Physics potentials of a magnetized iron calorimeter detector

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INO collaboration

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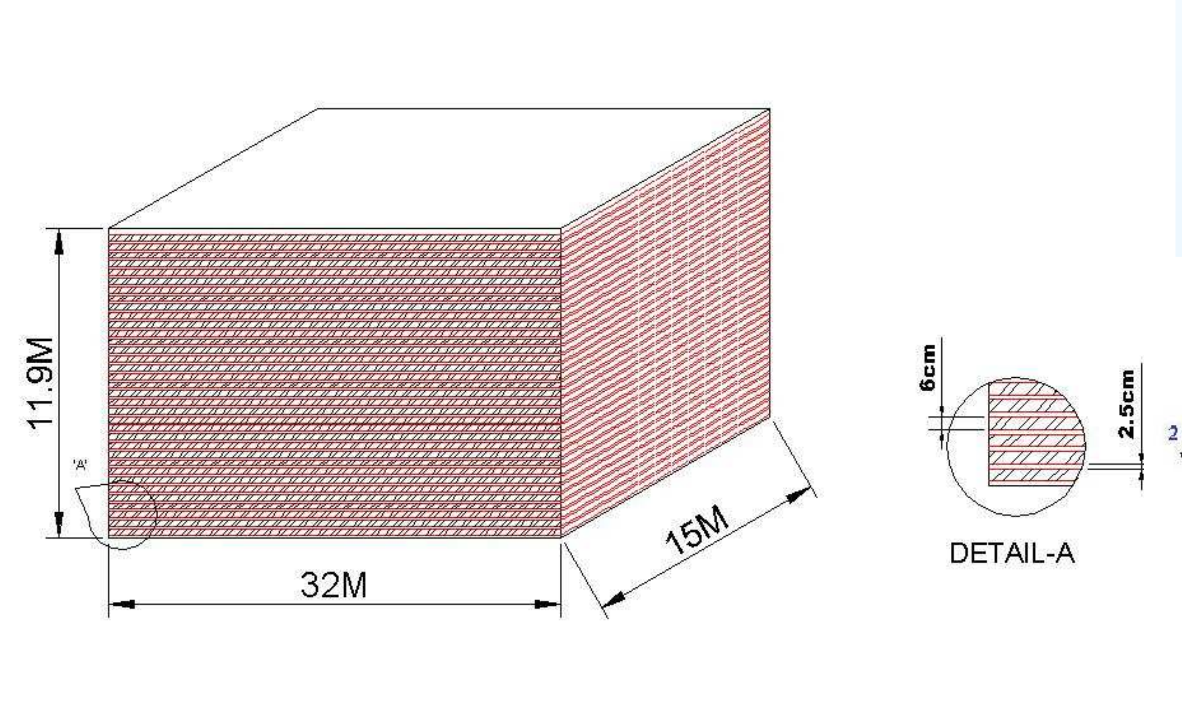
Magnetized Iron Calorimeter Detector

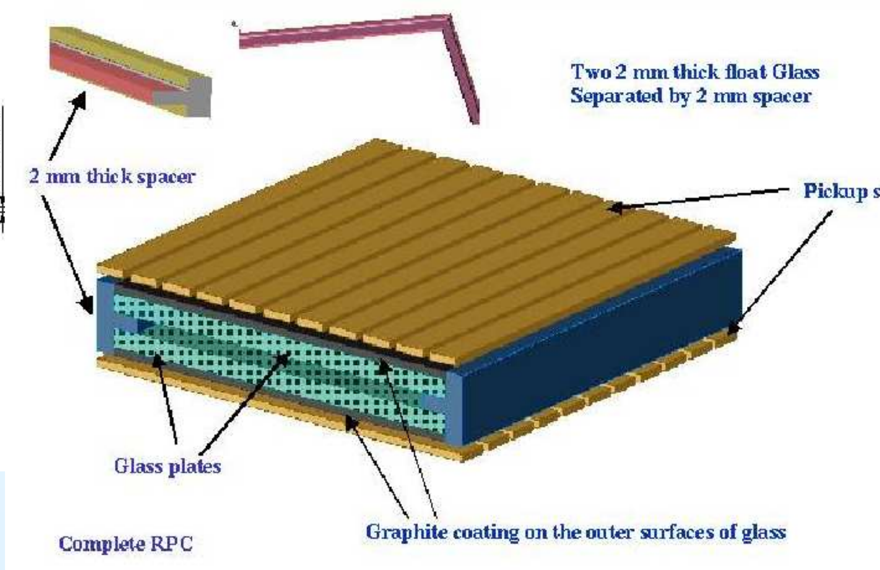
- Currently feasibility study for such a detector is underway in India by the India-Based Neutrino Observatory (INO) collaboration.
- Detector choice based on
  - Technological capabilites available in the country
  - Existing/Planned other neutrino detectors in the world
  - Modularity and the possibility of phasing
  - Compactness and ease of construction
- MONOLITH collaboration had earlier proposed similar design

The detector

- Magnetised iron calorimeter ($\sim$ 50kT)
- 140 horizontal (vertical) iron layers interspersed with Glass RPC
- Modular structure



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



Current Activities

- Detector R & D
- Physics Studies
- Detector Simulation
- Data Acquisition System
- Site Survey
- Human Resource Development

Interim Report submitted to funding agencies

Cost Estimates and Time Schedule

- Cost
  - Lab. Construction $\sim$ 90 crores INR (1 crore = 10 million)
  - Detector $\sim$ (200 (iron) + 200 (others)) crores in INR

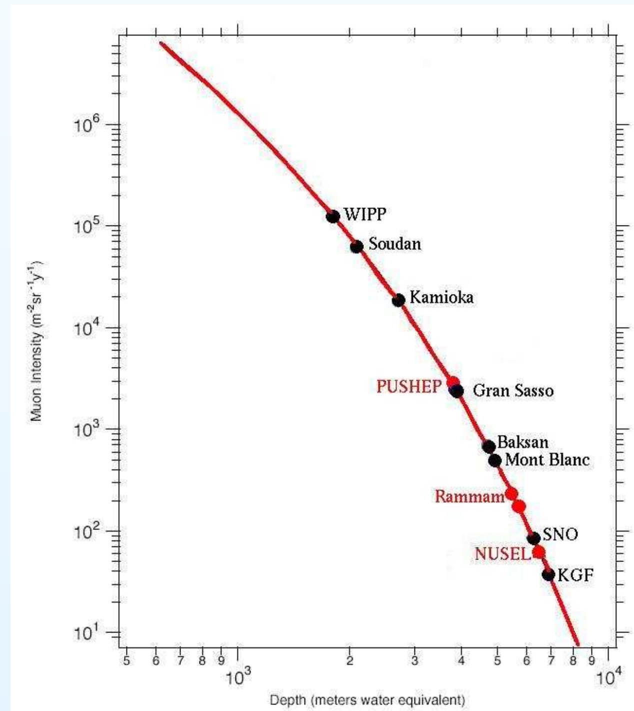
Total cost $\sim$ 500 crores in INR (1 Euro $\approx$ INR 50)

- Time Scale : $\sim$ 5 years from approval

Details: INO interim report, http://www.imsc.res.in/˜ ino

Site

- Two sites were considered –Rammam in North India and PUSHEP in South India
- PUSHEP is recommended for ease of accessibility, less seismicity..

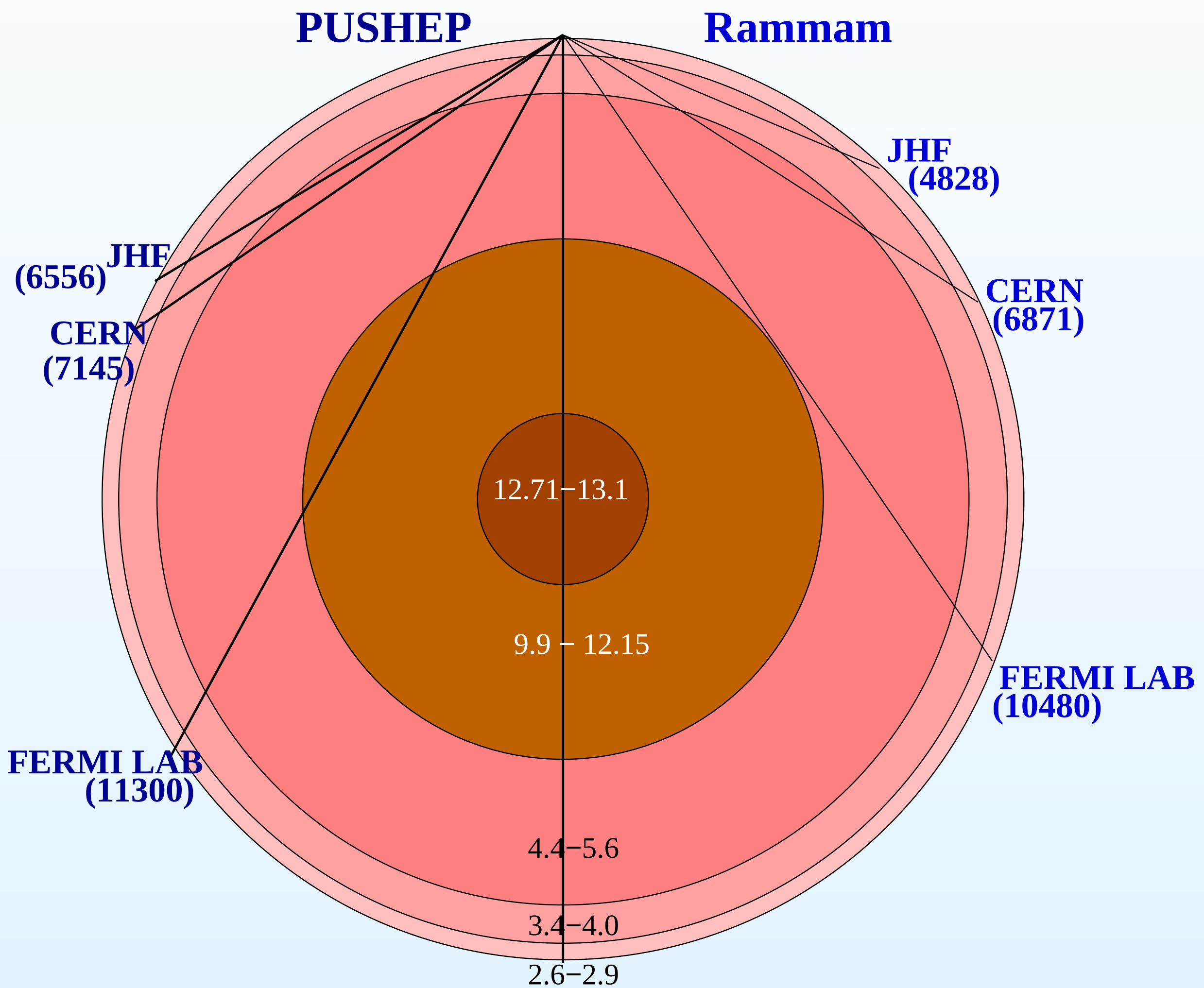


Geotechnological studies are going on

Physics Goals for INO

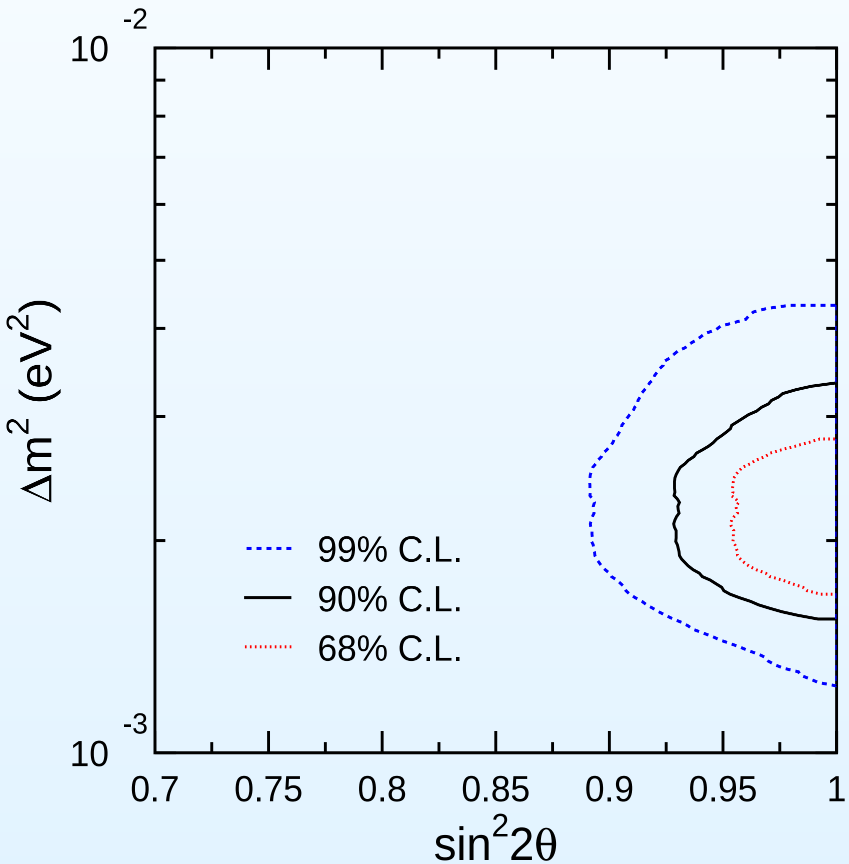
- First phase – measurement of atmospheric neutrino flux
  - Reconfirmation of the first oscillation dip as a function of L/E
  - Improved precision of oscillation parameters
  - Determination of the octant of θ_{23}
  - Matter effects and determination of sign of Δm^2_{31}
  - Probing CPT violation, Lorentz violation
  - Discrimination between $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_s$
  - Constraining long range leptonic forces
- Second Phase – end detector for beta beams, neutrino factory
  - hierarchy, θ_{13}, CP violation
  - CERN to INO baseline $\sim$ 7000 km, the magic baseline

INO as a long baseline detector



Atmospheric Neutrino Oscillation Parameters . . .

- Two generation $\nu_\mu - \nu_\tau$ oscillation ($\theta_{atm} \equiv \theta_{23}$, $\Delta m^2_{atm} \equiv \Delta m^2{}_{32}$)
- $P_{\mu\mu} = 1 - \sin^2 2\theta_{atm} \sin^2 \left(\frac{\Delta m^2_{atm} L}{4E} \right)$
- $\theta_{23} - (\pi/2 - \theta_{23})$ symmetry



Y. Ashie et al. hep-ex/05404034

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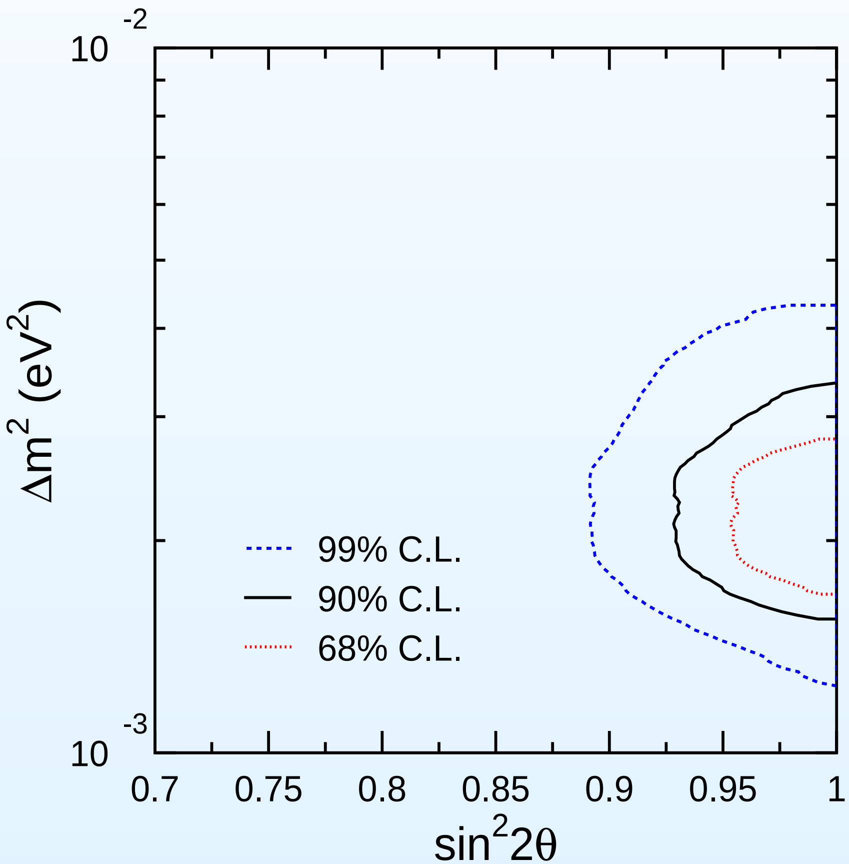

- Best-fit

Δm^2_{atm} = 2.1 $\times 10^{-3}$ eV^2, $\sin^2 2\theta_{atm} = 1.0$

Y. Ashie et al. hep-ex/05404034

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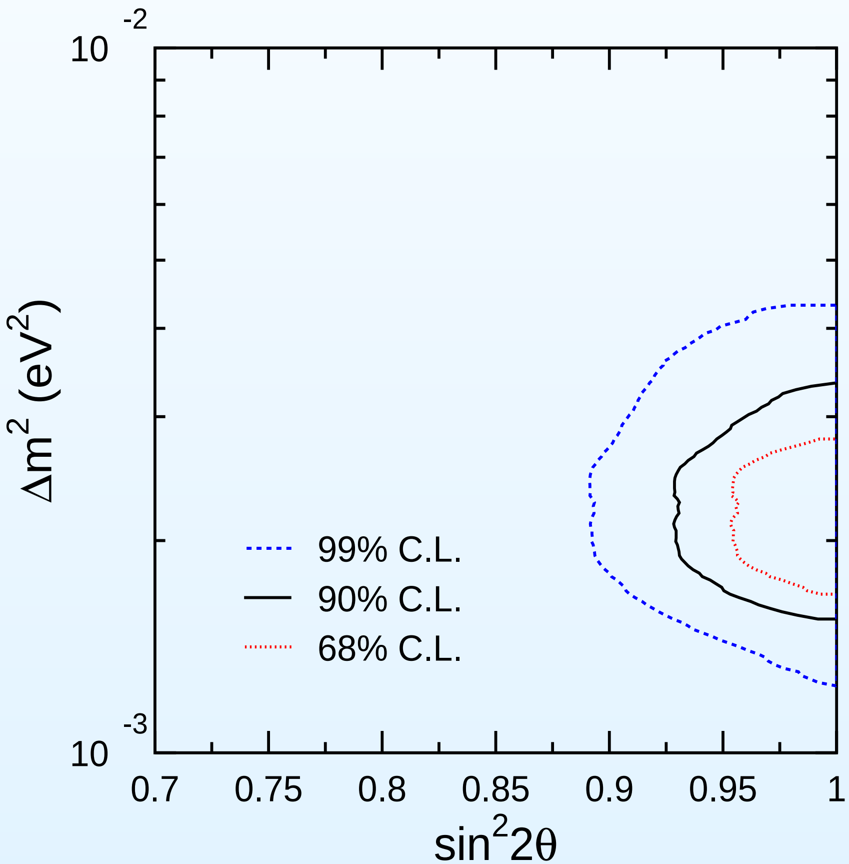


- 3σ range ($\Delta\chi^2 = 9$, 1 parameter)

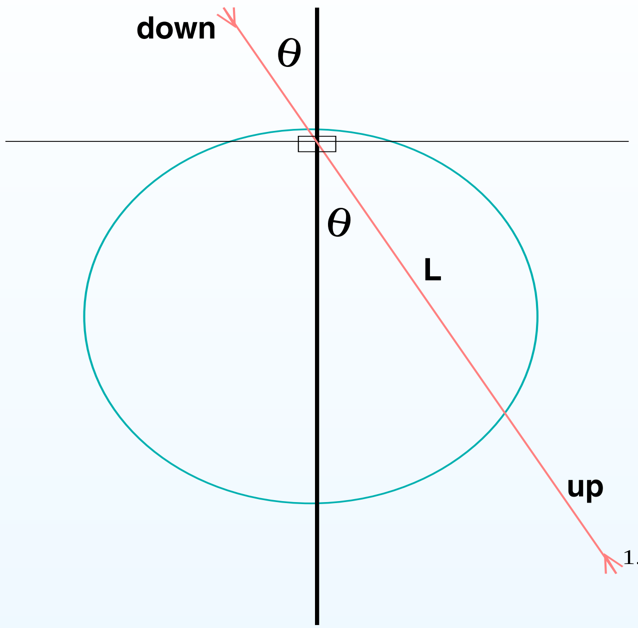
Δm^2_{atm}= 1.3 - 4.2 $\times 10^{-3}$ eV^2,
$\sin^2 2\theta_{atm} > 0.9$ (SK Zenith)

spread in Δm^2_{atm} = 53%
spread in $\sin^2 2\theta_{23}$ = 5%

- Improvement in Δm^2_{atm} spread with L/E data
- $\delta(\sin^2\theta_{23}) \sim 32\% \Rightarrow \sin^2\theta_{23}$ precision is worse than $\sin^2 2\theta_{23}$ precision near maximal mixing
  $\delta(\sin^2\theta) = \frac{\delta(\sin^2 2\theta)}{\cos 2\theta}$

Y. Ashie et al. hep-ex/05404034

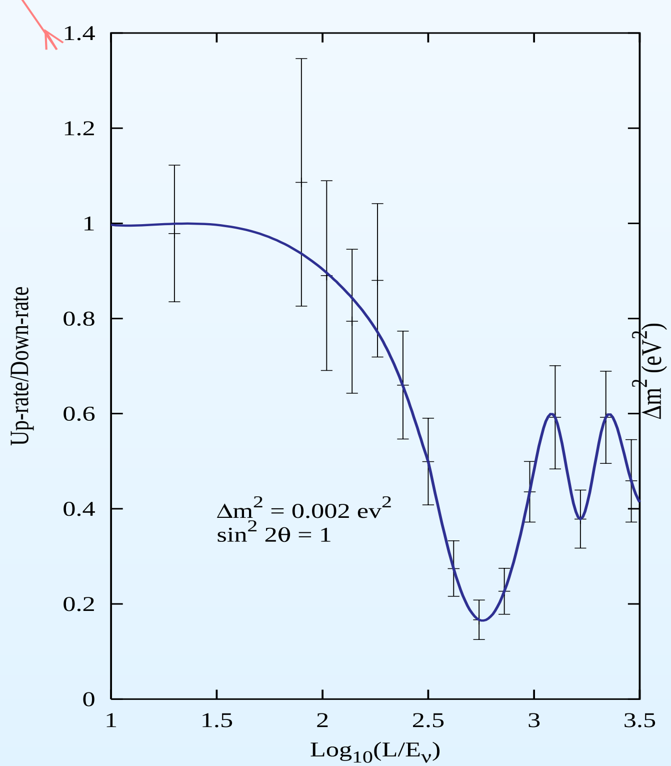
Disappearance of ν_μ vs L/E

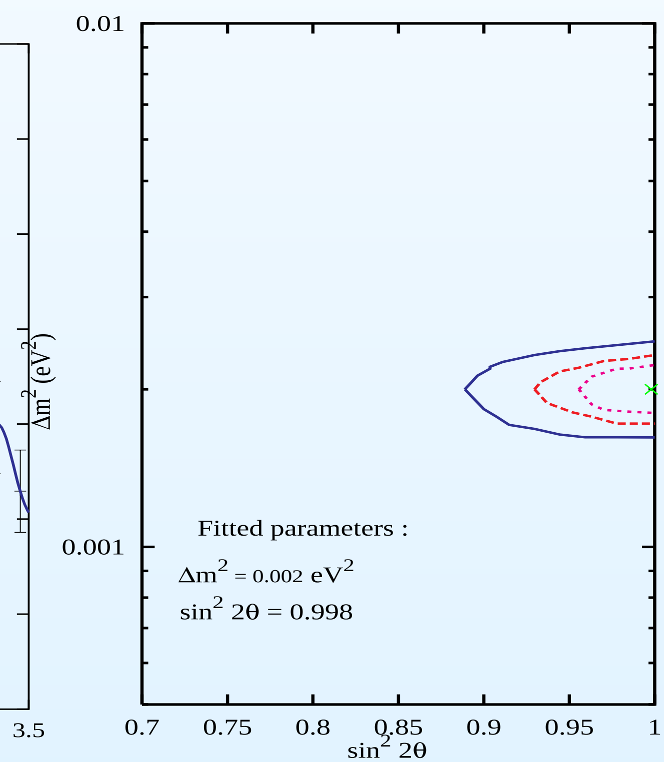


$$\frac{N_{up}(L/E)}{N_{down}(L/E)} \simeq P_{\mu\mu}$$

$$= 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} L/4E$$

Expect to determine Δ_{31} with 10% precision





Comparison with Long Baseline Experiments

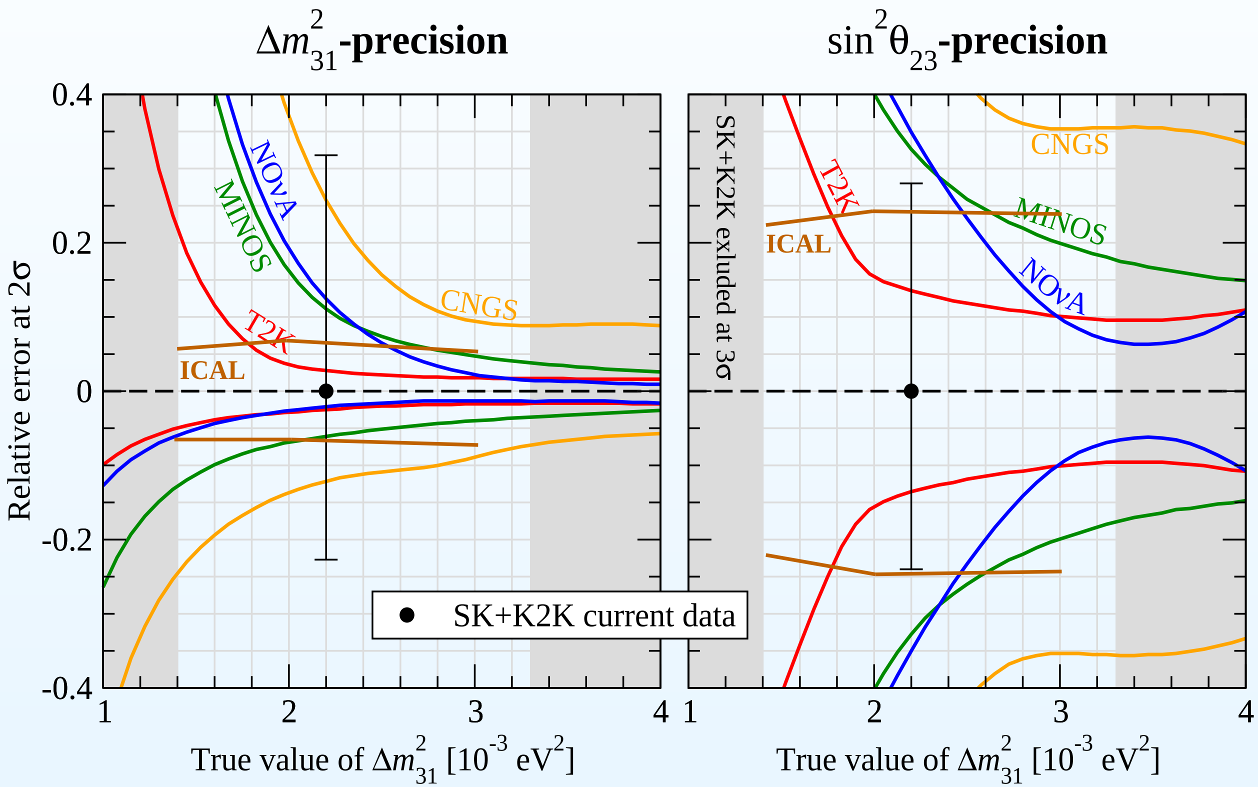
- 3σ spread ($\Delta m^2{}_{13}$ = 2×10^{-3} eV^2, $\sin^2\theta_{23} = 0.5$).

	$\lvert\Delta m^2{}_{13}\rvert$	$\sin^2\theta_{23}$
current	44%	39%
MINOS+CNGS	13%	39%
T2K	6%	23%
Nova	13%	43%
INO, 50 kton, 5 years	10%	30%

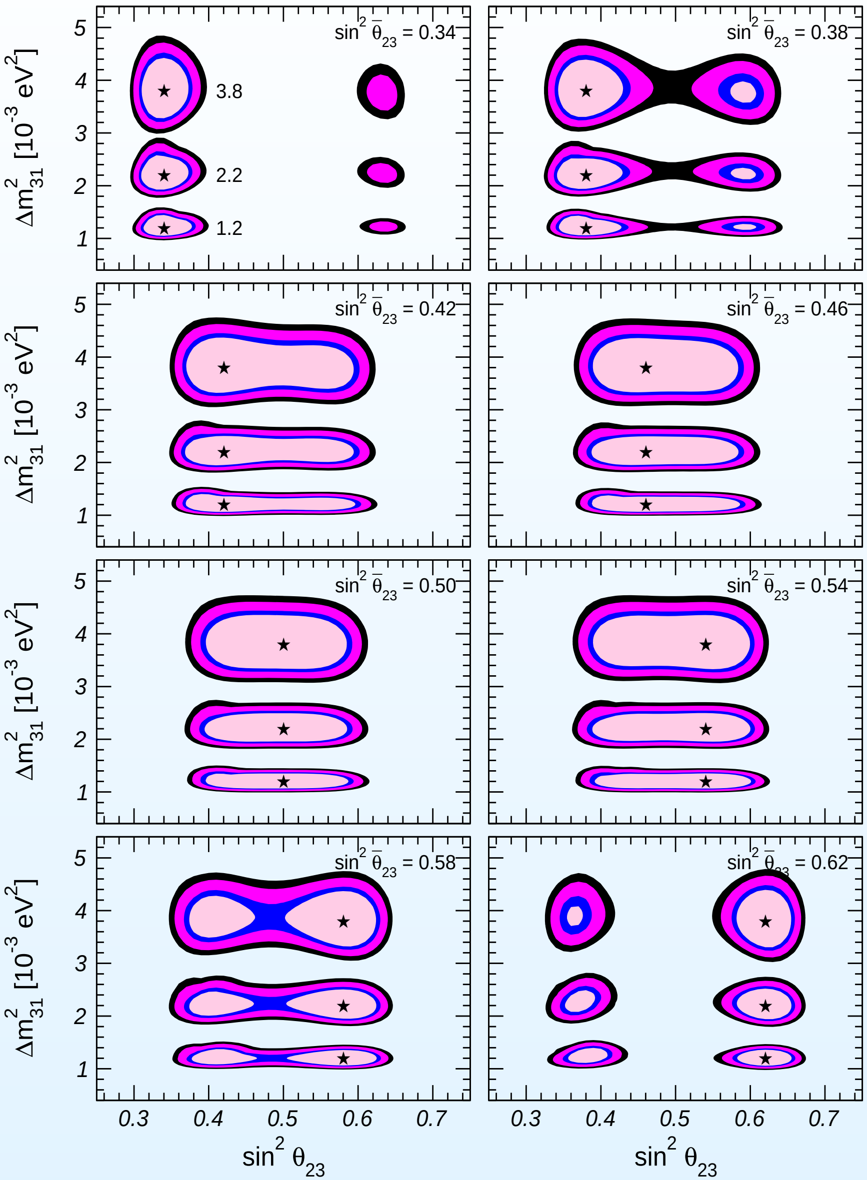
M. Lindner, hep-ph/0503101

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

Comparison with Long Baseline Experiments



Constraints from future SK Data



3σ spread after 20 SKyr

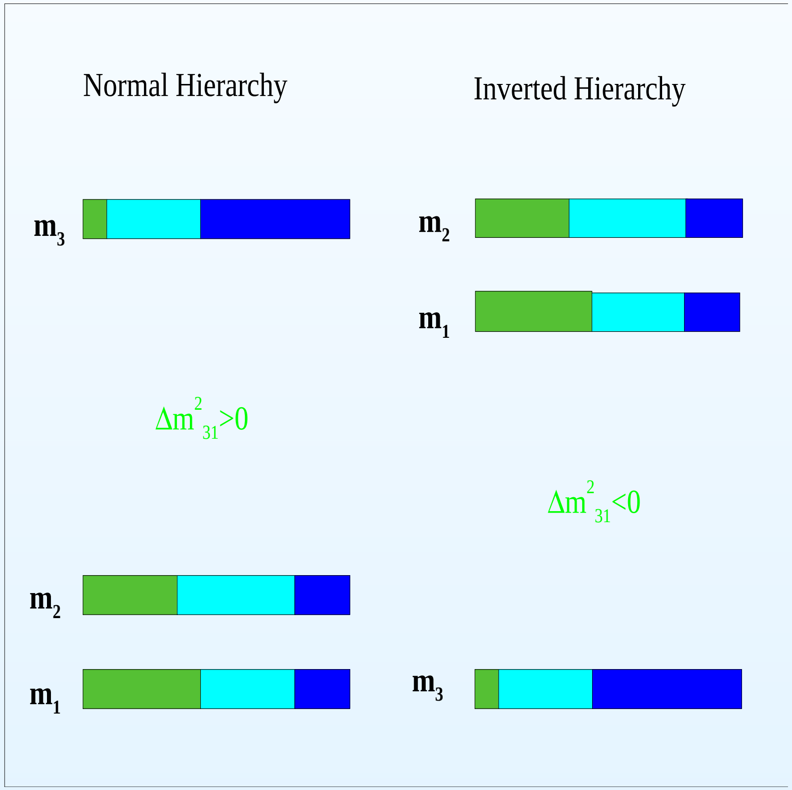
- ($\Delta_{31} = 0.002\text{eV}^2$, $\sin^2\theta_{23} = 0.5$)

Δm^2_{32} = 17% $\sin^2\theta_{23}$ = 24%

Gonazalez-Garcia et al. hep-ph/0408170

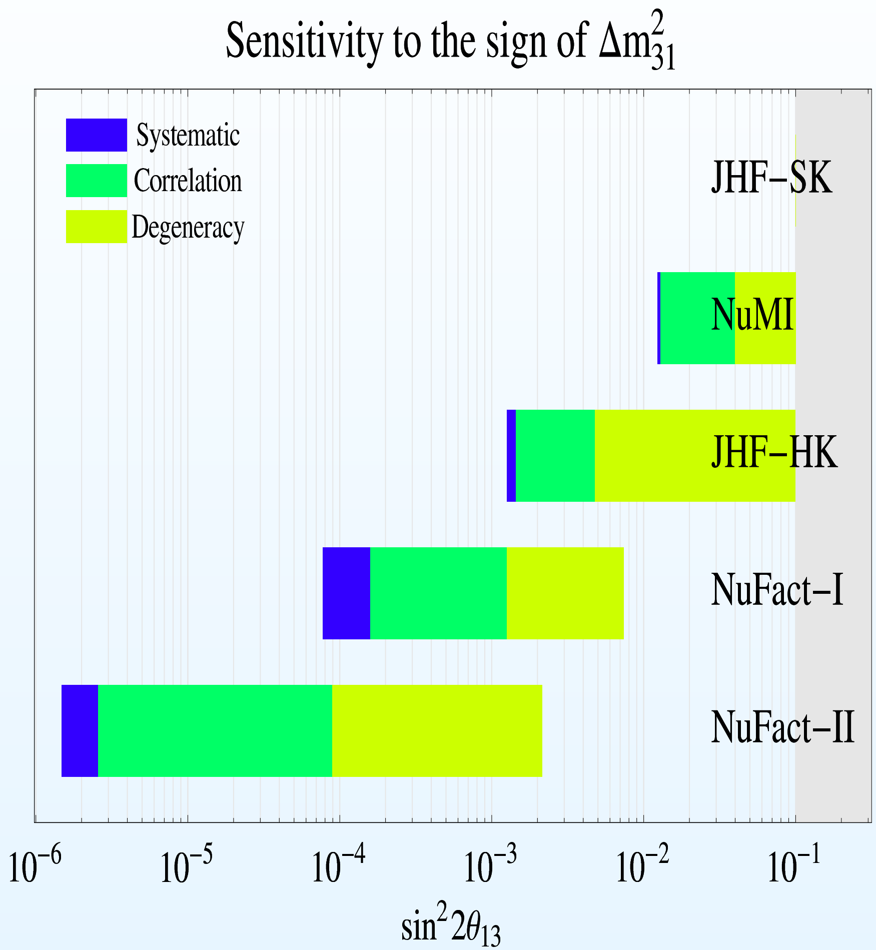
Ambiguity in Mass Hierarchy

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



- 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

Ambiguity in Mass Hierarchy

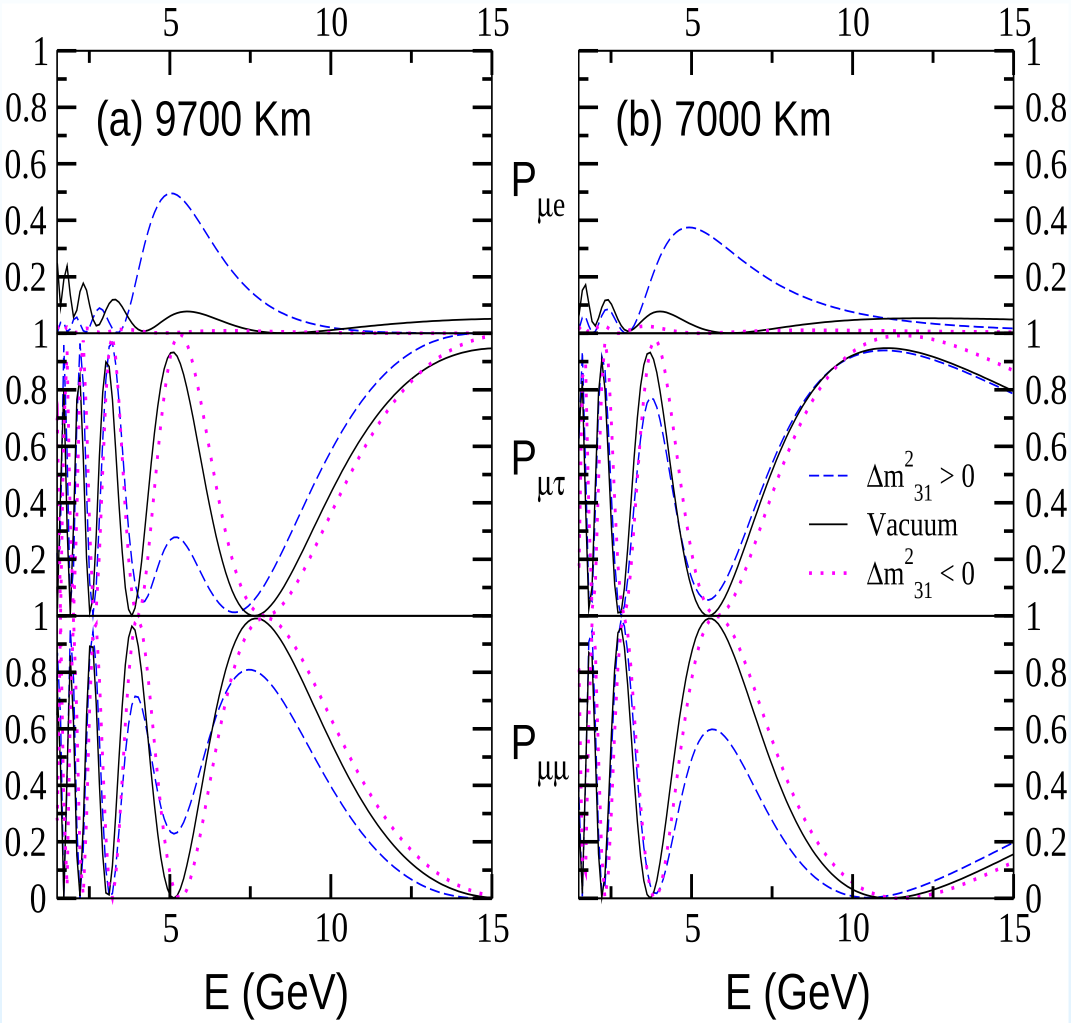


M. Lindner, hep-ph/0503101

- Hierarchy difficult to determine in superbeams
- Sensitivity limited by correlation and degeneracies
- Synergistic use of experiments
- Use of Magic Baseline

Earth Matter Effects at Long Baselines

- Problem of δ_{CP} degeneracy less at longer baselines



- Significant matter effect in $P_{\mu\tau}$ at 9700 km and for E $\sim$ 5 GeV
- Genuine three flavour effect
- Impact on $P_{\mu\mu}$ ⇨ $P_{\mu\mu} = 1 - P_{\mu e} - P_{\mu\tau}$
- At 7000 km drop in $P_{\mu\mu}$ induced by $P_{\mu e}$
- At 9700 km rise in $P_{\mu\mu}$ induced by $P_{\mu e}$ and $P_{\mu\tau}$

R. Gandhi et. al, PRL, 2005

Determining Hierarchy by Atmospheric Neutrinos

- Using μ^- rates in magnetized iron calorimeter detectors like INO

$$\phi_{\mu^-}/\phi^0{}_{\mu^-} \approx P_{\mu\mu} + rP_{e\mu} \qquad r = \phi^0{}_e/\phi^0_\mu$$
$$= P_{\mu\mu}(1-r) - rP_{\mu\tau} + r$$

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

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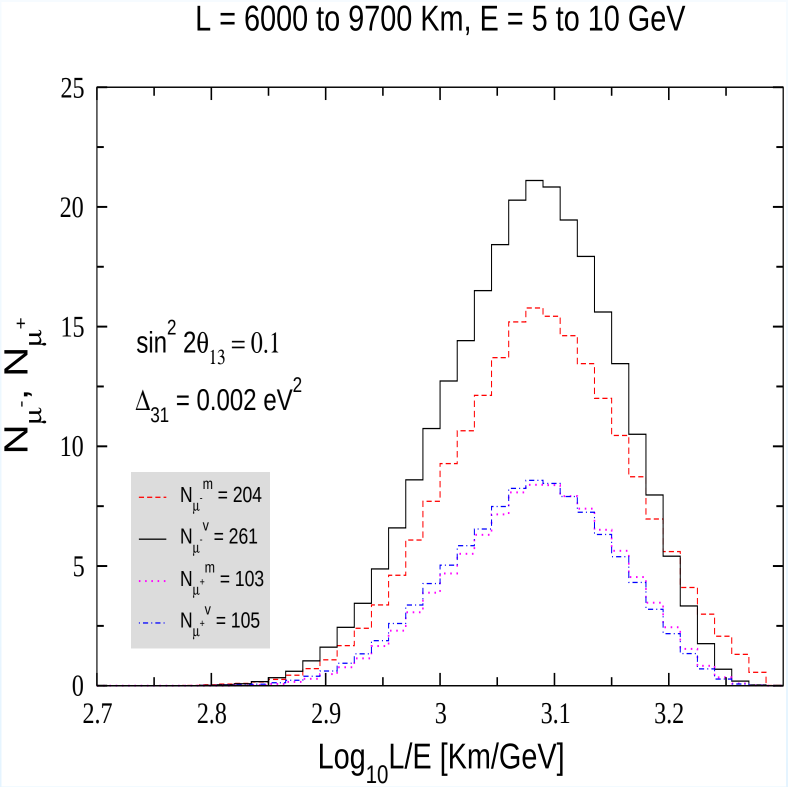

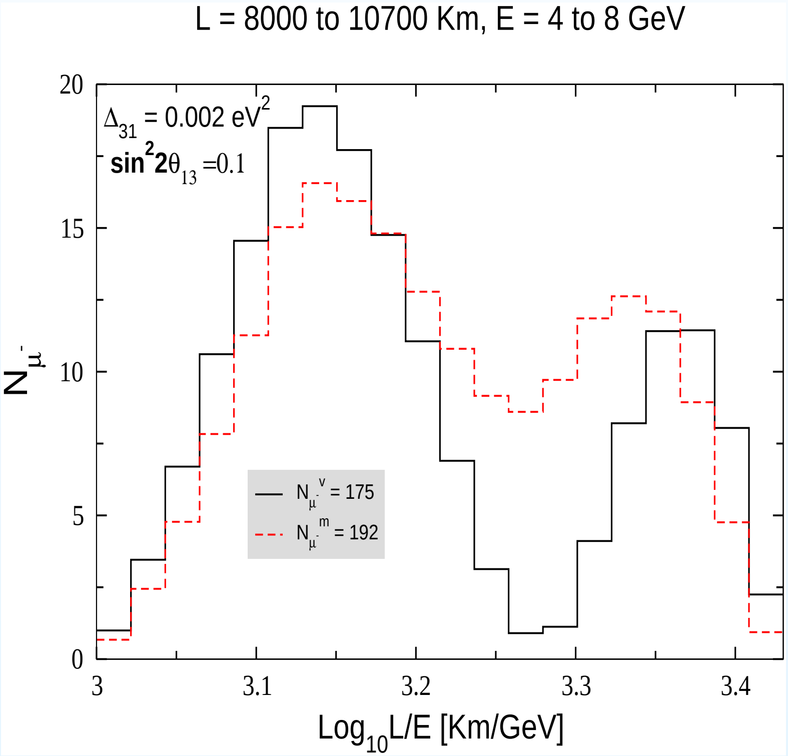

Gandhi et al., hep-ph/0411252

Palomarez-Ruiz, hep-ph/0406096

Murthy,Indumathi hep-ph/0407336

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- For $\Delta {m^2}_{31} > 0$ matter effect in ν_μ ($\mathrm{N}^{\mathrm{mat}}_{\mu^+} \approx \mathrm{N}^{\mathrm{vac}}_{\mu^+}$)
- 3-4σ signal for matter effects at $\sin^2 2\theta_{13} = 0.1$ for 1000kTy using the total event rates for fixed values of parameters
- Parameter uncertainties spoil the sensitivity

Bin by bin χ^2-analysis

- Results for a iron calorimeter detector
  - χ^2 analysis of μ^- event in 24 L/E bins
  - 15% energy and 15^o angular resolution
  - 10% systematic error
  - 85% efficiency
  - Marginalized over Δm^2_{31}, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$

$\sin^2 2\theta_{13}$	$\chi^2_{\rm min}$ 500 kt yr	$\chi^2_{\rm min}$ 1000 kt yr
0.05	2.7	3.7
0.1	6.6	8.9

Gandhi et al. work in progress.

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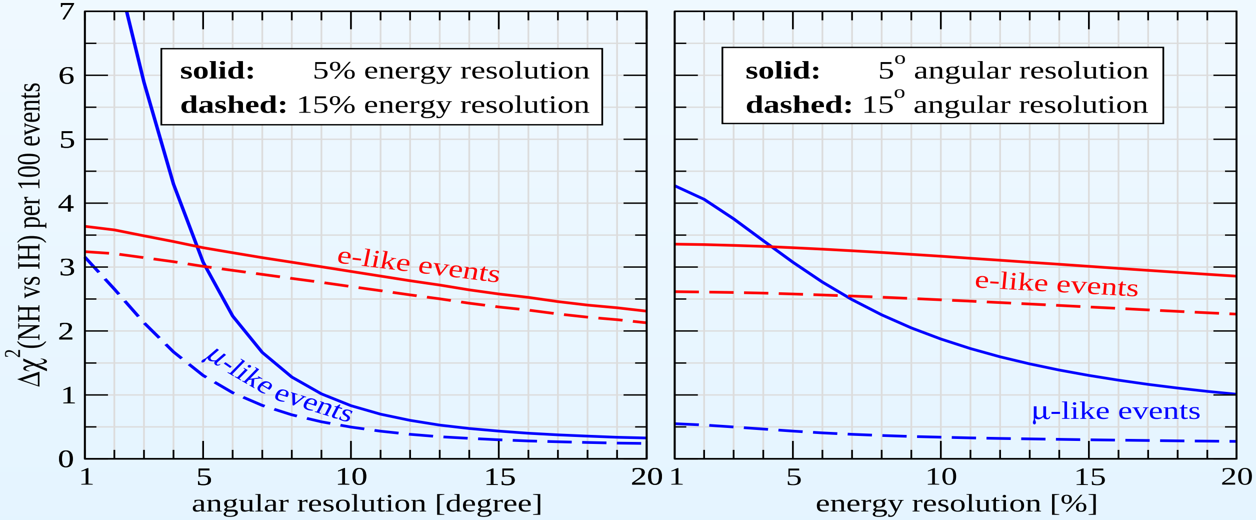
Gandhi et al. work in progress.

- Effect of Smearing



Petcov and Schwetz,hep-ph/0511277

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Gandhi et al. work in progress.

- Comparison with water-Cerenkov detector
  - No charge sensitivity: $N_\mu = N_\mu^+ + N_\mu^-$

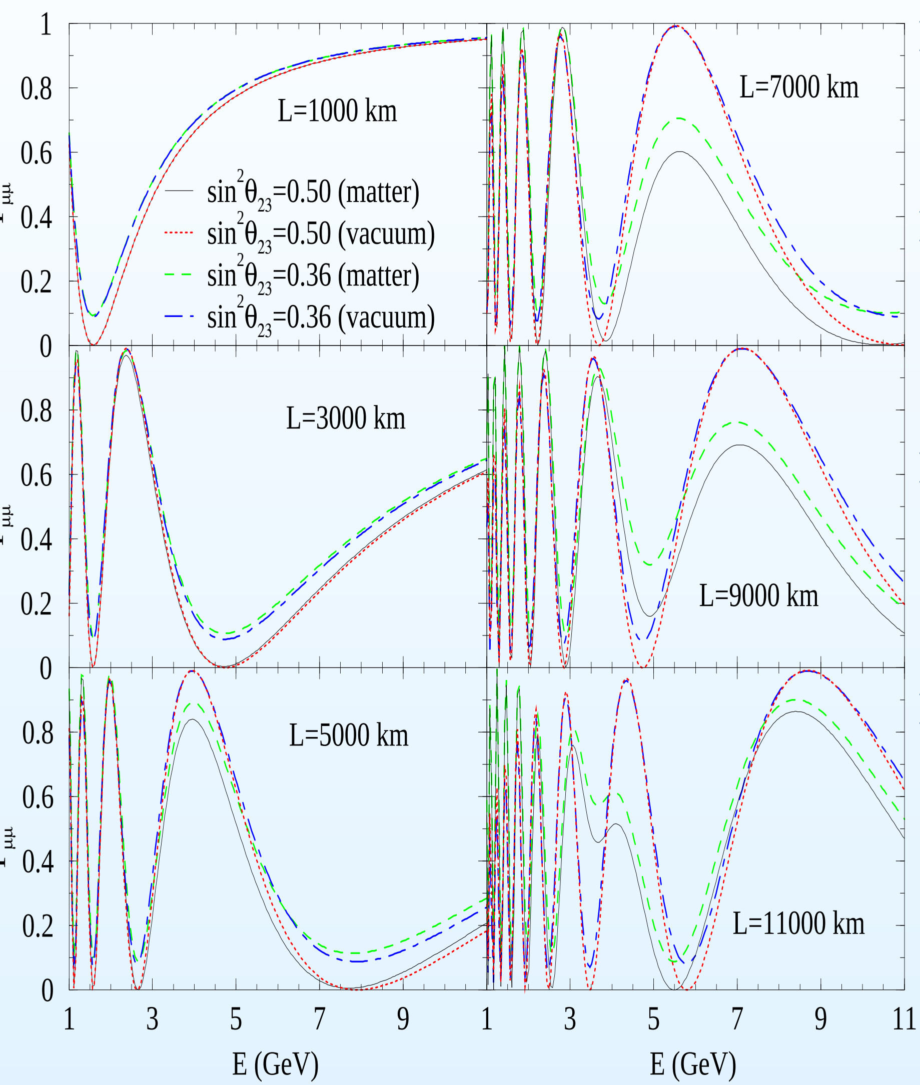
$\sin^2 2\theta_{13}$	$\chi^2_{\rm min}$ (6 Mt yr)
0.05	1.9
0.1	4.4

Gandhi et al., hep-ph/0406145

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 $|D|$?



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

$$P^m_{\mu\mu}{}^1 = c^2_{13}{}^m \sin^2 2\theta_{23} \sin^2 [1.27(\Delta_{31} + A + \Delta^m_{31})L/2E]$$

$$P^m_{\mu\mu}{}^2 = s^2_{13}{}^m \sin^2 2\theta_{23} \sin^2 [1.27(\Delta_{31} + A - \Delta^m_{31})L/2E]$$

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

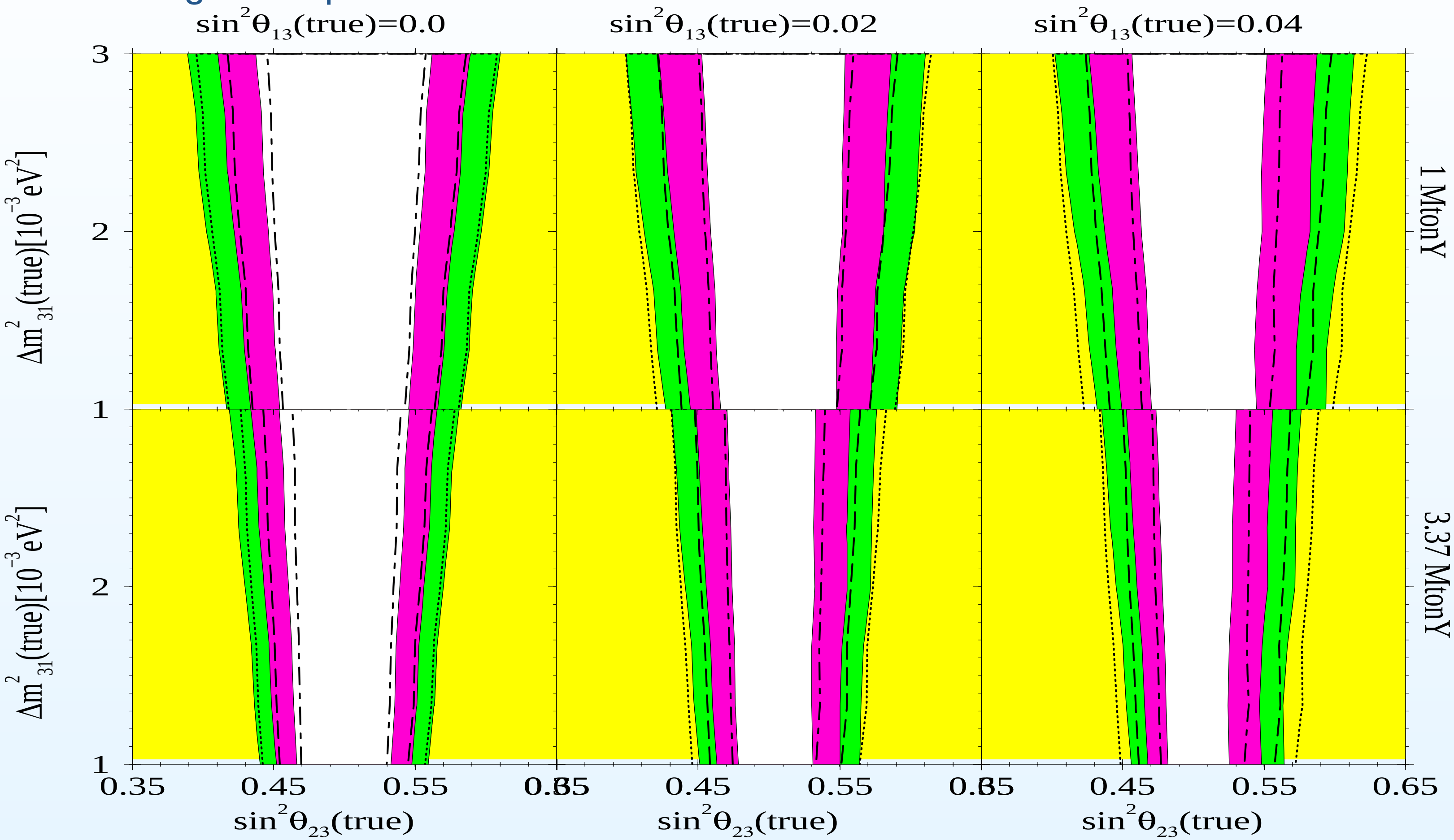
- Dependence on θ_{23} in the form $\sin^4 \theta_{23}$
- Octant sensitivity ?

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

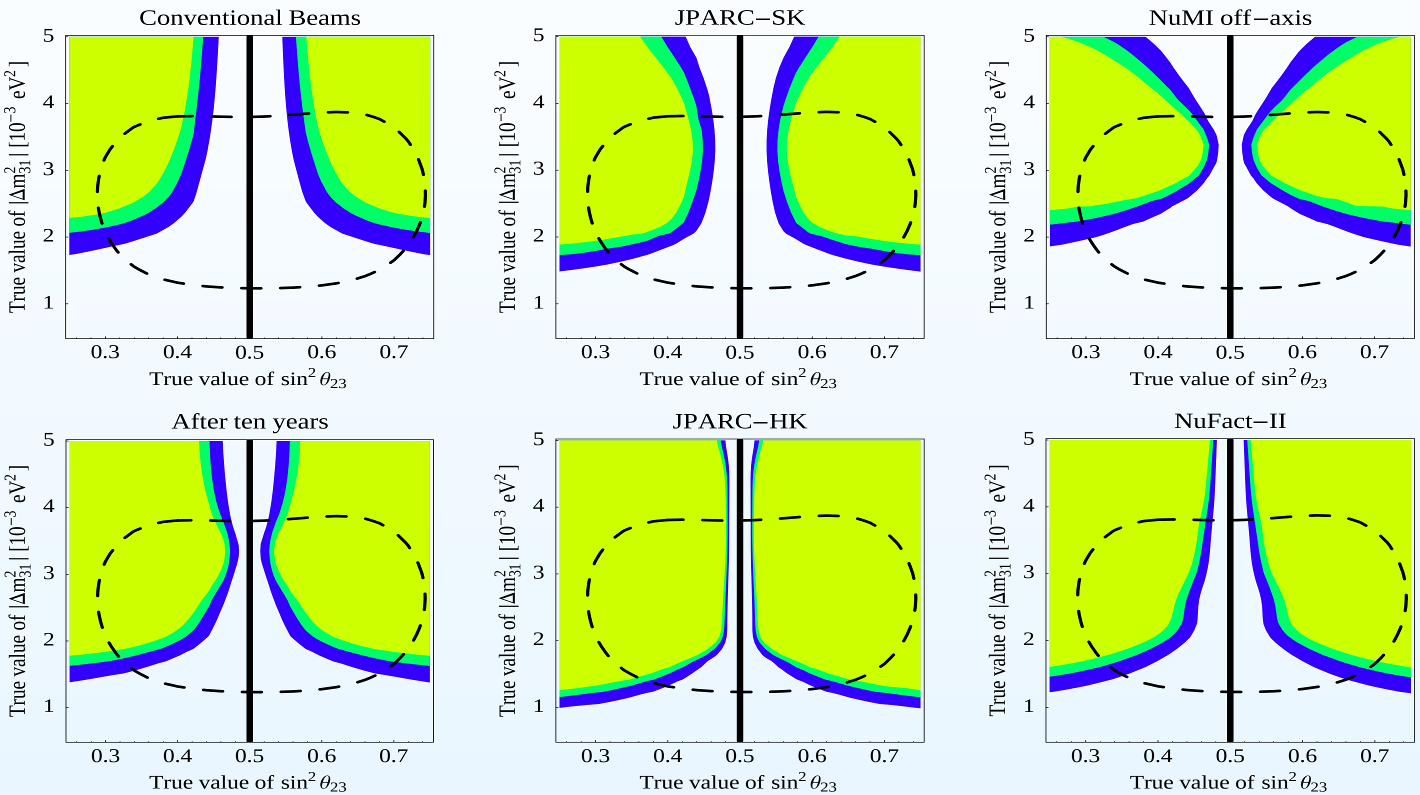


- $|D|$ can be measured to $\sim 17\%(20\%)$ at 3σ for $s^2_{13} = 0.04(0.00)$ with 1 MtonY exposure and 50% detector efficiency

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

Is the atmospheric mixing maximal?

- Using long baseline experiments

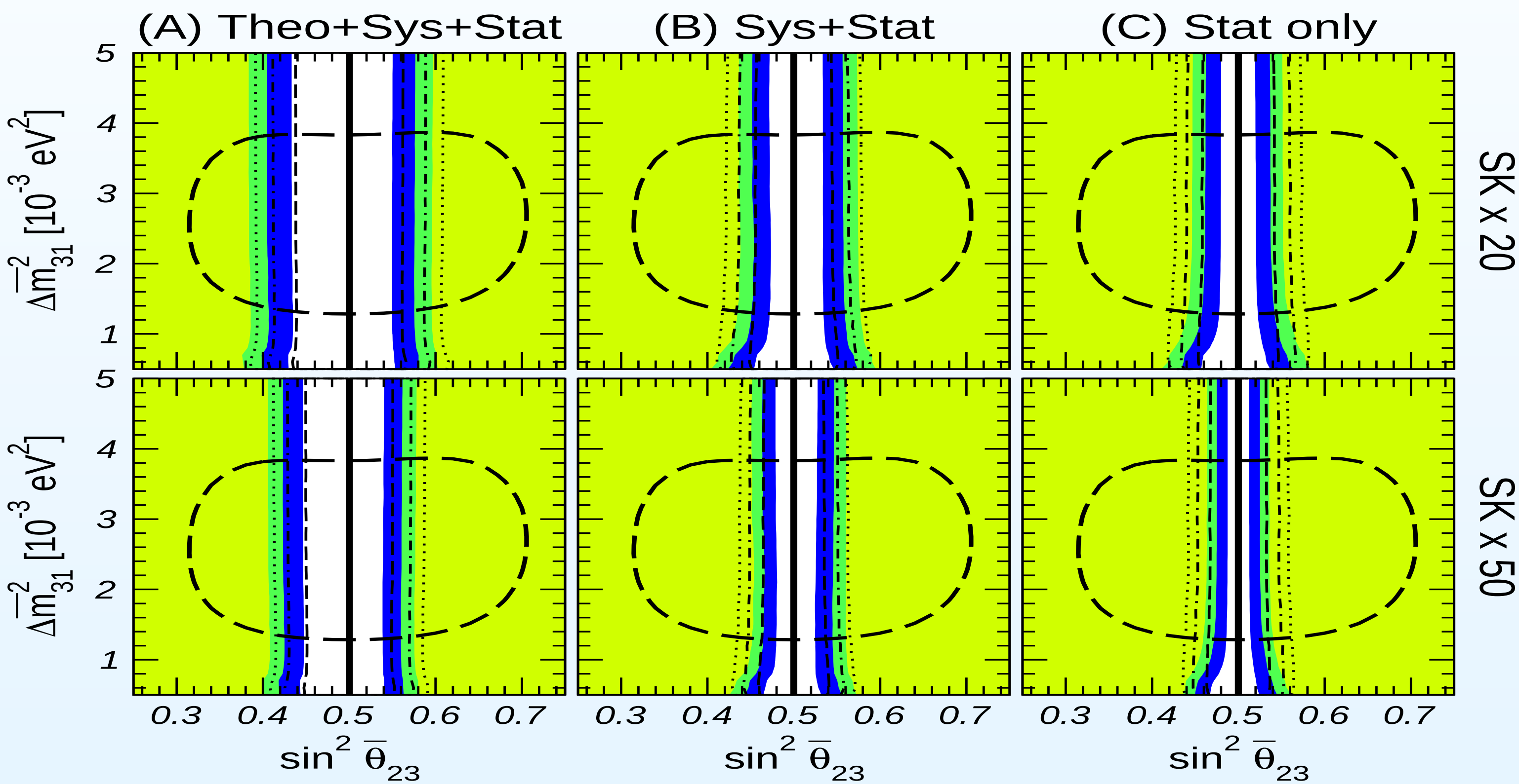


Antusch, et al, hep-ph/0404268

- Maximality can be tested to $\sim 14\%$ at 3σ for $\Delta m^2_{\rm atm} = 2.5 \times 10^{-5}$ eV^2 after 10 years.

Is the atmospheric mixing maximal?

- Using atmospheric neutrino data in SK
- Sensitivity comes from $\Delta m^2{}_{21}$ driven oscillations
- Main effect in sub-GeV e-effects ⇨ electron excess



Gonzalez-Garcia et al, hep-ph/0408170

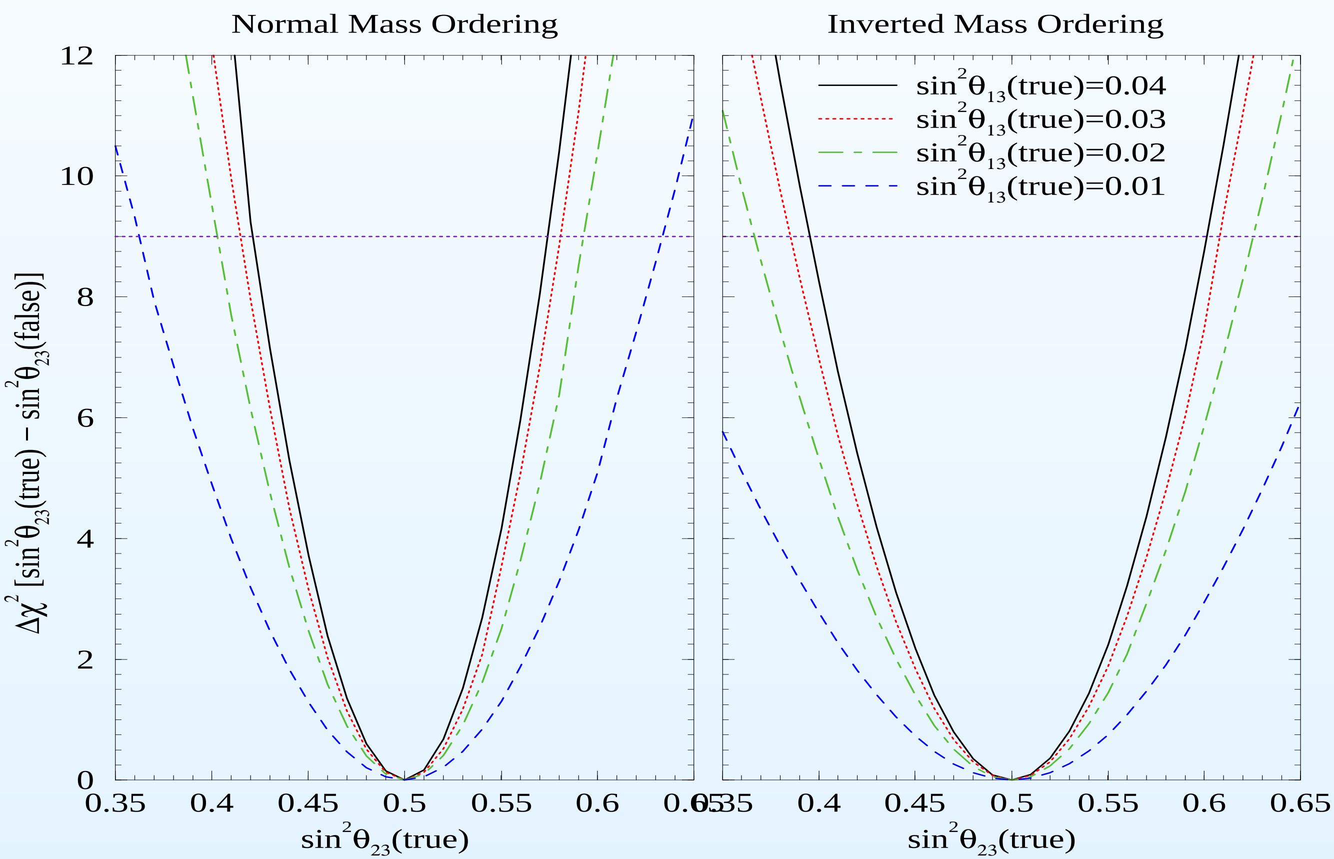
Also Huber et al. hep-ph/0501037

Maximality can be tested to $\sim$ 21% at 3σ at all $\Delta m^2_{\rm atm}$ with SK20

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:

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

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:

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

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

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

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

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 neurtrino energy and direction
  - Physics Performance
    - Analysis of reconstructed events to extract physics.

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, Liquid Scintillator and Liquid Argon Detectors as well as the long baseline and reactor experiments
- Can be used as a far detector for neutrino factories

Should be an International Facility