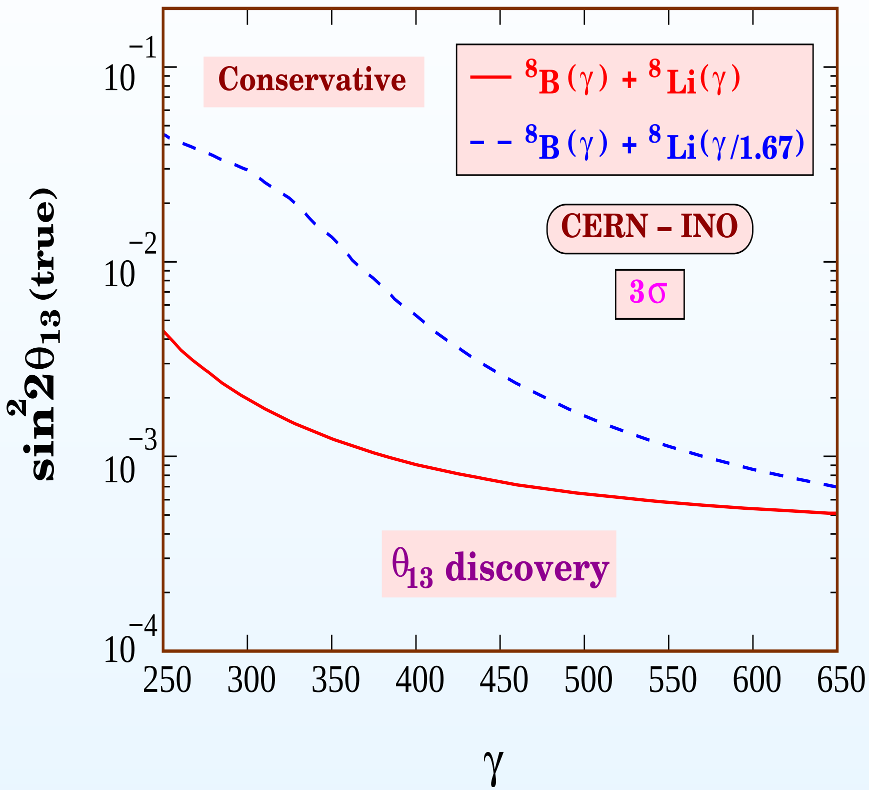
$$E_{res} = \frac{|\Delta m^2_{\rm atm}| \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

- For $\Delta m^2_{\rm atm} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} = 0.1$ and the PREM profile $\rho_{av} = 4.13$ gm/cc, $E_{res} \simeq 7.5$ GeV
- Maximal oscillations when $\sin^2 2\theta^m_{13} \simeq 1$ and $\sin^2(\frac{(\Delta m^2_{\rm atm})^m L}{4E}) \simeq 1$ simultaneously

Gandhi,Ghoshal,Goswami,Mehta,Umashanakar , hep-ph/0408361

- At the magic baseline, largest oscillations come when $E \simeq 6$ GeV
- CERN-INO β-beam experiment can capture maximal matter effect

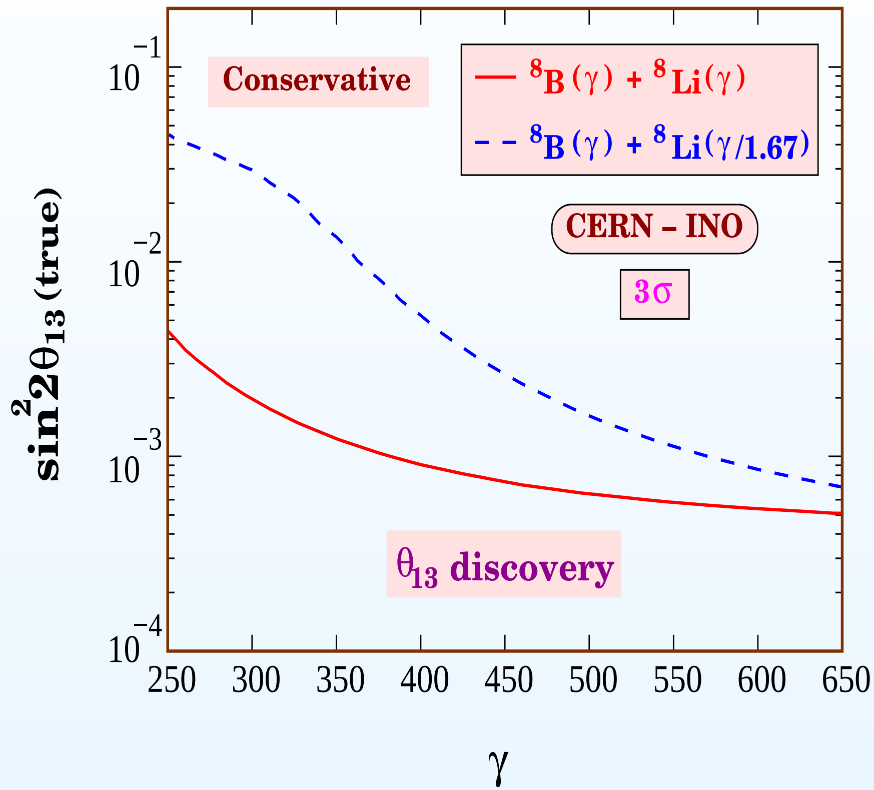
Reach of The CERN-INO β-beam Experiment

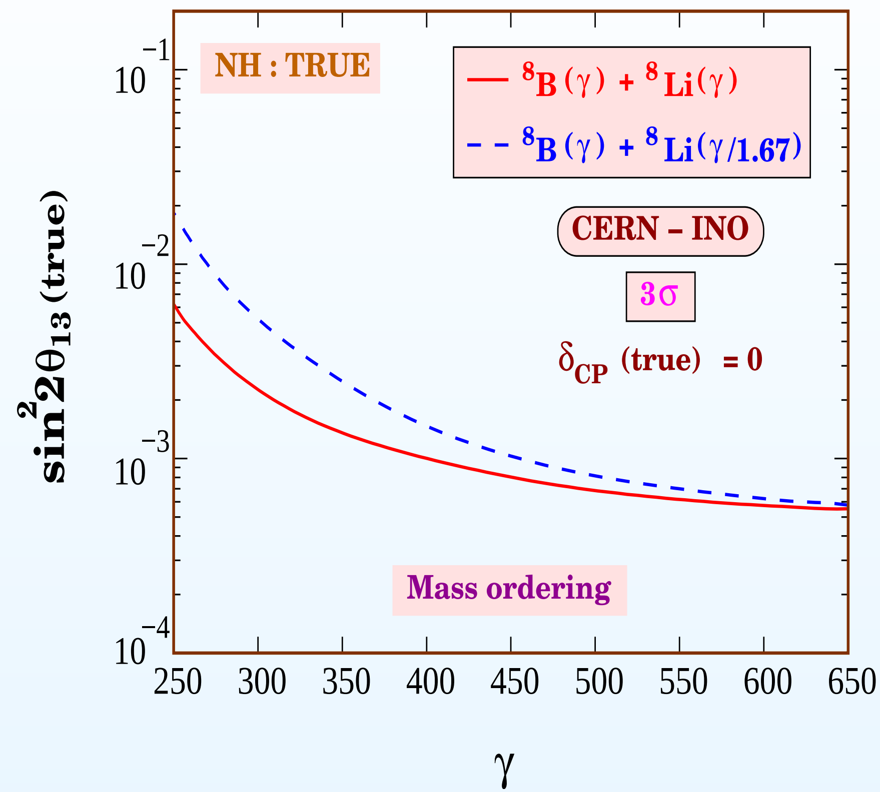


- Signal for θ_{13} at 3σ if $\sin^2 2\theta_{13}$(true) $\geq 5.1 \times 10^{-4}$

Agarwalla, Choubey, Raychaudhuri, arXiv:0711.1459

Reach of The CERN-INO β-beam Experiment





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- Mass Hierarchy at 3σ if $\sin^2 2\theta_{13}$(true) $\geq 5.6 \times 10^{-4}$

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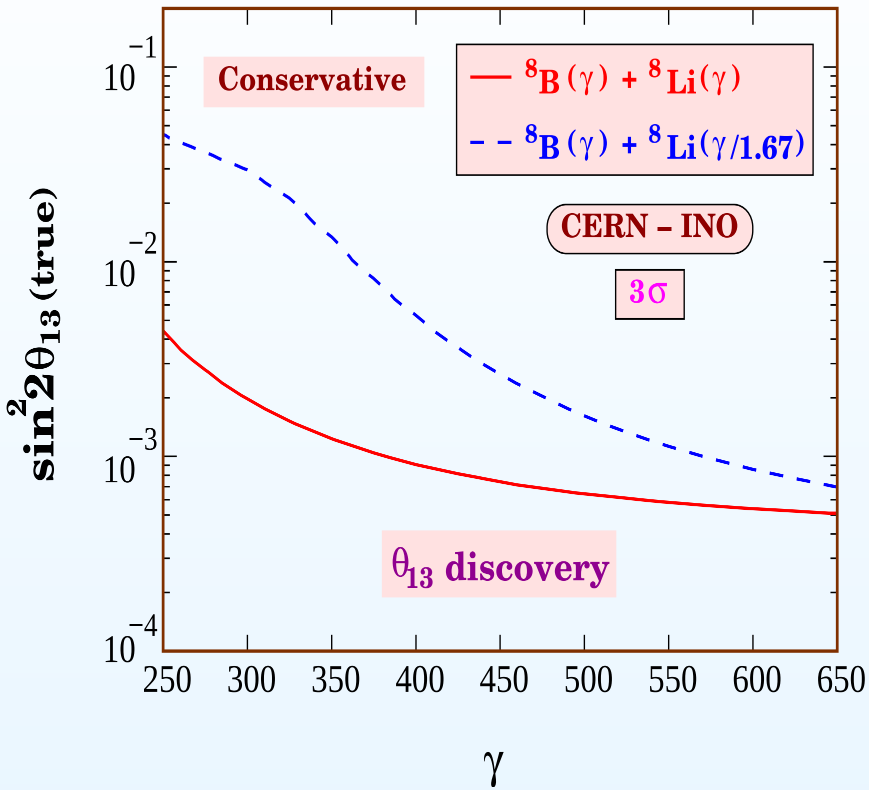

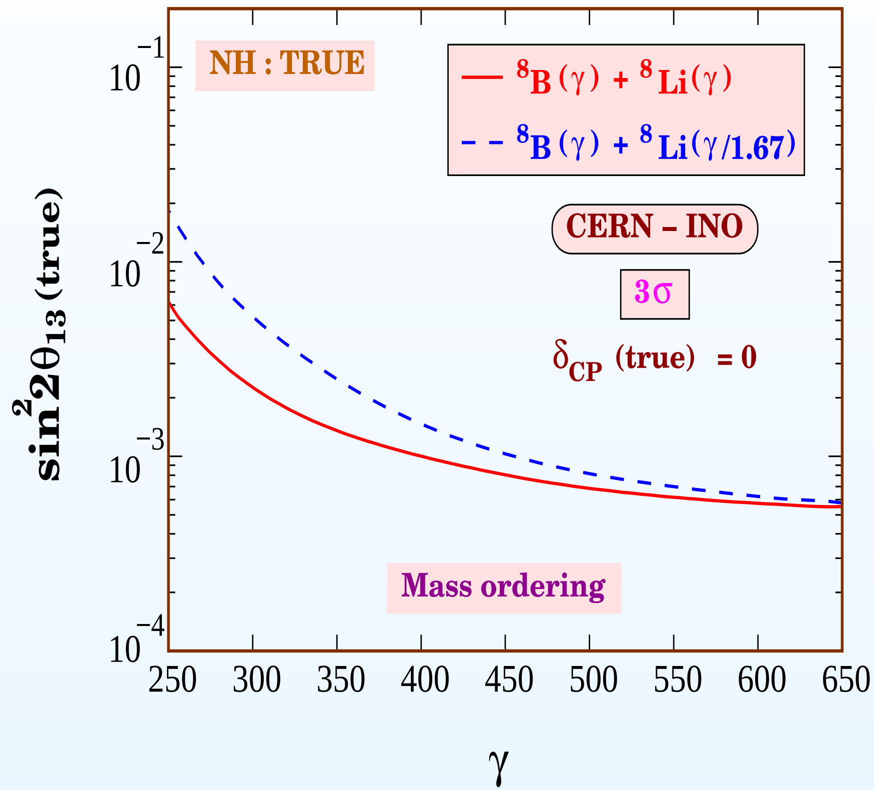

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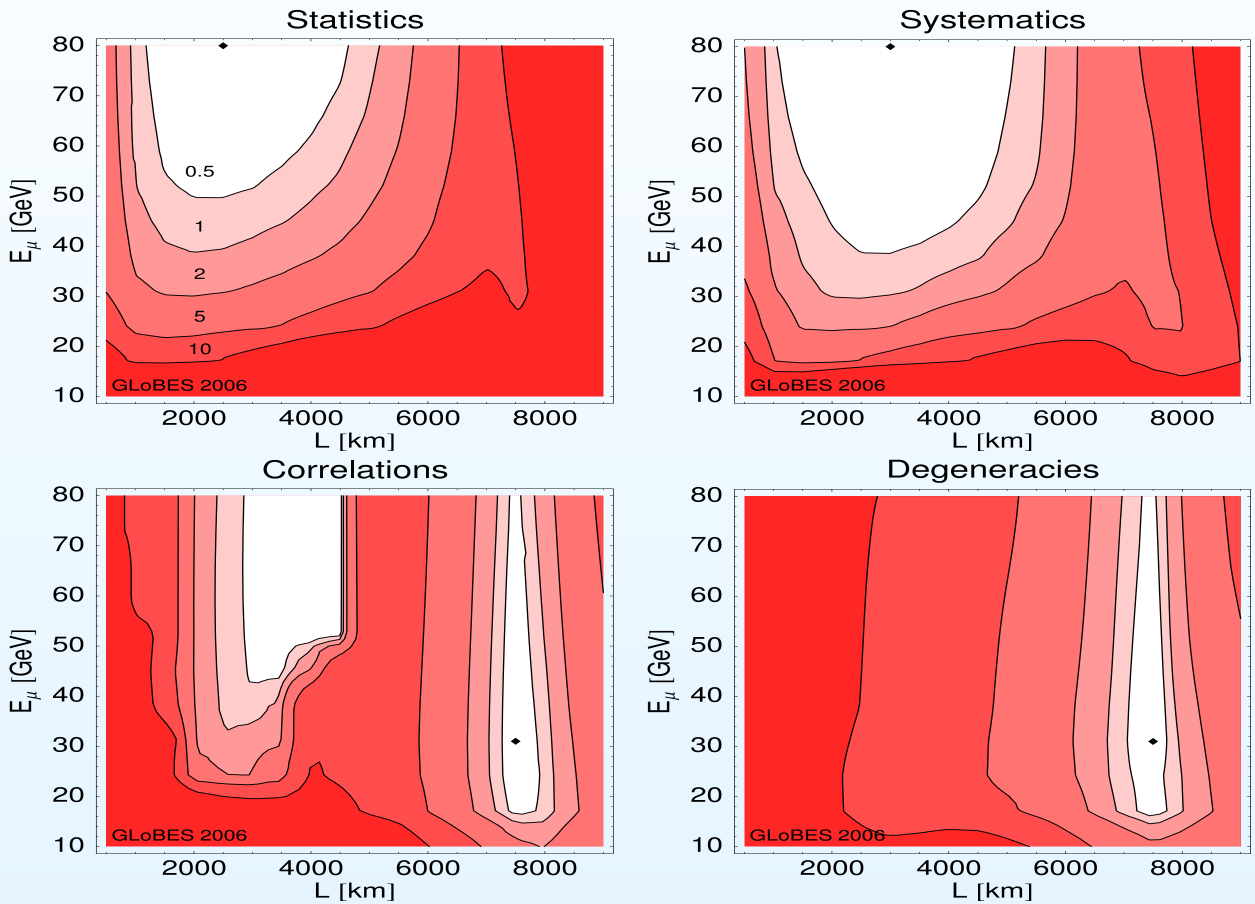
INO and Neutrino Factory

- ICAL@INO will be a 50–100 kton Magnetized Iron Calorimeter detector
- ideal candidate for a NuFact detector

INO and Neutrino Factory

- Sensitivity to $\sin^2 2\theta_{13} \lesssim 2.0 \times 10^{-4}$ (3σ)



Huber *et al.*, hep-ph/0606199

Best sensitivity comes at the Magic Baseline

INO Time Line

- Phase I: 12-18 months
  - Draw up detailed design report for tunnel and cavern
  - Detailed design report on detector structure, RPCs. pickup electrodes, electronics and power supply system

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Expected to start the first module by 2012

INO: Approval Status

- INO Interim Project Report presented to DAE and DST in May, 2005.
- A presentation on INO proposal was made to SAC-PM in August 2005
- Interim report sent to panel of International Reviewers in 2006
- It was discussed by the Mega Science Committee set up by Planning Commission in September 2006 and recommended for funding in the XIth 5 year plan starting from April 2007
- It is an "in principle" funding and clearances are sought for environment and forest department

Budget: $\sim$ 500 crores in INR (≈ 150 million US Dollars)

Conclusion

- A large magnetized iron calorimeter detector has substantial physics potential using atmospheric neutrinos.
  - Reconfirmation of L/E dip and precision of Δm^2_{31}
  - Matter effect and Sign of Δm^2_{31}
  - Determination of octant of θ_{23}
  - CPT violation, Long Range Forces .....
- It will complement the planned water Cerenkov and Liquid Argon Detectors as well as the long baseline and reactor experiments
- In its second phase it can serve as a end detector for a beta-beam or beam from a neutrino factory
- Location is close to the Magic Baseline from all major accelerator facilities
- Clean measurement of hierarchy and θ_{13}

More details at http://www.imsc.res.in/˜ ino