Atmospheric Neutrinos and INO

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UKIERI
UK-India Education and Research Initiative

Three Neutrino Oscillation Parameters

- $$U = \overset{\Delta m^2_{31}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \overset{\Delta m^2_{21}}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

  $$\leftarrow \mathrm{atm} + \mathrm{LBL} \rightarrow \qquad \leftarrow \mathrm{reactor} \rightarrow \qquad \leftarrow \mathrm{solar} \rightarrow$$

- Since θ_{13} is small and $\Delta m^2_{21} << \Delta m^2_{31}$ the solar and atmospheric neutrino oscillations are almost decoupled and can be explained by two flavour oscillations

Three Neutrino Oscillation Parameters

- Known Parameters

Parameters	Best − fit	3σ range
Δm^2_{21}	$7.7 \times 10^{-5} eV^2$	$(7.1 - 8.3) \times 10^{-5} eV^2$ (8%)
Δm^2_{31}	$2.5 \times 10^{-3} eV^2$	$(1.8 - 3.3) \times 10^{-3} eV^2$ (29%)
$\sin^2\theta_{12}$	0.32	$0.26 - 0.42$ (23%)
$\sin^2\theta_{23}$	0.5	$0.34 - 0.68$ (33%)

- Bounded Parameters

  $\sin^2\theta_{13} \leq 0.044$,

  $\Sigma m_i \leq (0.17 - 2.0)$ eV

- No information on

  $sgn(\Delta m^2_{31})$ (nature of mass spectrum)

  Octant of θ_{23}

  CP phases

Important Future Goals

- Improve the errors in $\delta(\sin^2\theta_{12})$
- Improve the errors in $\delta(\Delta m^2_{31})$
- Improve the errors in $\delta(\sin^2\theta_{23})$
- Determine the octant of θ_{23}
- Ascertaining if θ_{13} is different from zero and improve sensitivity
- Determination of $sgn(\Delta m^2_{31})$
- Discovering the leptonic CP phase δ
- Search for non-standard interactions and new physics
- Sterile neutrinos

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

Atmospheric neutrinos . . .

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

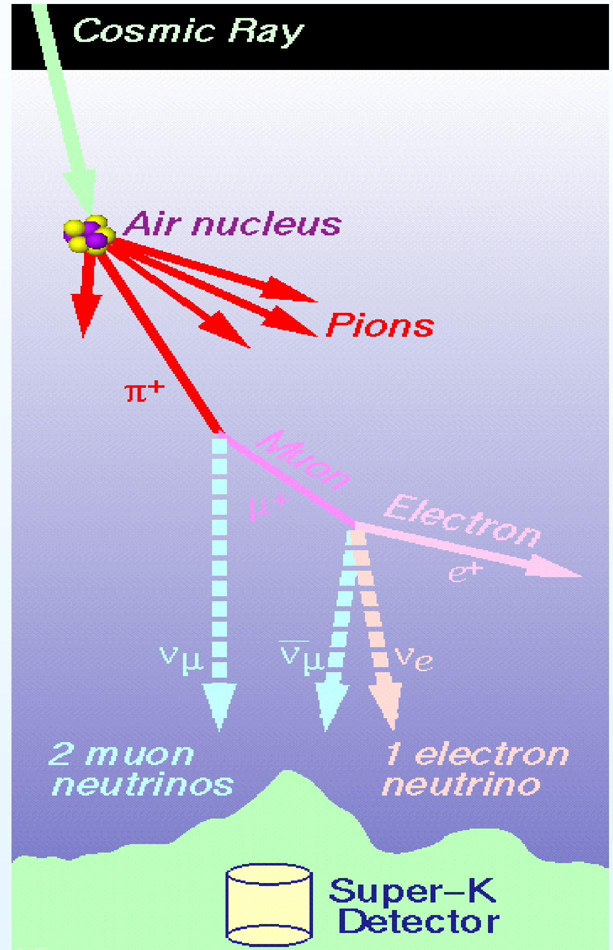
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

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

$\nu_\mu : \nu_e$ = 2: 1 (expected)

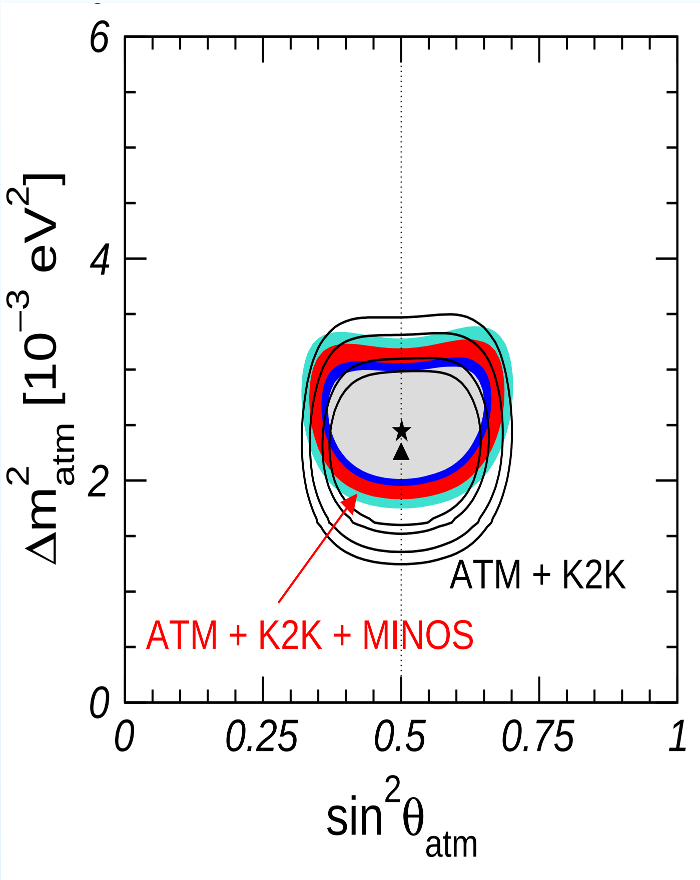
$\nu_\mu/\nu_e \sim$ 0.9 – 1 (observed)

- Energy: 100 MeV - TeV
- Pathlength: 15 -13,000 km
- Provides broad L/E band



Status of Atmospheric parameters

- Two generation $\nu_\mu - \nu_\tau$ oscillation ($\theta_{atm} \equiv \theta_{23}$, $\Delta m^2_{atm} \equiv \Delta m^2{}_{31}$)
- $P_{\mu\mu} = 1 - \sin^2 2\theta_{atm} \sin^2 \left(\frac{\Delta m^2_{atm} L}{4E} \right)$
- $\theta_{23} - (\pi/2 - \theta_{23})$ symmetry



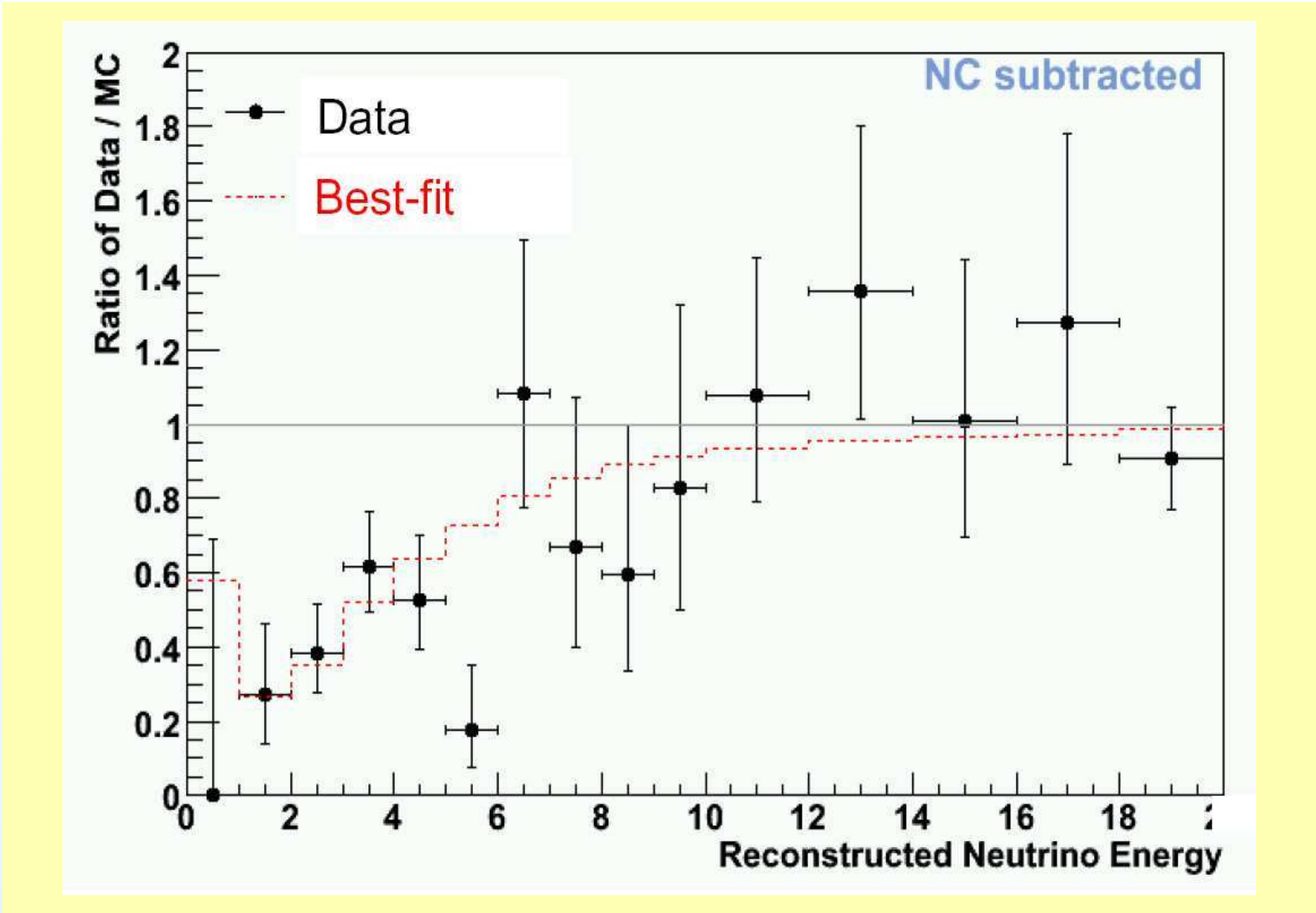
Exp	bf	3σ $range$
	$\Delta m^2_{31} [10^{-3} eV^2]$	
SK	2.0	1.0 – 3.8
$SK + K2K$	2.4	1.4 – 3.3
$SK + K2K$ $+MINOS$	2.5	1.8 – 3.3
	$\sin^2\theta_{23}$	
SK	0.5	0.34 – 0.68

Thomas Schwetz, 2006

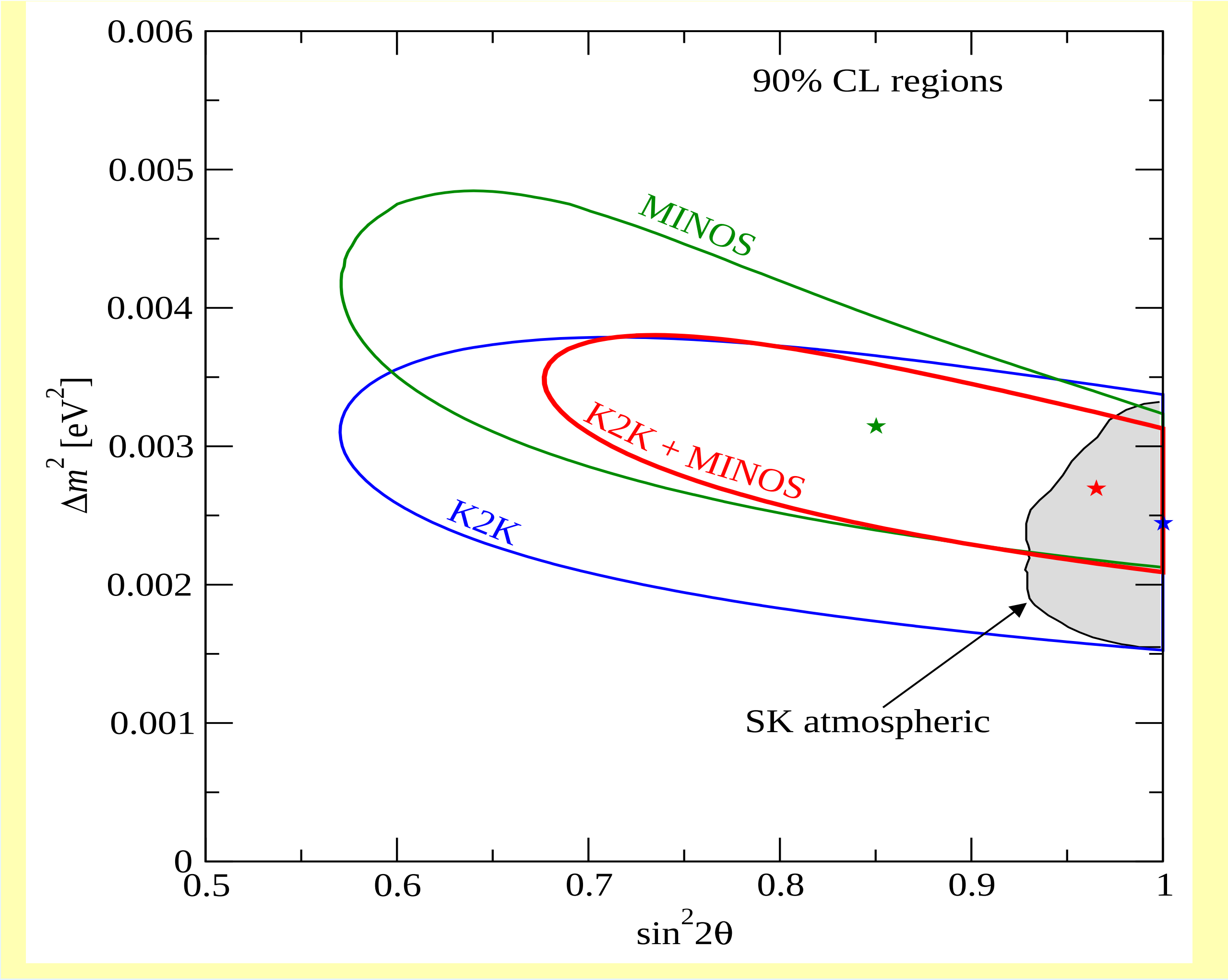
- Precision

$\Delta m^2_{31} \sim$ 29% $\sin^2\theta_{23} \sim$ 33 %

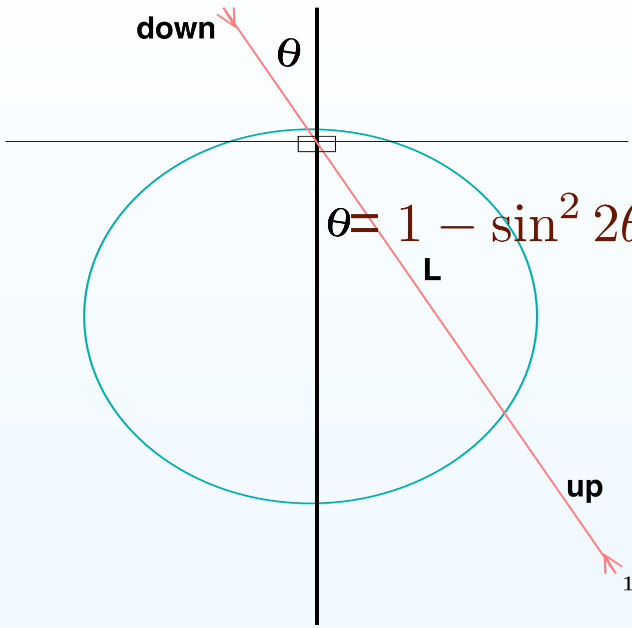
First Results from MINOS



Atmospheric parameters from MINOS



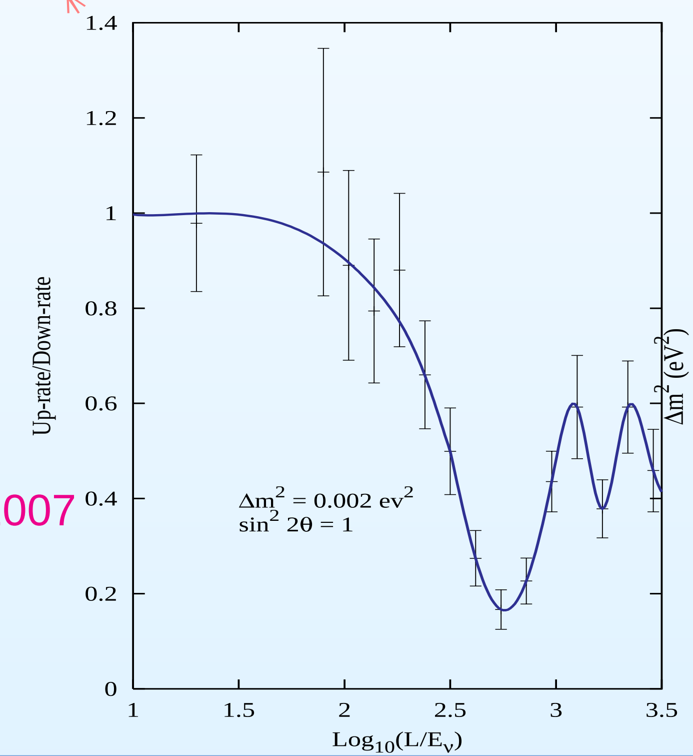
Disappearance of ν_μ vs L/E

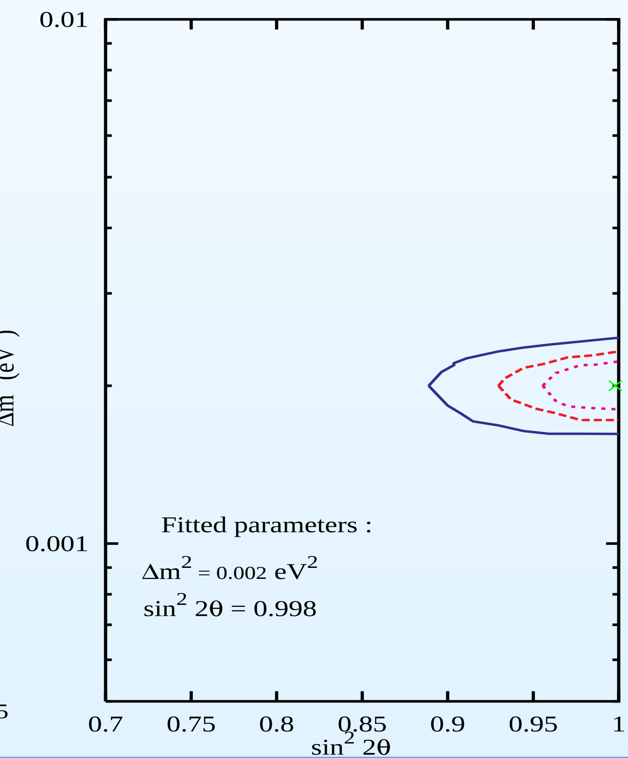


- $\frac{N_{up}(L/E)}{N_{down}(L/E)} \simeq P_{\mu\mu}$

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

- The longer baselines for upward going neu nos allow matter effects to develop when thr flavour effects are included

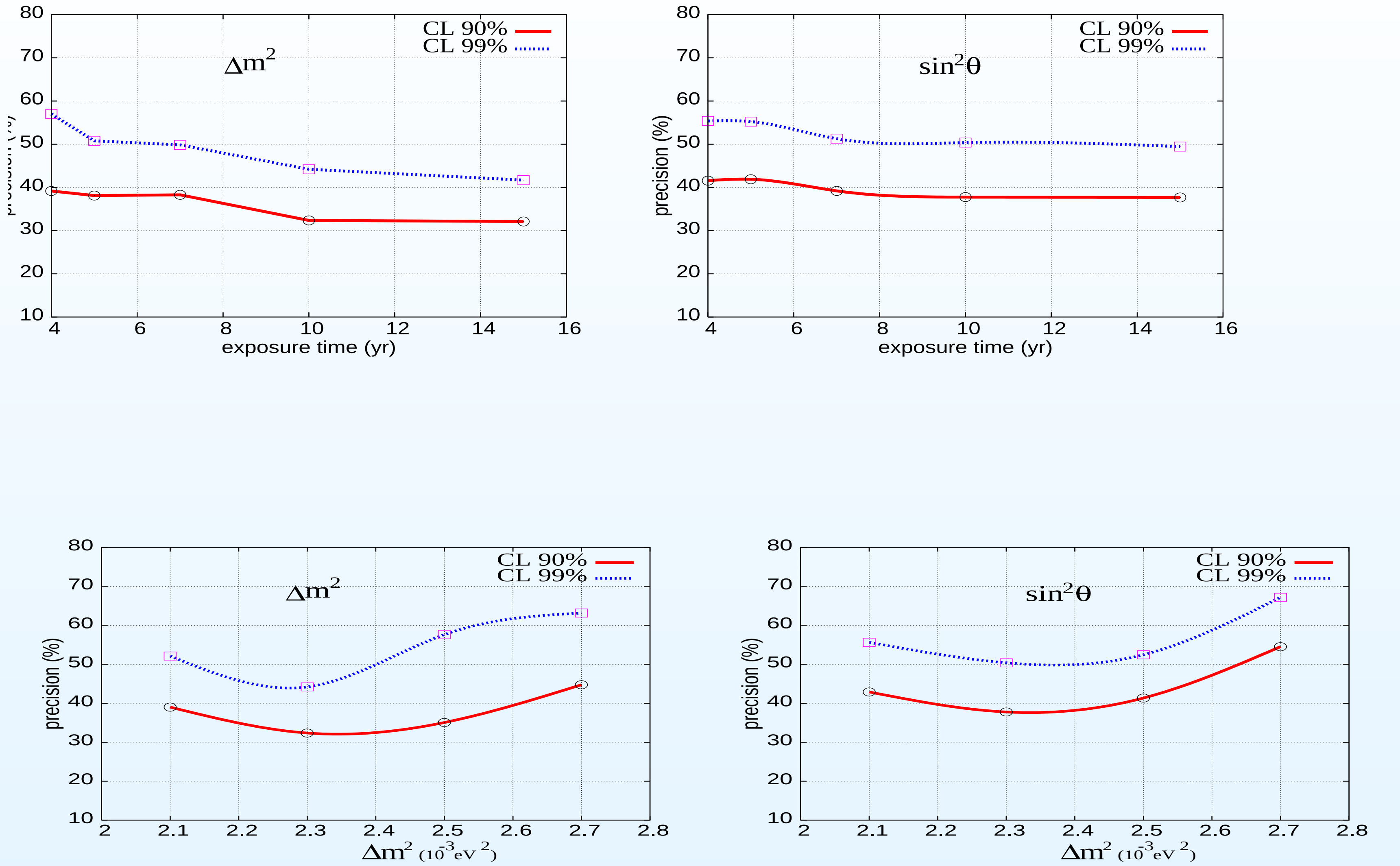




Expect to determine Δm^2_{31} with 10% precision

INO report, S. Bhattacharya et al. 2007

Precision of Atmospheric Parameters with INO



A. Samanta et al. IJMP, 2007

Comparison with Long Baseline Experiments

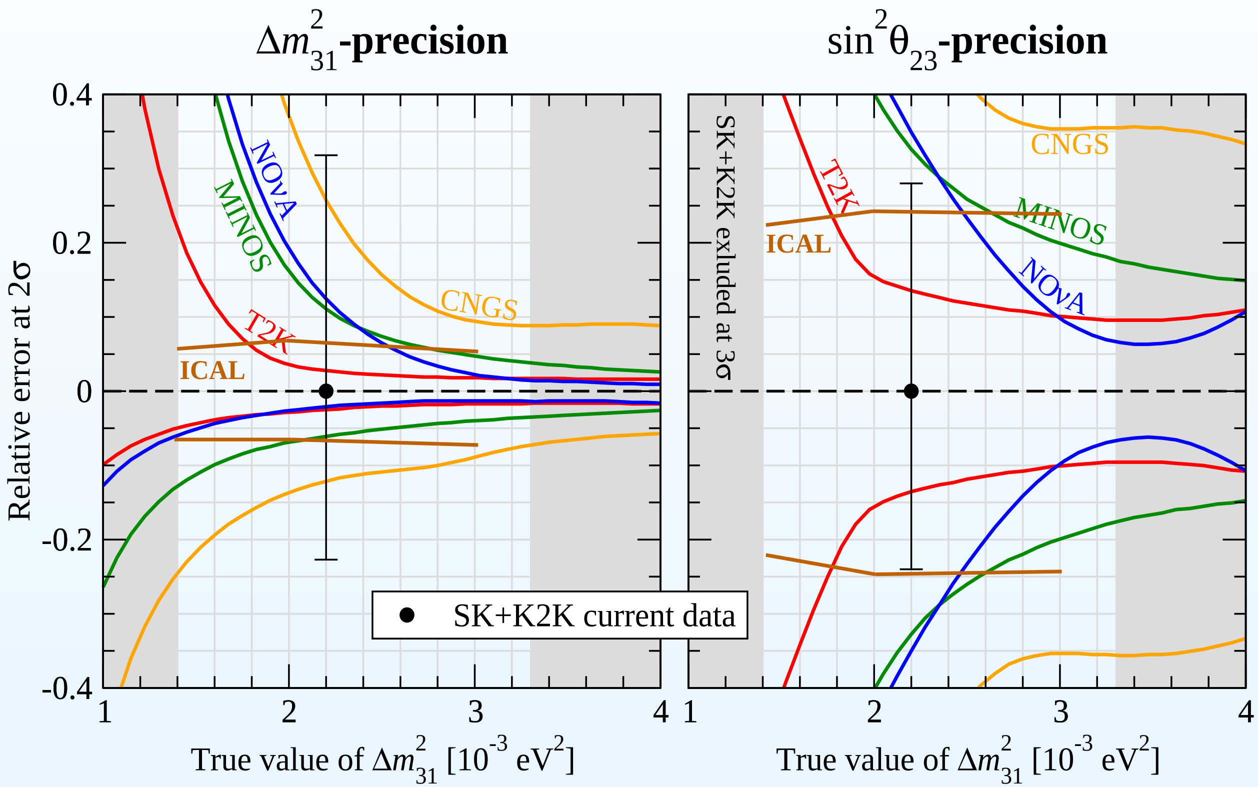
- 3σ spread ($\Delta m^2{}_{13}$ = 2×10^{-3} eV^2, $\sin^2\theta_{23} = 0.5$).

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

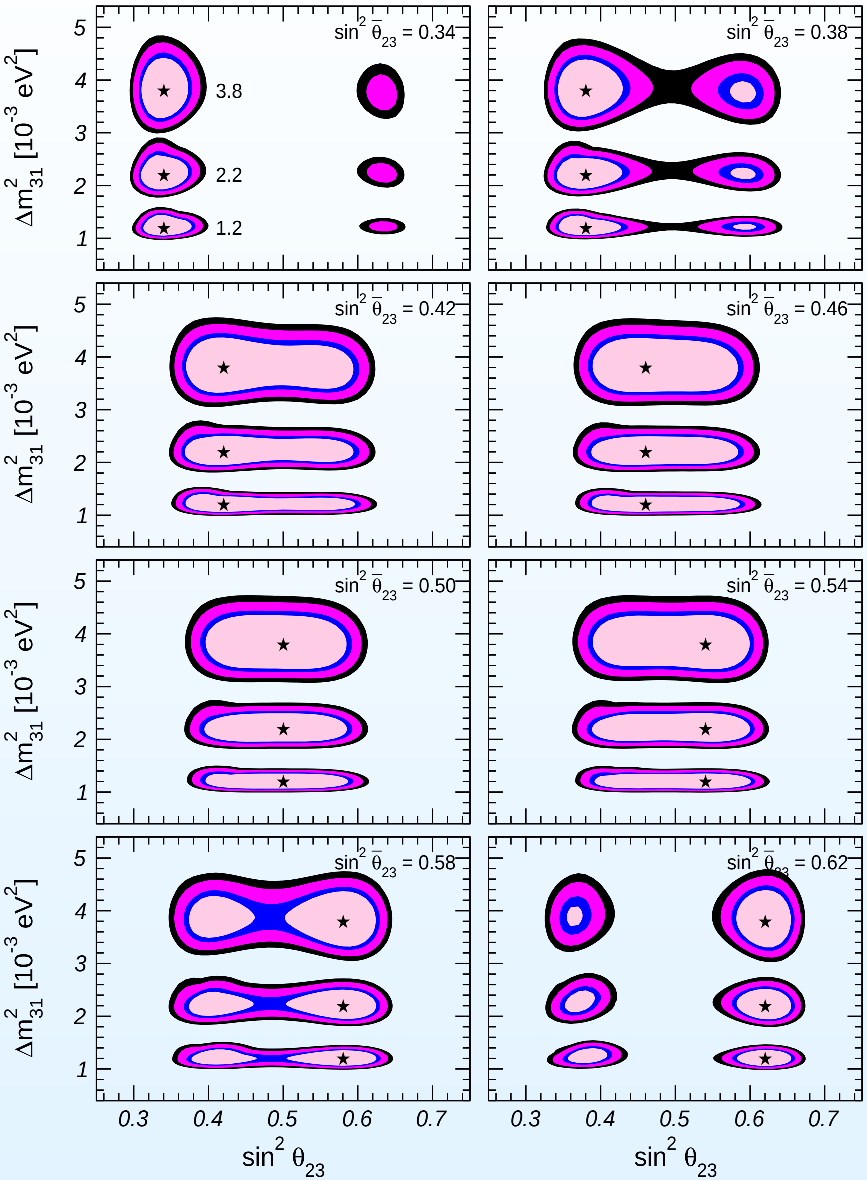
M. Lindner, hep-ph/0503101

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

Comparison with Long Baseline Experiments



Constraints from future SK Data



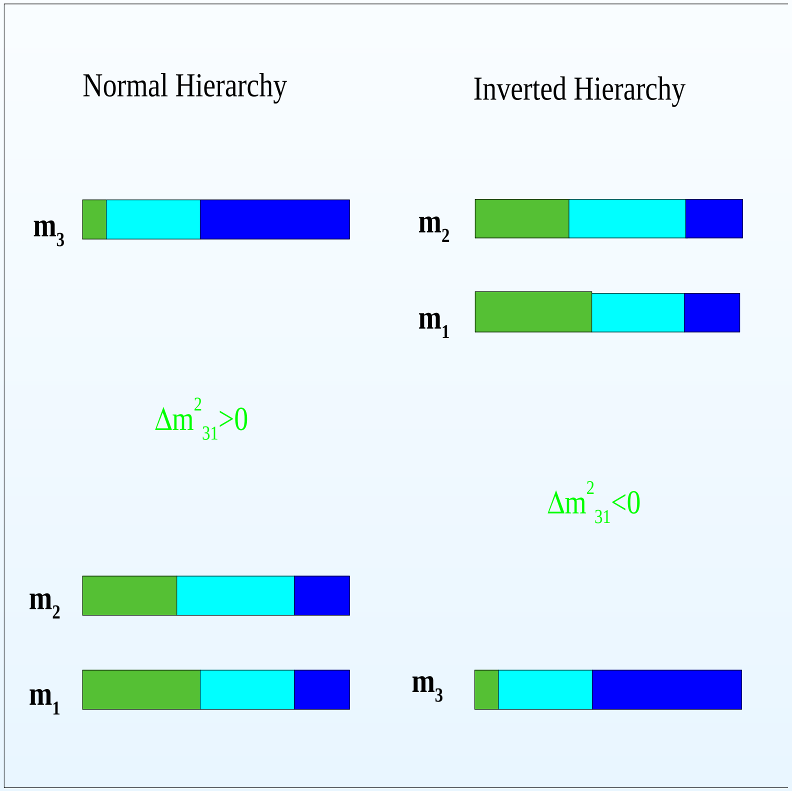
3σ spread after 20 SKyr

- ($\Delta m^2_{31} = 0.002$eV^2, $\sin^2\theta_{23} = 0.5$)

Δm^2_{31} = 17% $\sin^2\theta_{23}$ = 24%

Gonazalez-Garcia et al. hep-ph/0408170

Ambiguity in Mass Hierarchy



- Normal Hierarchy :

$$m_3^2 = m_1^2 + \Delta m_{21}^2 + \Delta m_{32}^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2$$

$$m_3^2 \approx \Delta m_{atm}^2 >> m_2^2 \approx \Delta m_{\odot}^2 >> m_1^2$$

- Inverted Hierarchy :

$$m_2^2 = m_3^2 + \Delta m_{23}^2$$
$$m_1^2 = m_3^2 + \Delta m_{23}^2 - \Delta m_{21}^2$$

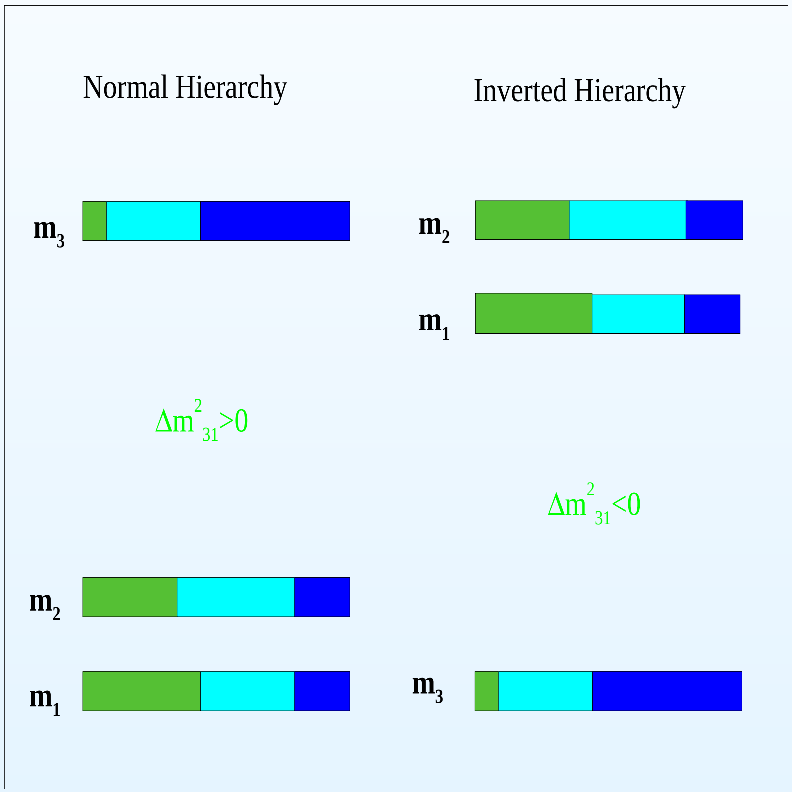
$$m_1^2 \approx \Delta m_{atm}^2 \approx m_2^2 >> m_3^2$$

- Quasi-Degenerate

$$m_3 \approx m_2 \approx m_1 >> \sqrt{\Delta m_{atm}^2}$$

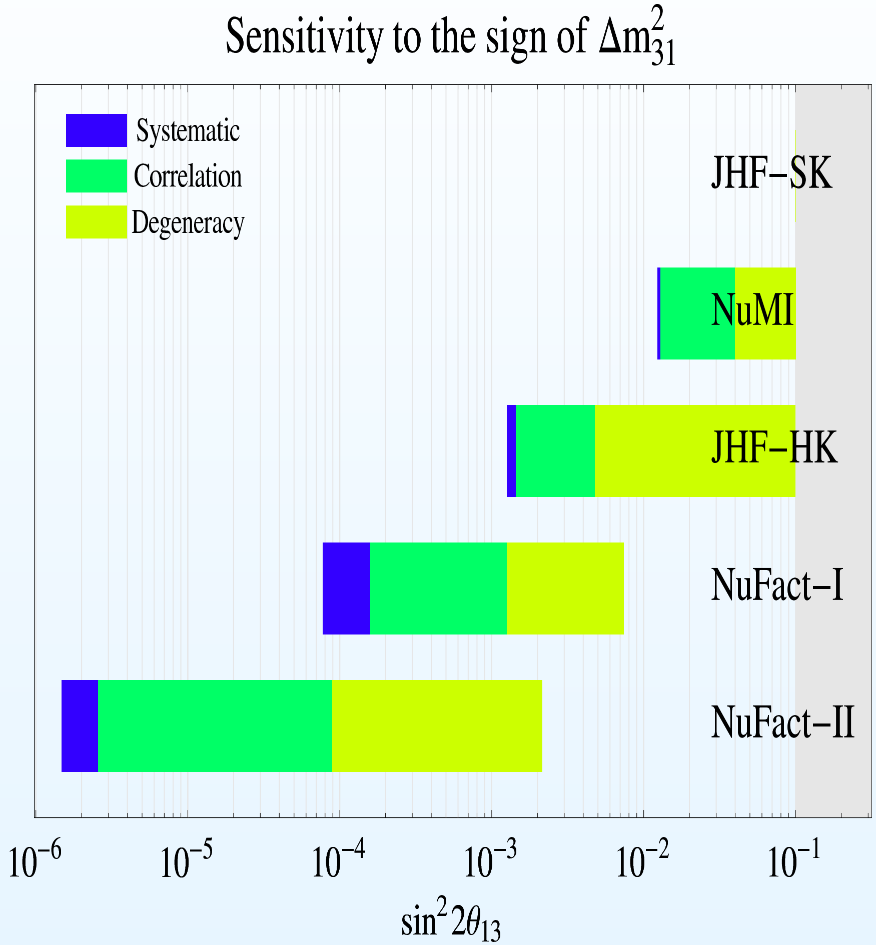
Ambiguity in Mass Hierarchy

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



- 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

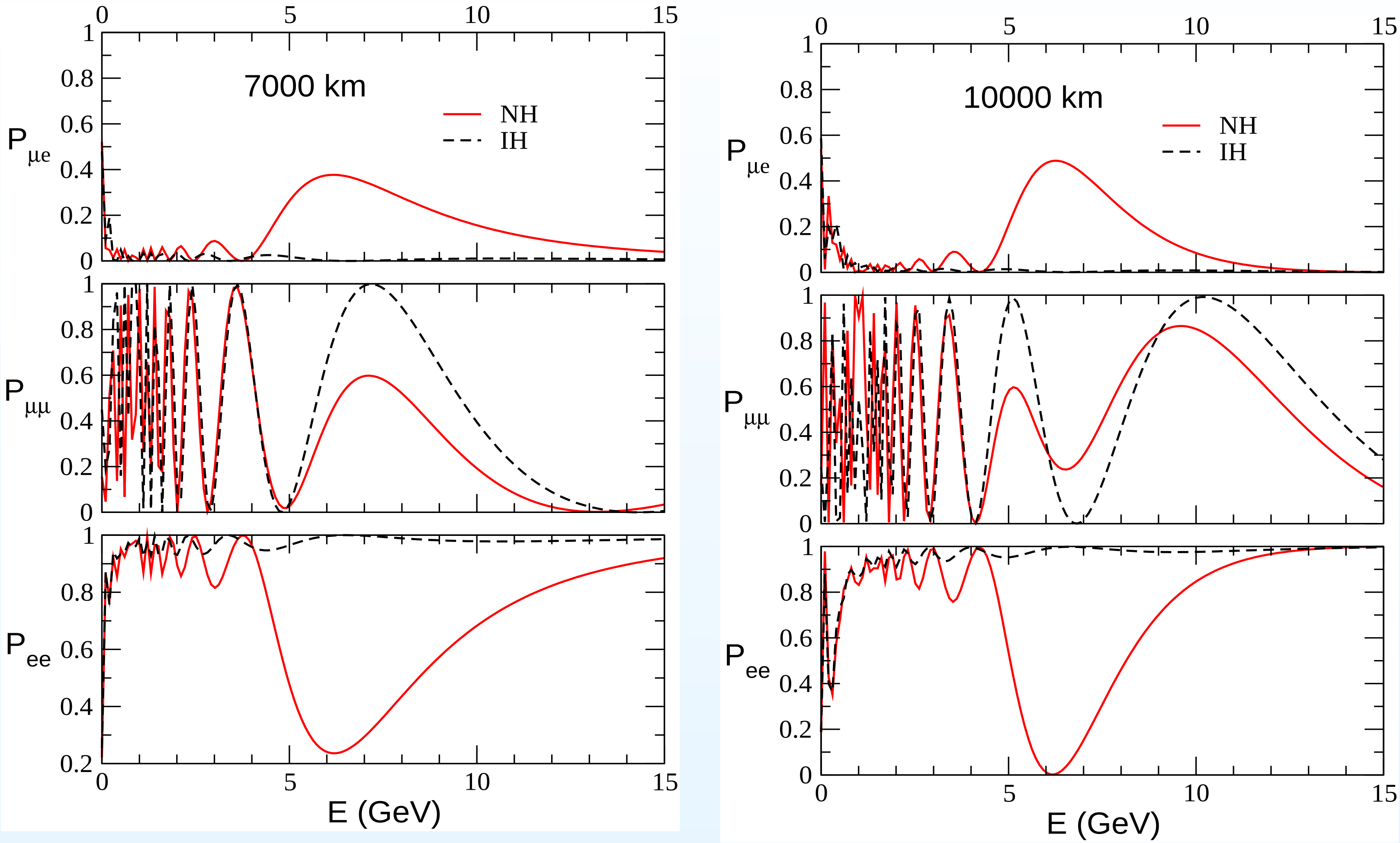
Ambiguity in Mass Hierarchy



M. Lindner, hep-ph/0503101

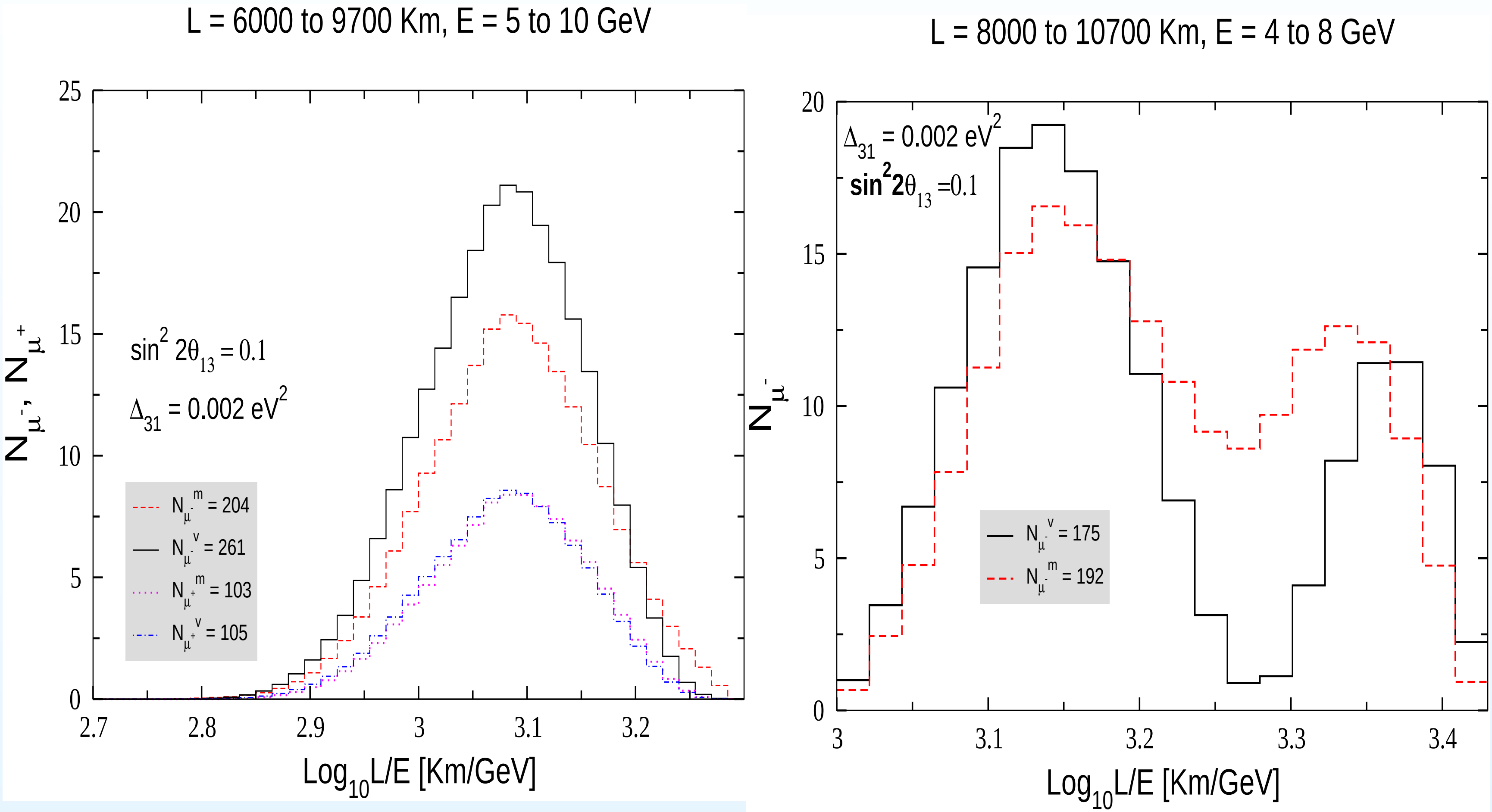
- Hierarchy difficult to determine in superbeams
- Sensitivity limited by correlation and degeneracies
- Synergistic use of experiments
- Use of Magic Baseline

Matter effect at large baselines



- Large matter effects at long baselines
- ν_μ survival probability can rise or fall in matter
- Problem of δ_{CP} degeneracy less

Hierarchy Sensitivity in Atmospheric ν events



- For $\Delta m^2_{31} > 0$ matter effect in ν_ν 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

Atmospheric Neutrinos 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
  $10^o, 15\%$

Statistical analysis

- Energy and $\cos\theta_z$ range divided into 8 $\times$ 18 = 144 bins
- INO: $\chi^2 = \chi^2_\mu + \chi^2_{\bar{\mu}}$

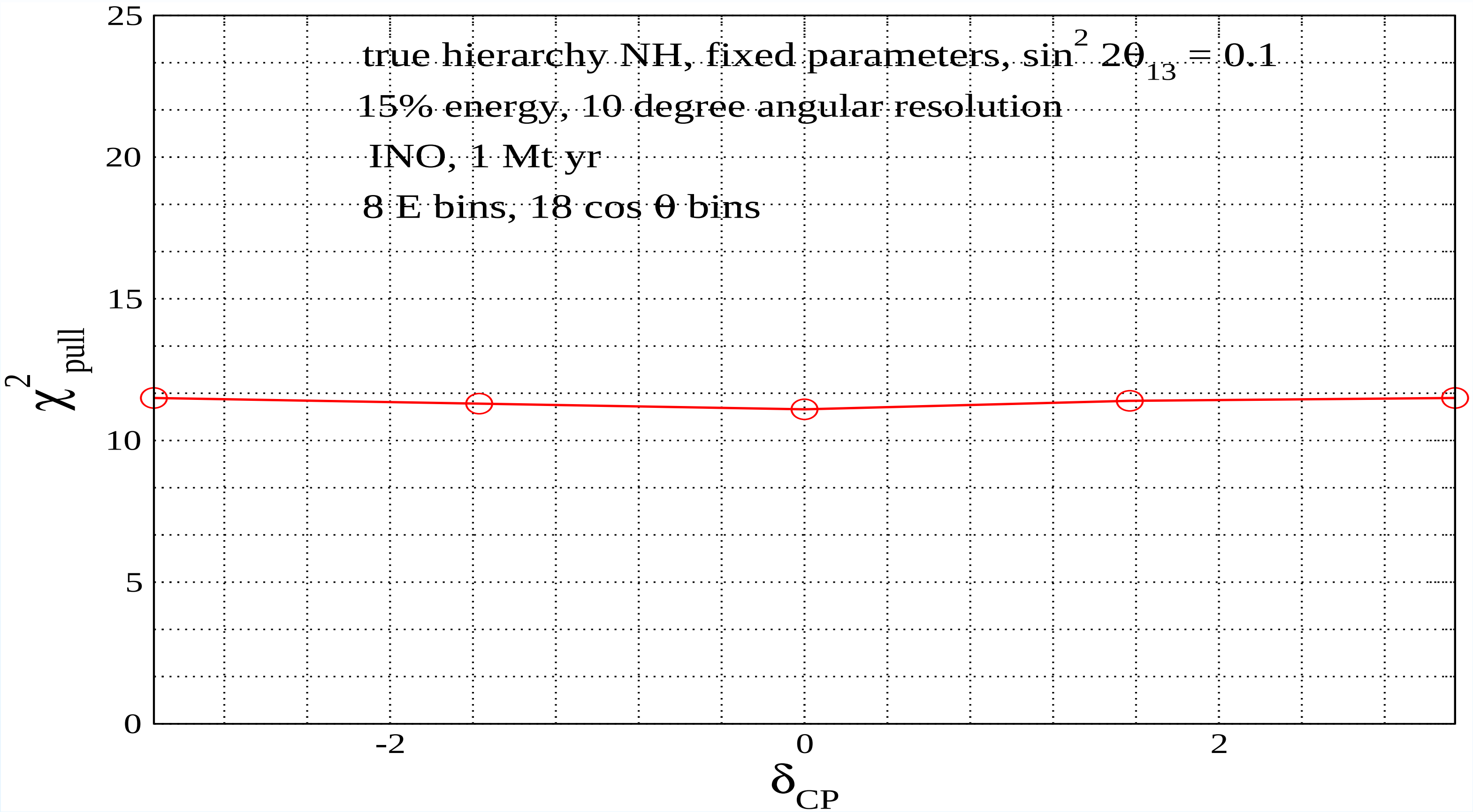
$$\chi^2_{\rm pull} = \min_{\xi_k}\left[\sum_{i=1}^{n} \frac{(N^i_{\rm theory} - N^i_{\rm expt} + \sum_{k=1}^{\rm npull} \xi_k c^k_n)^2}{(\sigma^i)^2} + \sum_{k=1}^{\rm npull} \xi_k^2\right]$$

- Values of theoretical and systematic uncertainties:
  - ➢ Flux normalization error 20 %
  - ➢ Energy dependent tilt factor 5 %
  - ➢ Zenith angle dependence uncertainty 5 %
  - ➢ Overall cross section uncertainty 10 %
  - ➢ Overall systematic uncertainty 5 %
- $N_{\rm expt} = N_{\rm NH}$, $N_{\rm theory} = N_{\rm IH}$

Statistical analysis

- Parameters uncertainties are taken care of by Marginalization
- Marginalization in $\mathrm{N}_{\mathrm{theory}}$, Δ_{21}, θ_{12} fixed, other parameters varied in the range:
- $\Delta m_{31}^2 = 2.35 \times 10^{-3} - 2.6 \times 10^{-3}$ eV^2
- $\sin^2\theta_{23} = 0.4 - 0.6$
- $\sin^2\theta_{13} = 0.0 - 0.05$ (3σ bound from CHOOZ is $<$ 0.044)
- "True" values of parameters fixed in $\mathrm{N}_{\mathrm{expt}}$

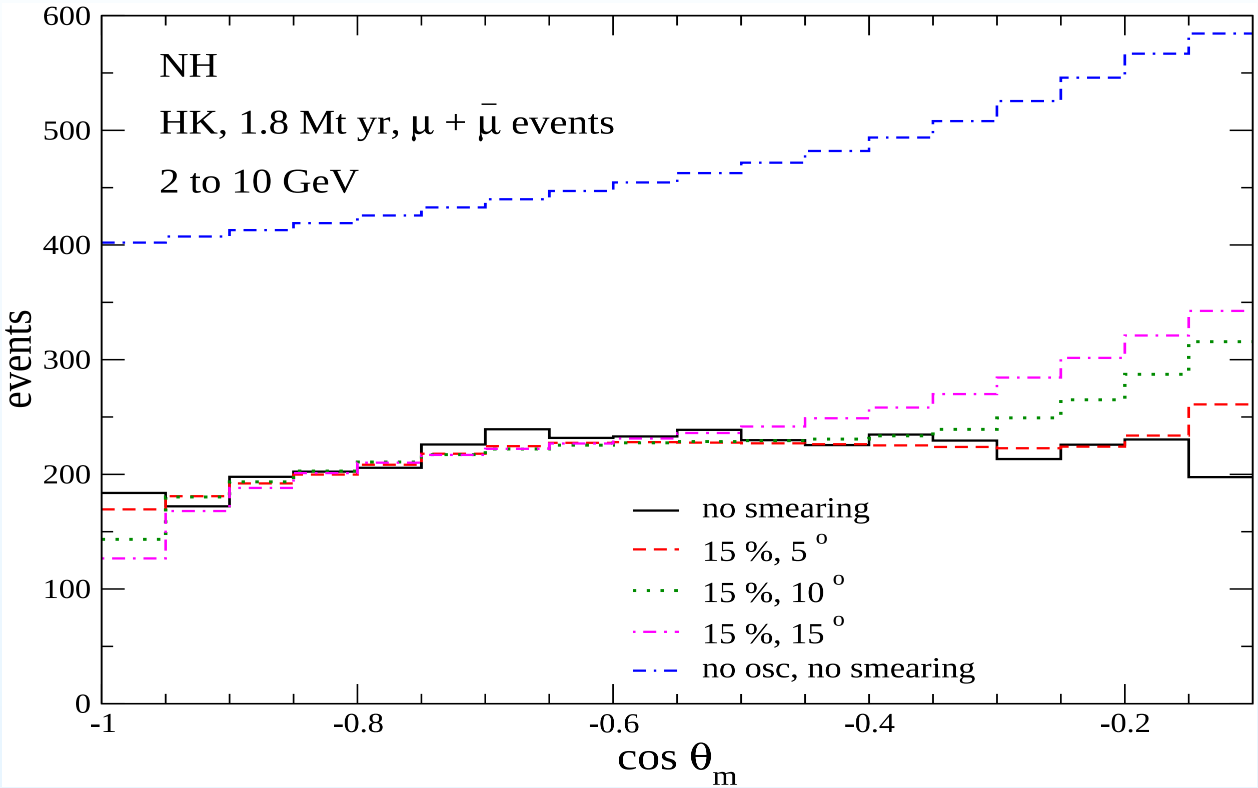
Effect of δ_{CP} on χ^2



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

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

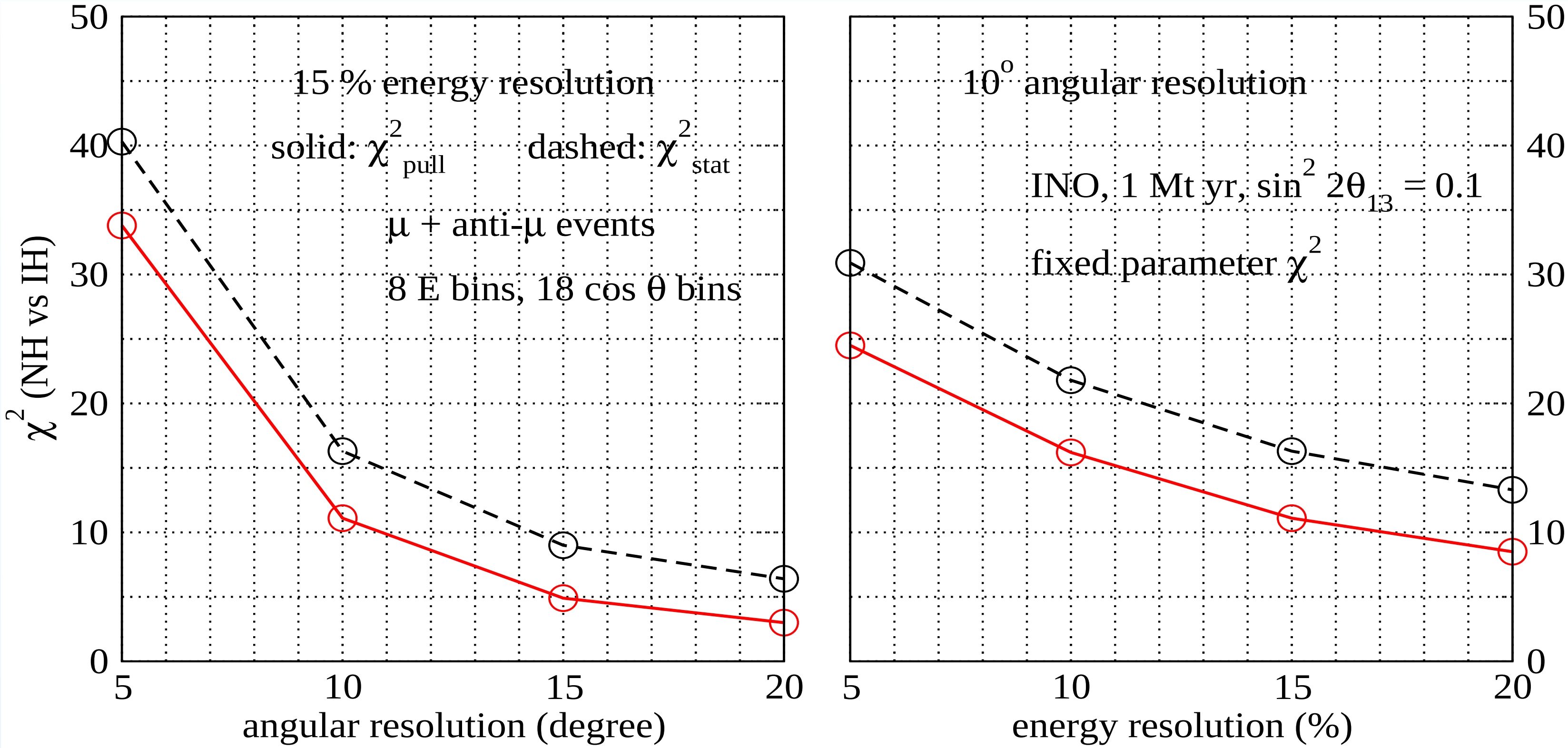
Effect of Smearing on Atmospheric ν Events



- 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



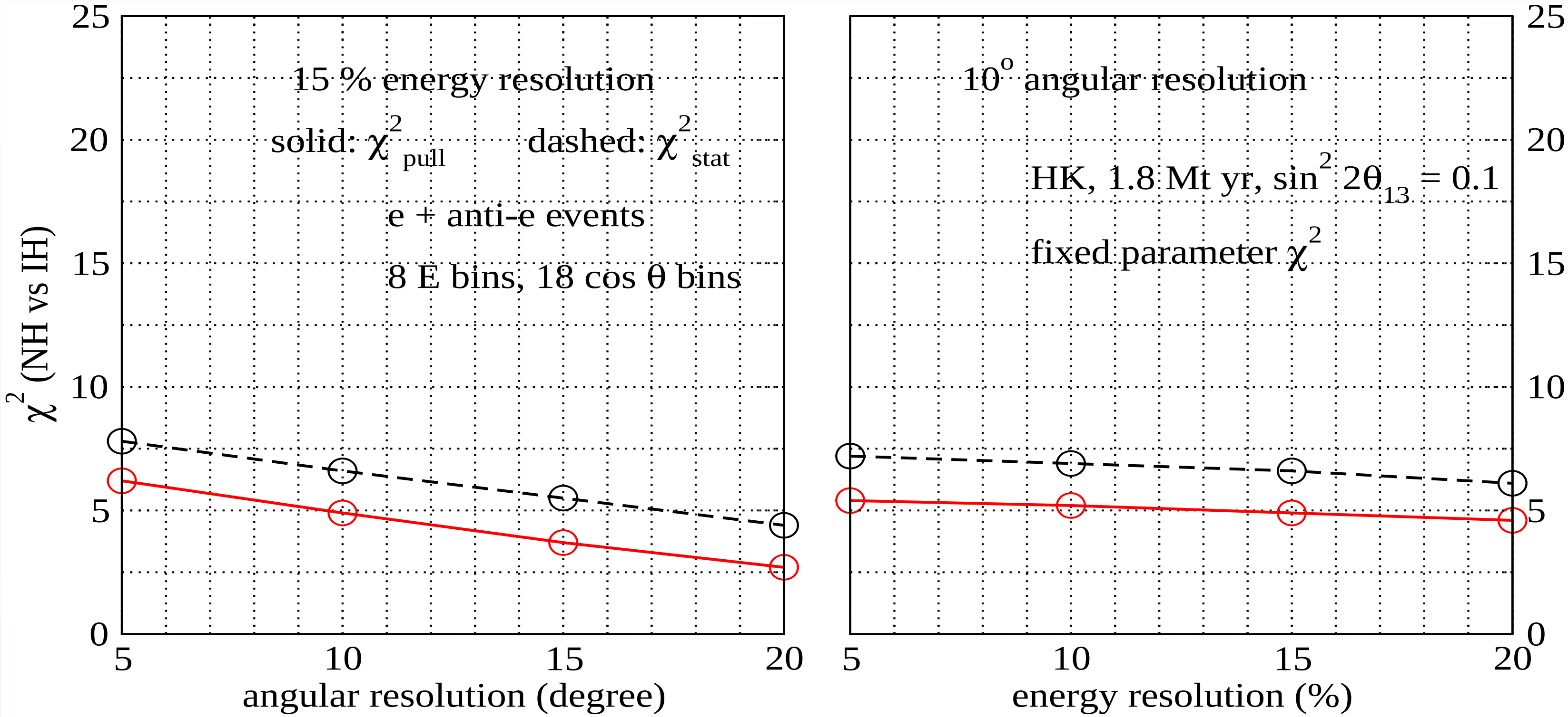
- With increased energy or angular smearing the χ^2 for muon like events decrease.

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

Effect of Smearing on χ^2

- Effect of smearing on electron-χ^2

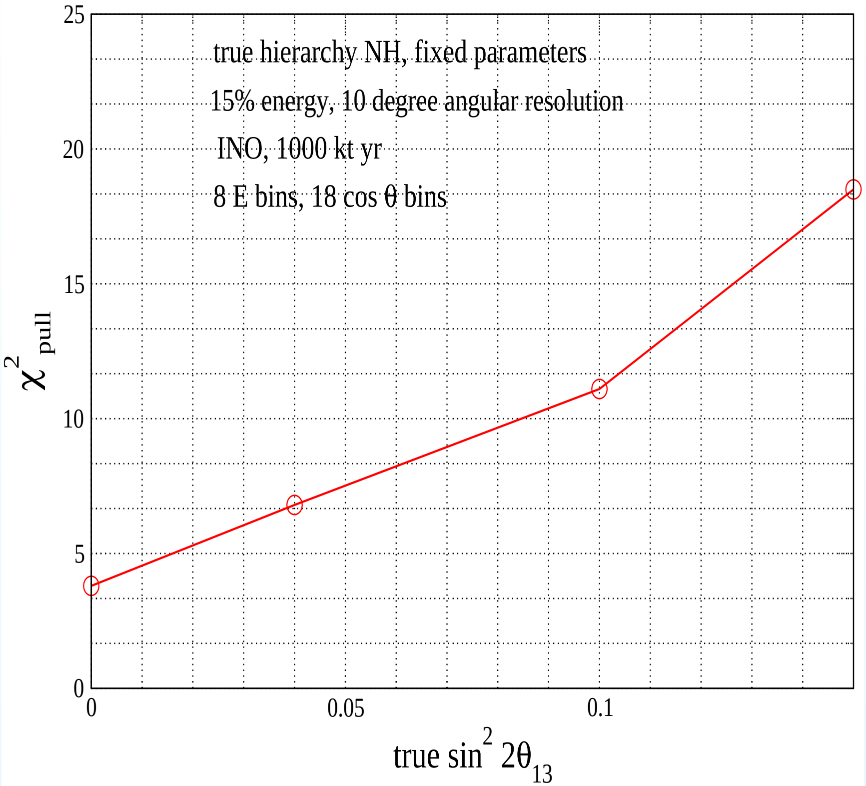


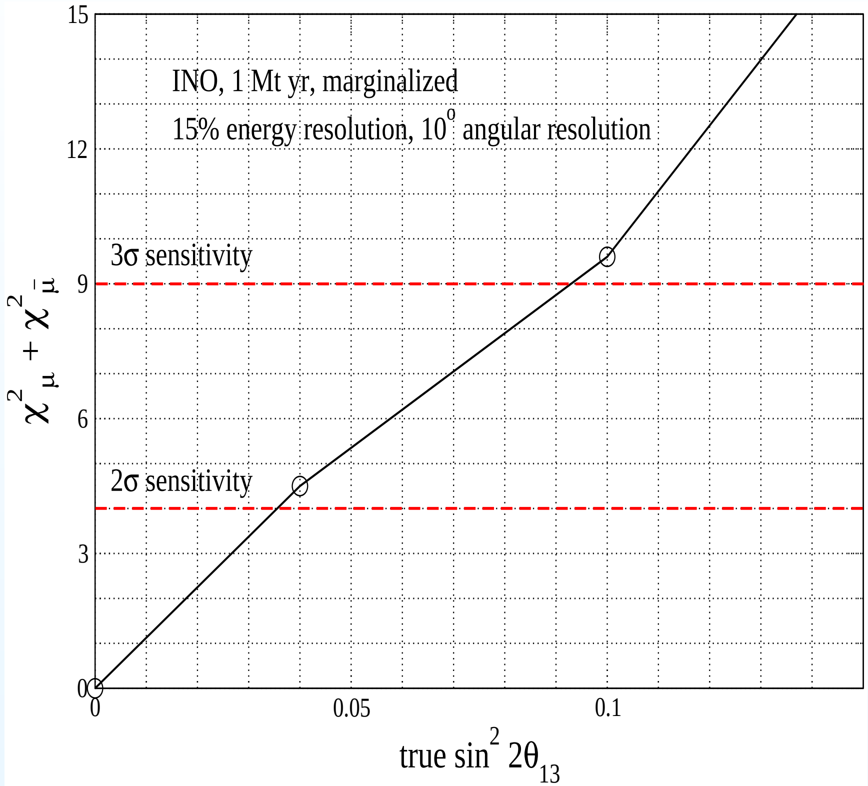
- The effect of smearing is less than that for muon events because the electron survival probability varies less rapidly with energy and zenith angle.

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 Sensitvity 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

Hierarch 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)
  $\chi^2 = \chi^2_\mu + \chi^2_{\bar{\mu}} + (\chi^2_e + \chi^2_{\bar{e}})_{1-5GeV} + (\chi^2_{e+\bar{e}})_{5-10GeV}$

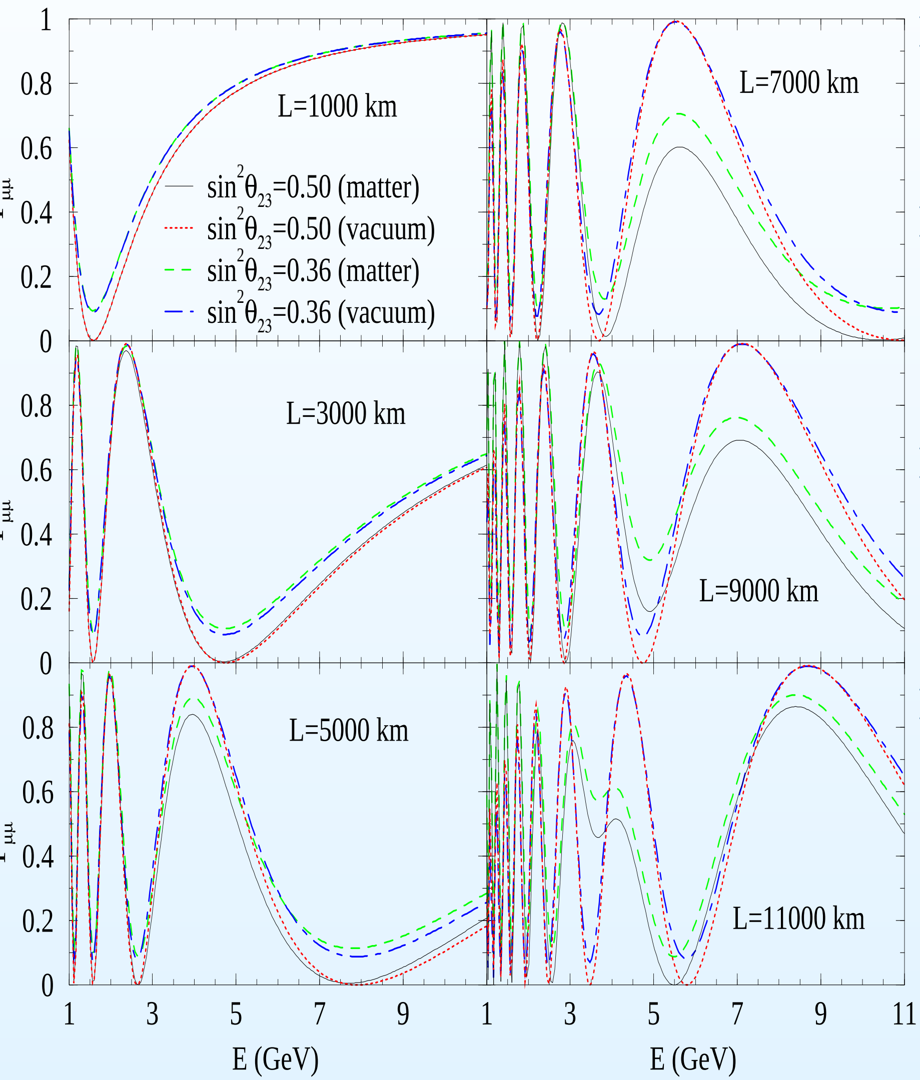
$\sin^2 2\theta_{13}$	$HK\chi^2$	$INO\chi^2$	LiqAr χ^2
0.0	0.0	0.0	0.0
0.04	3.6	4.5	13.8
0.1	5.9	9.6	27.5
0.15	7.1	16.9	

- LiqAr type detector has better energy smearing and partial charge identification of electrons (R. Gandhi et al. work in progress)

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 $|D|$?



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

$$P^{m}_{\mu\mu}{}^{1} = c^{2}_{13}{}^{m} \sin^2 2\theta_{23} \sin^2 \left[1.27(\Delta m^2_{31} + A + \Delta^{m}_{31})L/2\right.$$

$$P^{m}_{\mu\mu}{}^{2} = s^{2}_{13}{}^{m} \sin^2 2\theta_{23} \sin^2 \left[1.27(\Delta m^2_{31} + A - \Delta^{m}_{31})L/2\right.$$

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

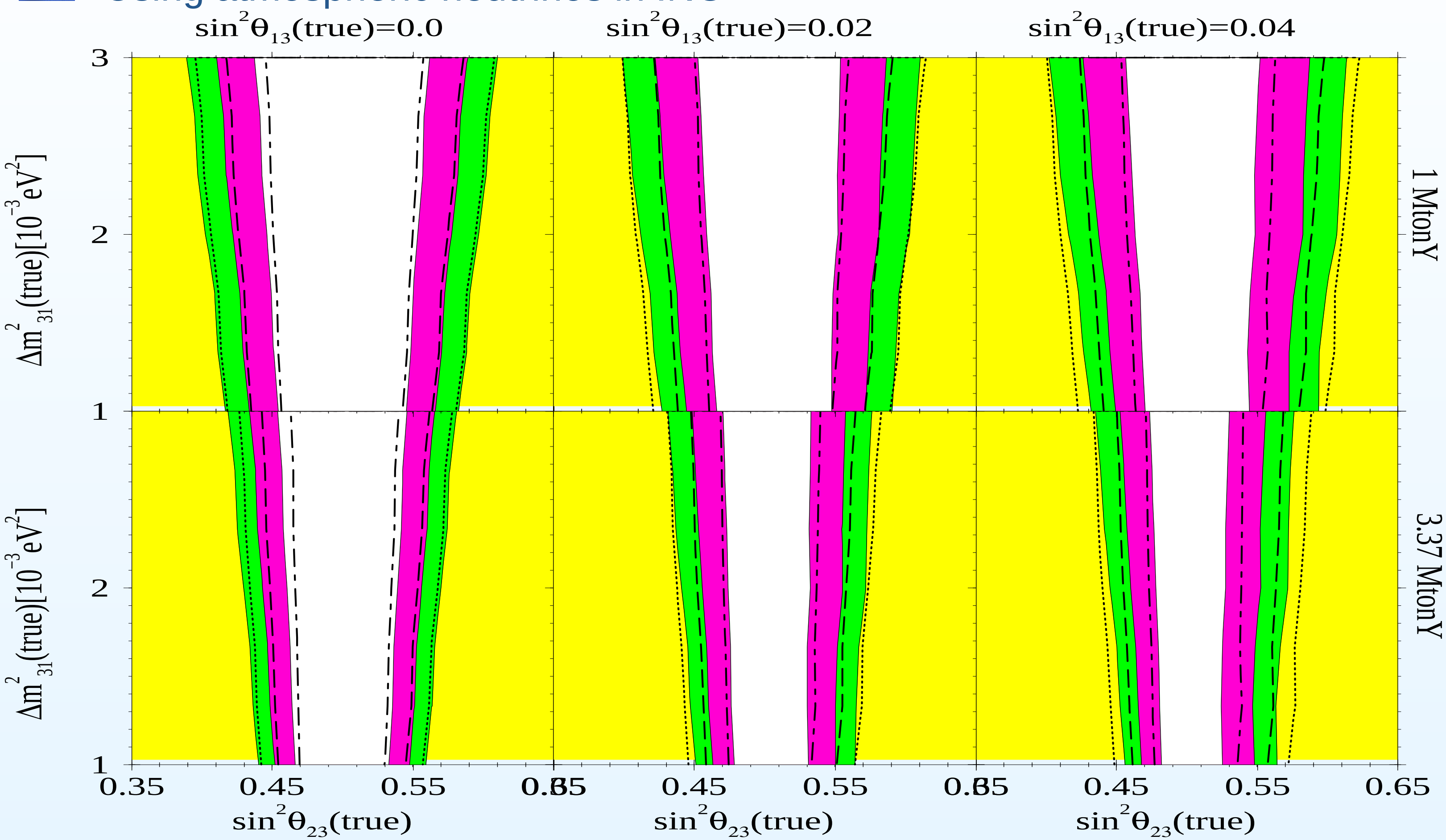
- Dependence on θ_{23} in the form $\sin^4 \theta_{23}$
- Octant sensitivity ?

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

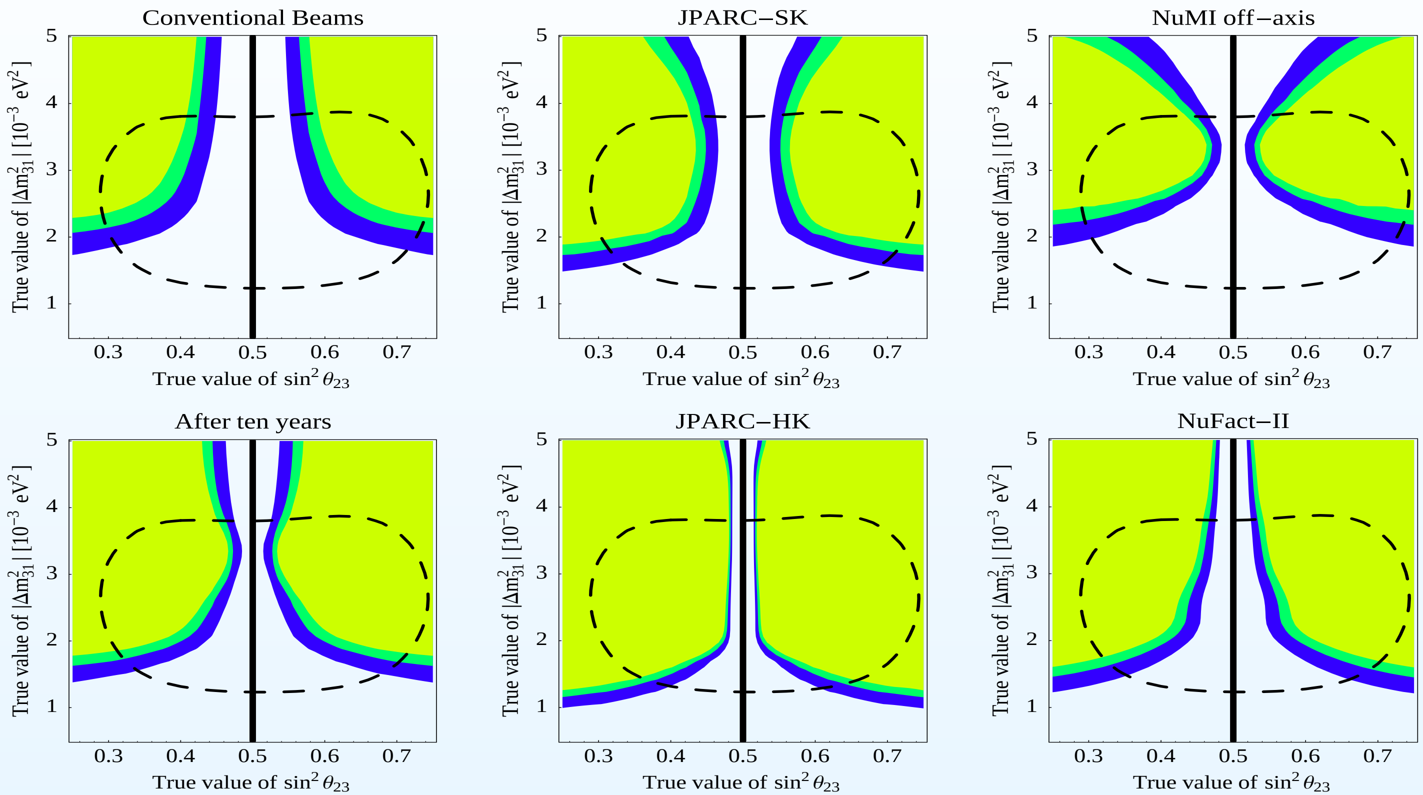


- $|D|$ can be measured to $\sim 17\%(20\%)$ at 3σ for $s^2_{13} = 0.04(0.00)$ with 1 MtonY exposure and 50% detector efficiency

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

Is the atmospheric mixing maximal?

- Using long baseline experiments

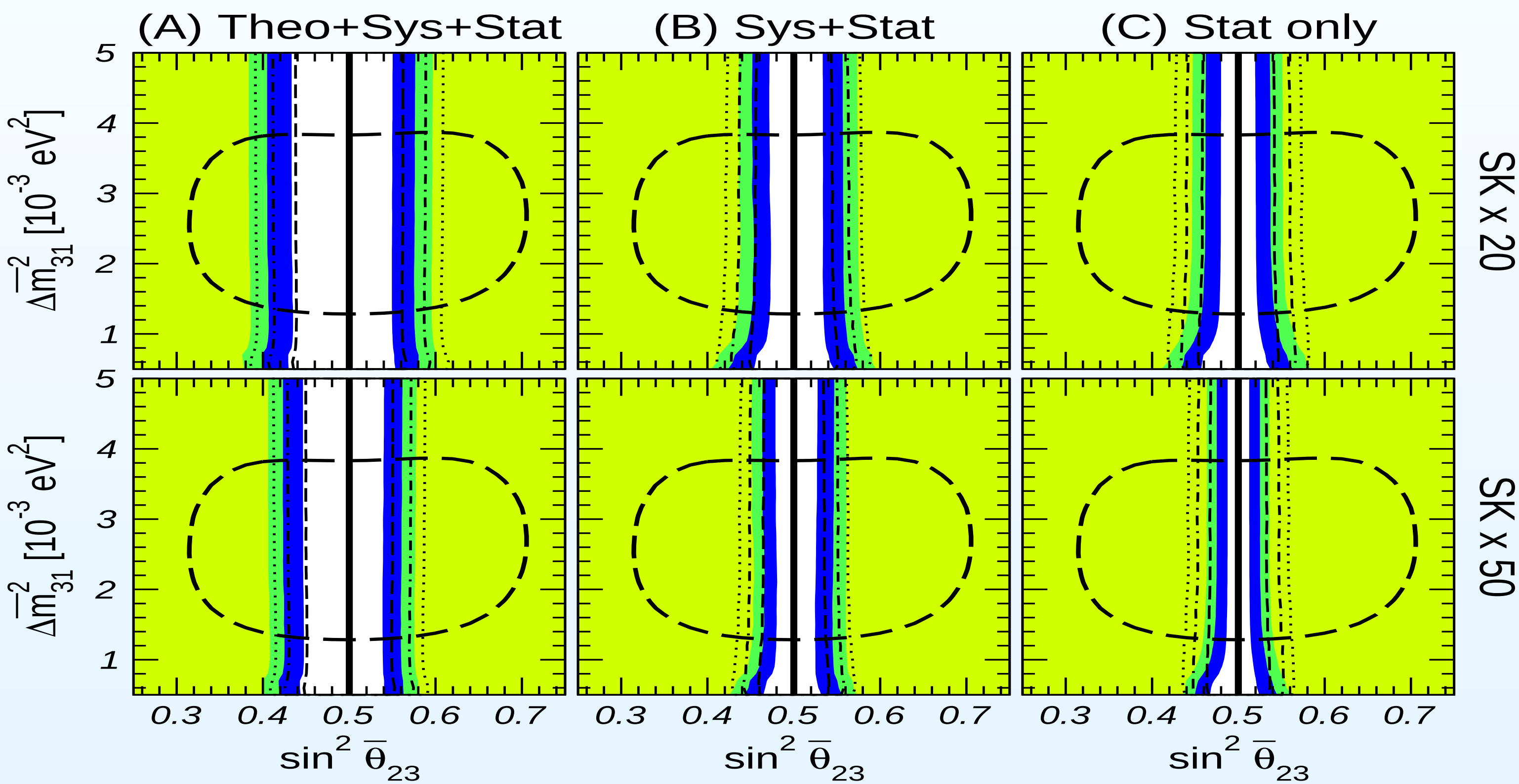


Antusch, et al, hep-ph/0404268

- 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

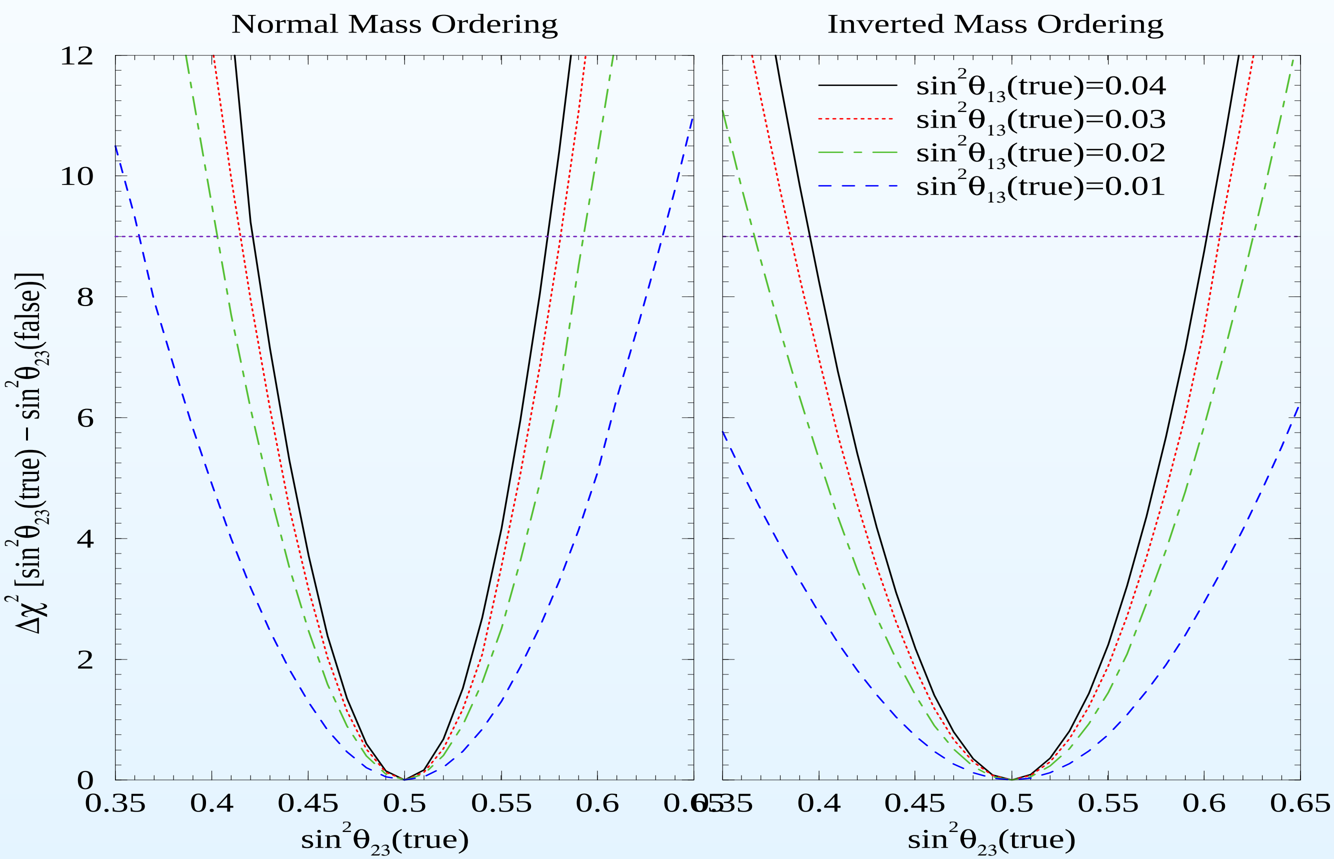
Also Huber et al. hep-ph/0501037

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.

CPT and Lorentz Violation

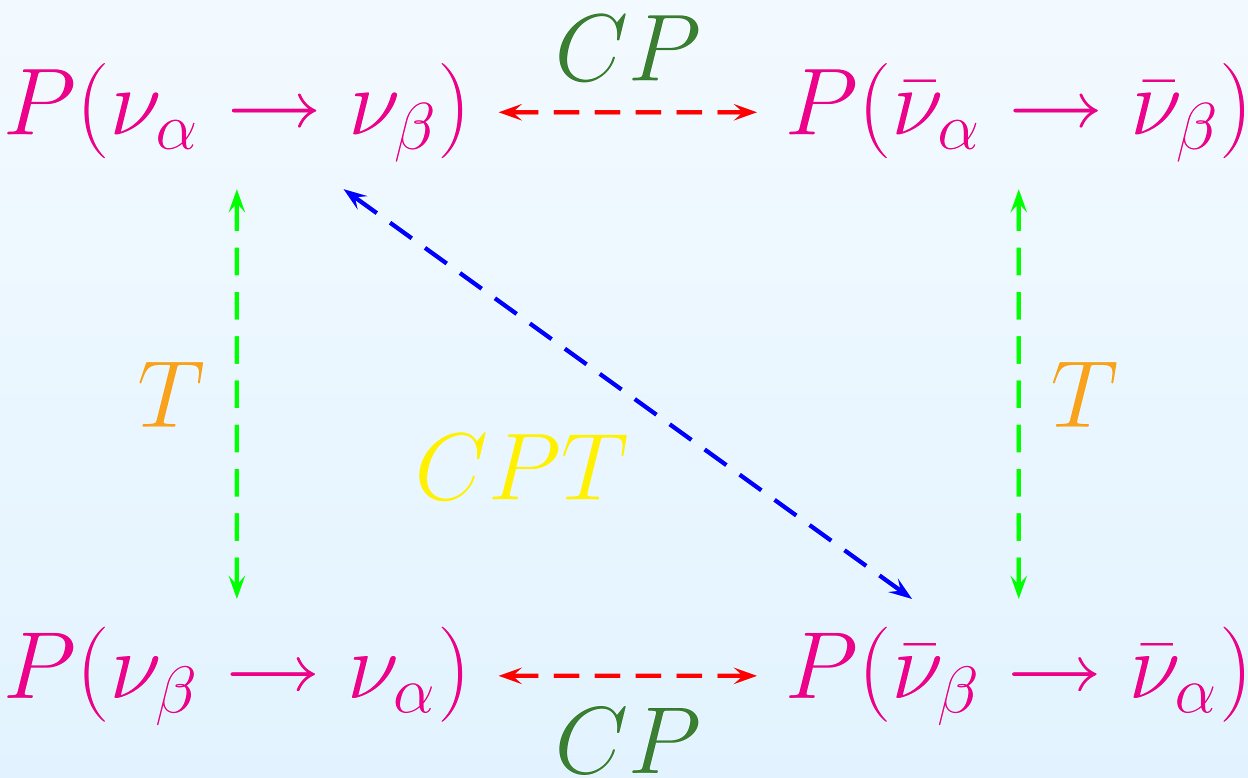
- CPT Invariance and Lorentz symmetry are pillars of modern physics. Tests of fundamental principles of invariance are important due to the far-reaching consequences of their violations.
- String or other unified theories may INDUCE small violations of CPT and Lorentz symmetry into the SM at low energies naturally, which can be tested at levels reachable by high precision experiments.

D. Colladay and V. A. Kostelecky, PRD 55, 6760 (1997); PRD 58, 116002 (1998)

S. R. Coleman and S. L. Glashow, PRD 59, 116008 (1999)

CP, T & CPT in ν oscillations

ν oscillations are sensitive to violation of Discrete symmetries : CP, T and CPT.



Violations of discrete symmetries . . .

- If CP is violated then

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta), \qquad \beta \neq \alpha$$

Violations of discrete symmetries . . .

- If CP is violated then

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta), \qquad \beta \neq \alpha$$

- If T is violated then

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Violations of discrete symmetries . . .

- If CP is violated then

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta), \qquad \beta \neq \alpha$$

- If T is violated then

$$P(\nu_\alpha \to \nu_\beta) \neq P(\nu_\beta \to \nu_\alpha), \qquad \beta \neq \alpha$$

- If CPT is violated then either

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\beta \to \bar{\nu}_\alpha), \qquad \beta \neq \alpha$$

or,

$$P(\nu_\alpha \to \nu_\alpha) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$$

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- Also, MATTER EFFECTS ➢ apparent (extrinsic) CP & CPT violation even if mass matrix is CP conserving

Atm ν, INO and CPT violation

- CPT violating term b gives Hamiltonian of the form

$$A = \frac{m^2}{2p} + b$$

which gives 2-flavour vacuum survival probability

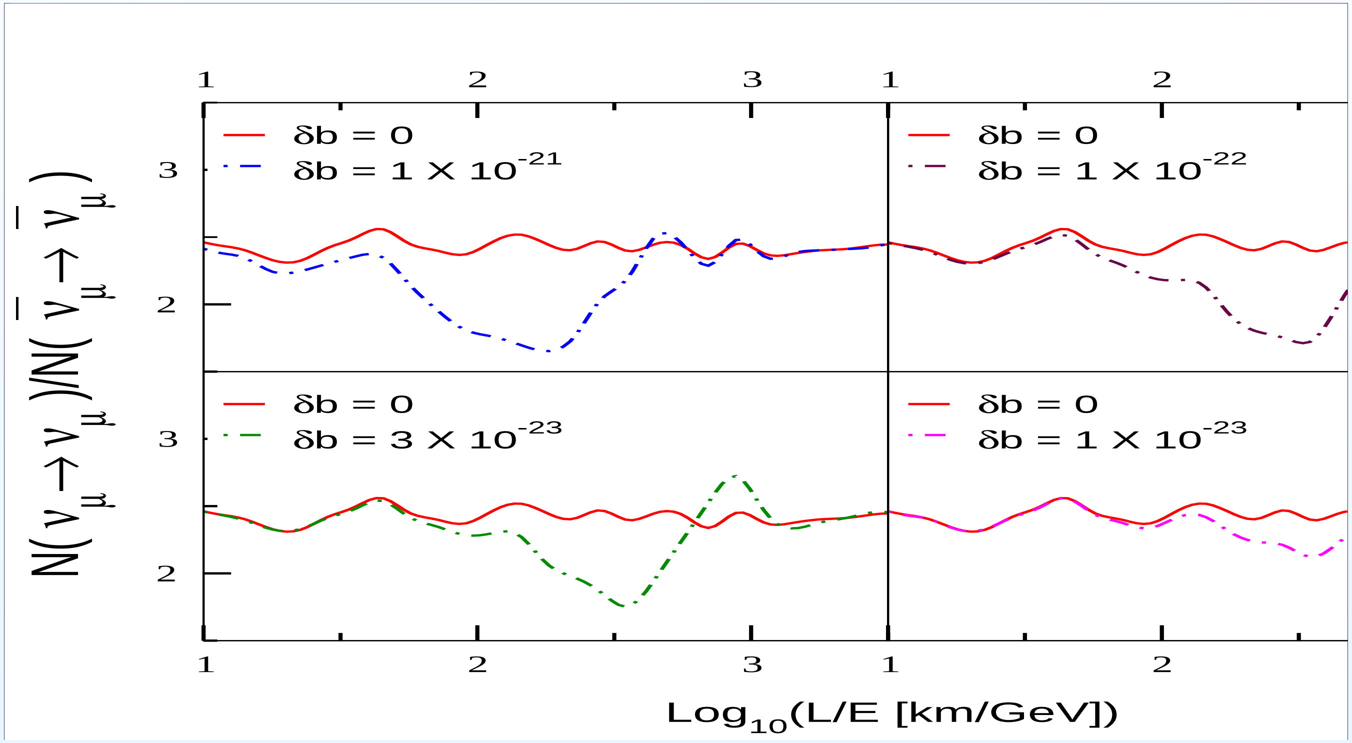
$$P_{\alpha\alpha}(L) = 1 - \sin^2 2\theta \sin^2[(\frac{\delta m^2}{4E} + \frac{\delta b}{2})L]$$

where $\alpha = \mu, \tau$ & $\delta m^2, \delta b$ are eigenvalue differences.

- For anti-neutrinos, $b \to -b$. Hence

$$\Delta P^{CPT}_{\alpha\alpha} = -\sin^2 2\theta \sin[\frac{\delta m^2 L}{2E}] \sin(\delta b L)$$

Atm ν, INO and CPT violation



Gandhi et al., PLB, 2004

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