Probing the Maximality and Octant of θ_{23} using ν_μ-Disappearance

Sandhya Choubey

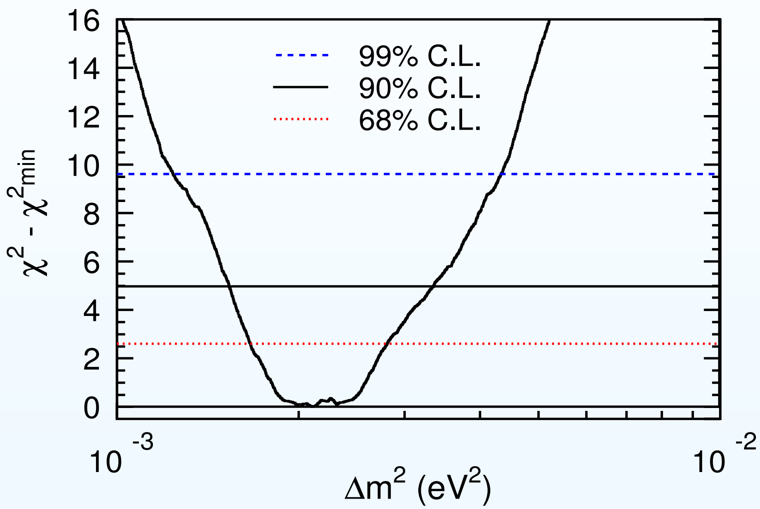
University of Oxford

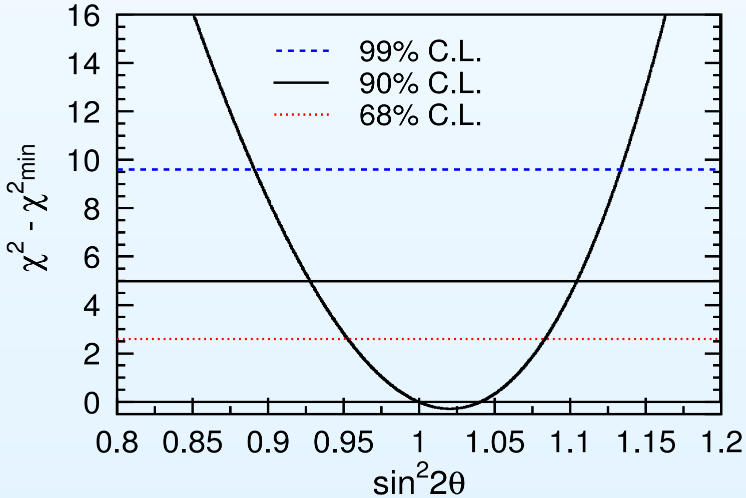
International Neutrino Factory and Superbeam Scoping Study

Imperial College, London, 14-21 November 2005

Atmospheric Neutrino Oscillation Parameters

Atmospheric Neutrino Oscillation Parameters





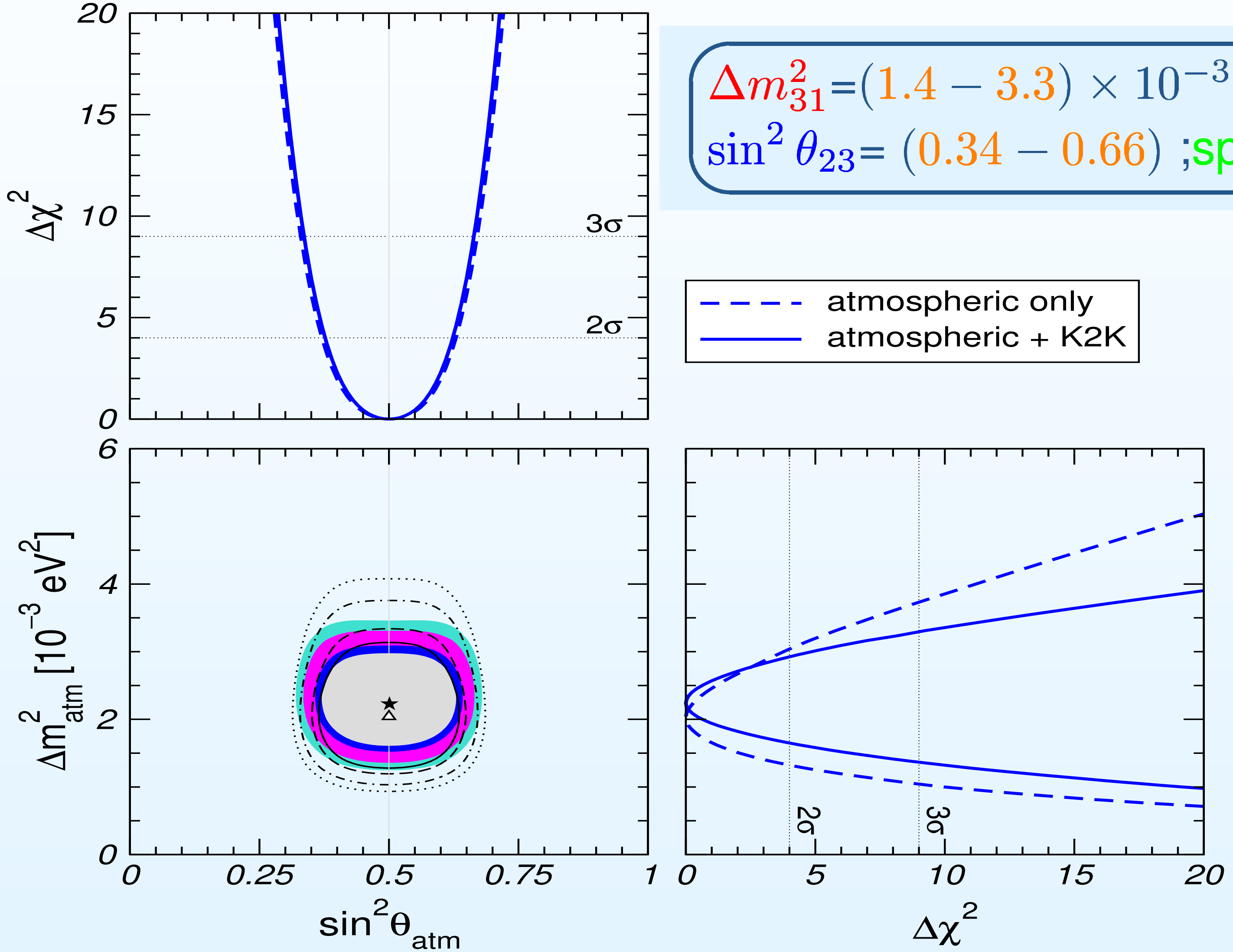
- 99.73% C.L. range

$\Delta m^2_{31} = (1.3 - 4.2) \times 10^{-3}$eV^2 ; spread=53%

$\sin^2 2\theta_{23} < 0.89$; spread=5.8%;
$\sin^2 \theta_{23} = (0.34 - 0.66)$; spread=34%

SK Collab, hep-ex/0502026

Combined Allowed Areas from SK+K2K



Δm^2_{31}=$(1.4 - 3.3) \times 10^{-3}$;spr=40%

$\sin^2\theta_{23}$= $(0.34 - 0.66)$;spread=34%

Maltoni et al, hep-ph/0405172

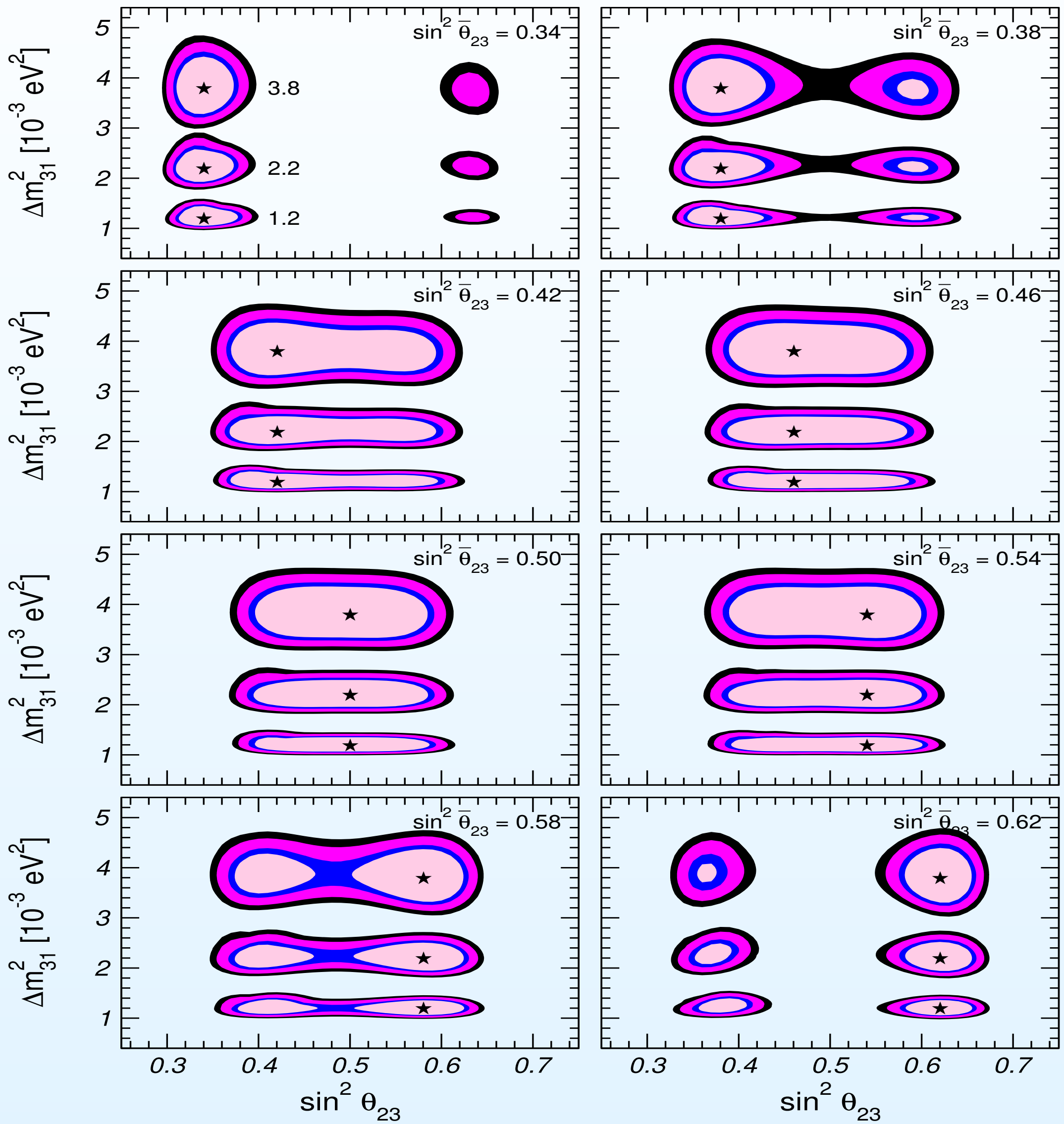
Future Precision Measurement

Potential of Long Baseline Experiments

Experiment	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{23}$
Current	44%	40%
MINOS+CNGS	13%	38%
T2K	6%	22%
NOνA	13%	42%
Combination	4.5%	20%

Huber et al hep-ph/0403068

Constraints from Future SK-like Atmospheric Data



•From 20 SKyr at 3σ,

$\Delta_{31} = 0.002$ eV^2,s^2_{23}= 0.5

spread in $\Delta m^2_{31} \sim 17\%$

spread in $\sin^2\theta_{23} \sim 24\%$

Gonzalez-Garcia et al, hep-ph/0408170

Measuring the Deviation of $\sin^2\theta_{23}$ from Maximal

Measuring the Deviation of $\sin^2\theta_{23}$ from Maximal

- Define: $D \equiv \frac{1}{2} - \sin^2\theta_{23}$

Measuring the Deviation of $\sin^2\theta_{23}$ from Maximal

- Define: $D \equiv \frac{1}{2} - \sin^2\theta_{23}$

- $|D|$ gives the deviation of $\sin^2\theta_{23}$ from its maximal value

Measuring the Deviation of $\sin^2\theta_{23}$ from Maximal

- Define: $D \equiv \frac{1}{2} - \sin^2\theta_{23}$

- $|D|$ gives the deviation of $\sin^2\theta_{23}$ from its maximal value
- $sgn(D)$ gives the octant of $\sin^2\theta_{23}$

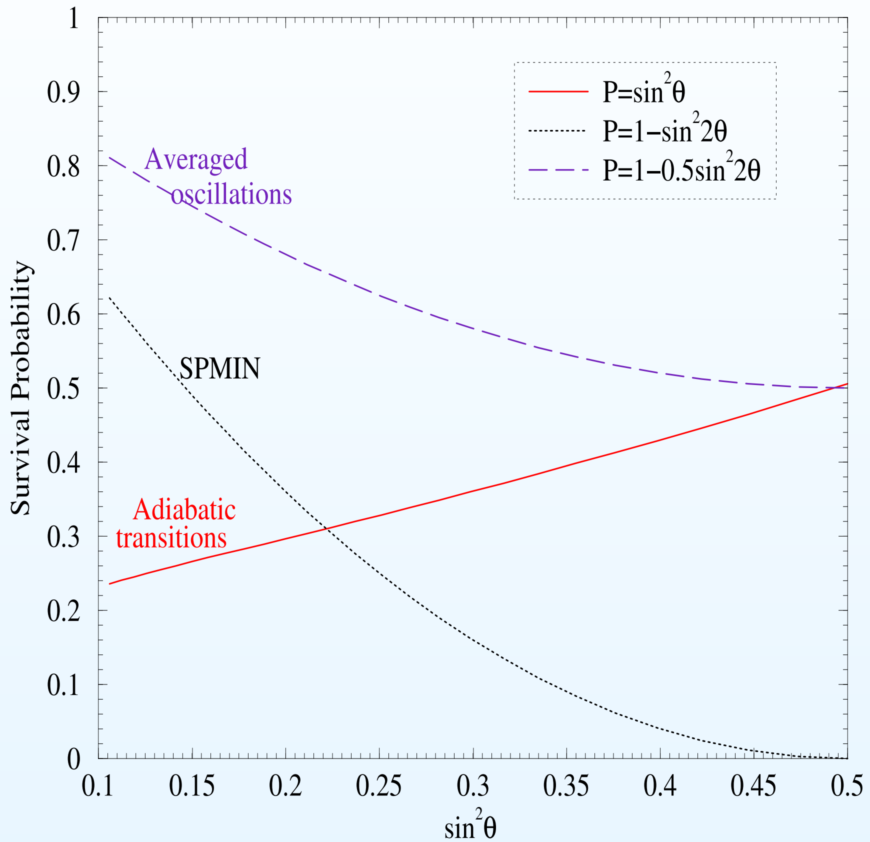
Measuring the Deviation of $\sin^2\theta_{23}$ from Maximal

- Define: $D \equiv \frac{1}{2} - \sin^2\theta_{23}$

- $|D|$ gives the deviation of $\sin^2\theta_{23}$ from its maximal value
- $sgn(D)$ gives the octant of $\sin^2\theta_{23}$

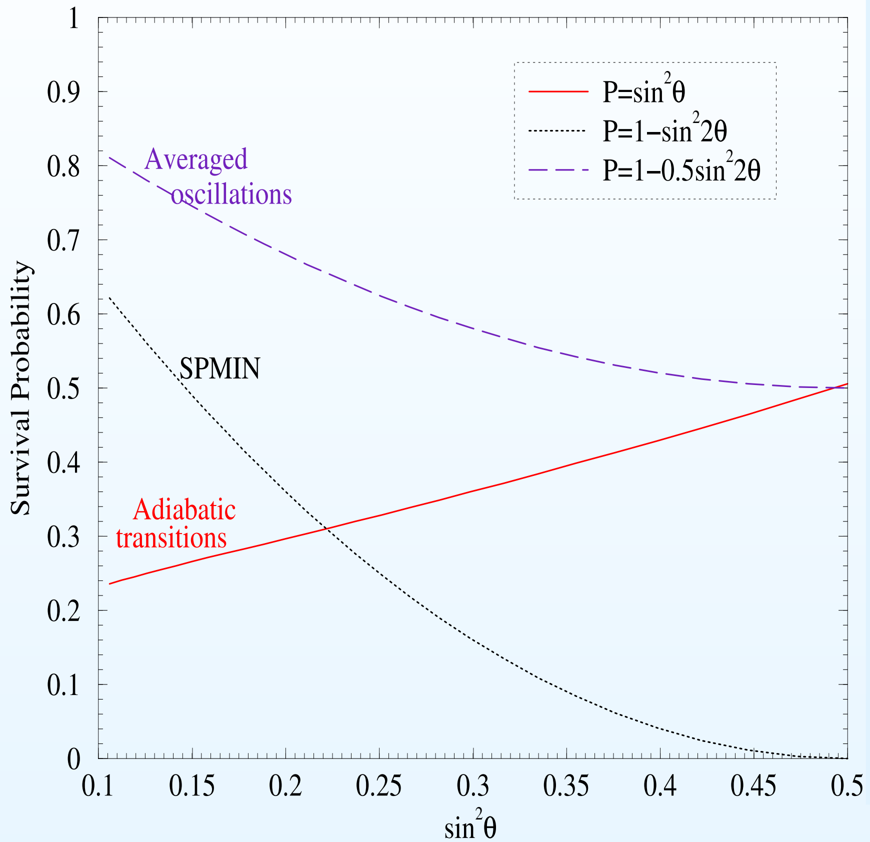
- Current 3σ limits on the magnitude and sign of D:
  - ⋆ $|D| < 0.16$ at 3σ from the SKI data
  - ⋆ No robust information on $sgn(D)$

Problem of Measuring the Deviation D from Maximal



- $(\Delta \sin^2\theta)_{LMA} \sim \Delta P$; (good even if $\sin^2\theta \sim 0.5$)
- $(\Delta \sin^2\theta)_{VAC} \sim \frac{\Delta P}{-4\cos 2\theta < \sin^2 \frac{\Delta m^2 L}{4E} >}$;
- $(\Delta \sin^2\theta)_{SPMIN} \sim \frac{\Delta P}{-4\cos 2\theta}$; (best if $\cos 2\theta \gtrsim 0.25 (\sin^2\theta \lesssim 0.375)$)

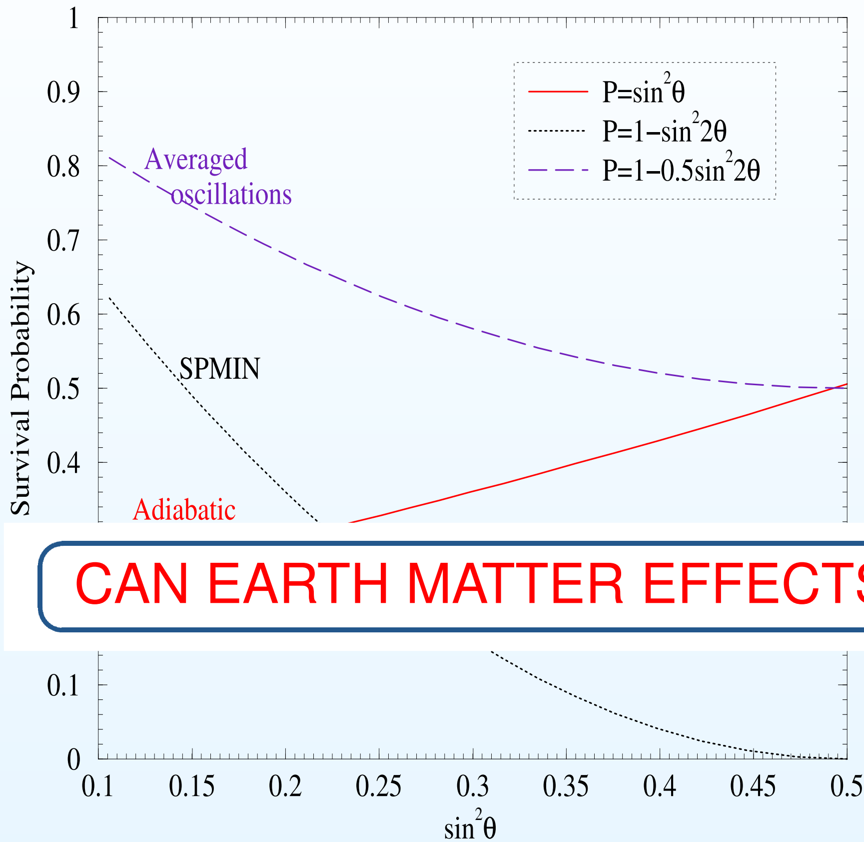
Problem of Measuring the Deviation D from Maximal



- SPMIN is best for measuring θ in vacuum oscillation experiments
- For θ close to maximal, oscillations in vacuum is bad
- Alas! Matter effects in earth for GeV neutrinos directly affect θ_{13}
- Besides, octant cannot be determined using a disappearance experiment in vacuum

- $(\Delta \sin^2\theta)_{LMA} \sim \Delta P$; (good even if $\sin^2\theta \sim 0.5$)
- $(\Delta \sin^2\theta)_{VAC} \sim \frac{\Delta P}{-4\cos 2\theta < \sin^2 \frac{\Delta m^2 L}{4E} >}$;
- $(\Delta \sin^2\theta)_{SPMIN} \sim \frac{\Delta P}{-4\cos 2\theta}$; (best if $\cos 2\theta \gtrsim 0.25 (\sin^2\theta \lesssim 0.375)$)

Problem of Measuring the Deviation D from Maximal

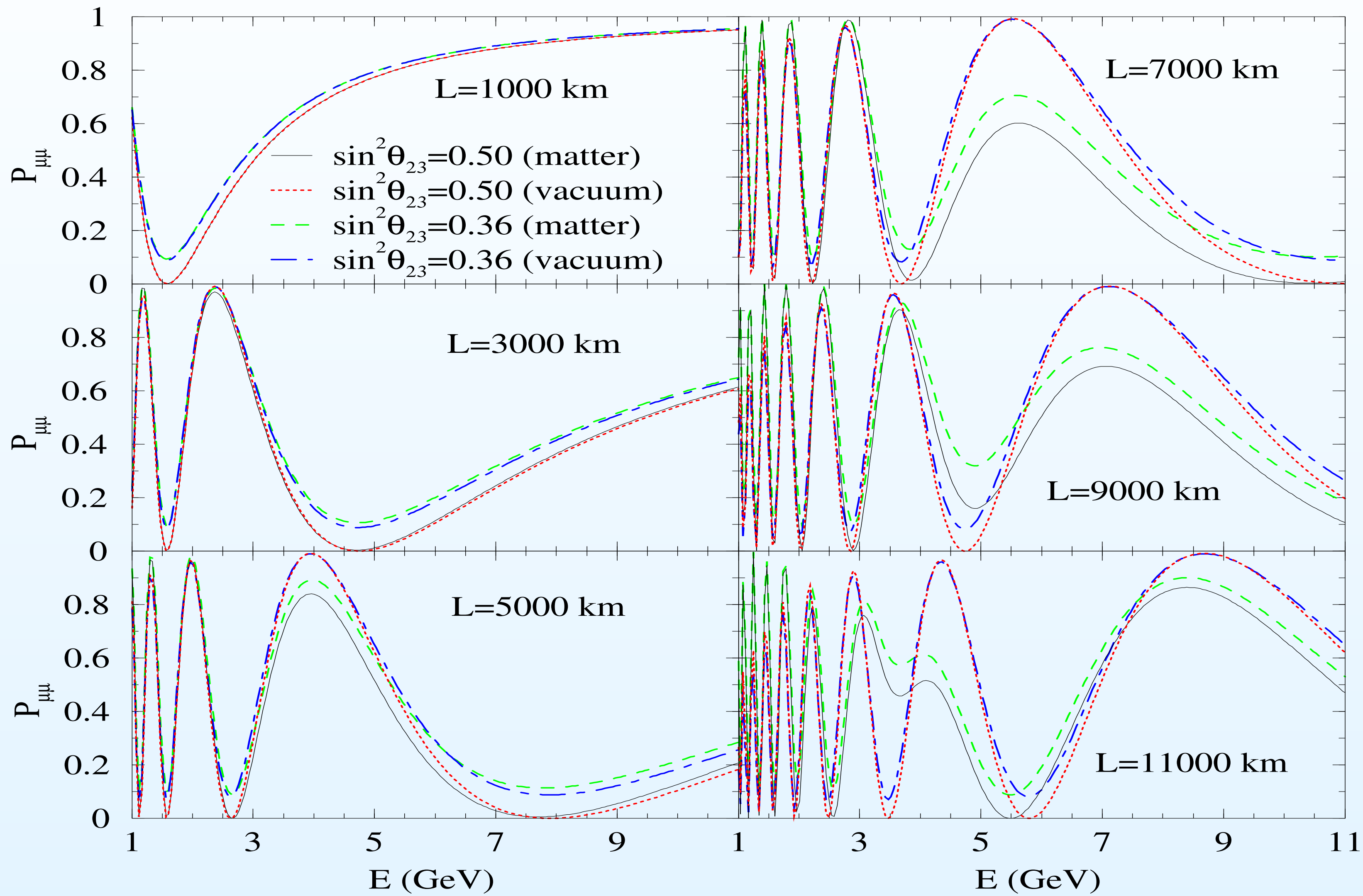


- SPMIN is best for measuring θ in vacuum oscillation experiments
- For θ close to maximal, oscillations in vacuum is bad
- Alas! Matter effects in earth for GeV neutrinos directly affect θ_{13}
- ... deter-mined using a disappearance experiment in vacuum

CAN EARTH MATTER EFFECTS HELP IN MEASURING θ_{23}?

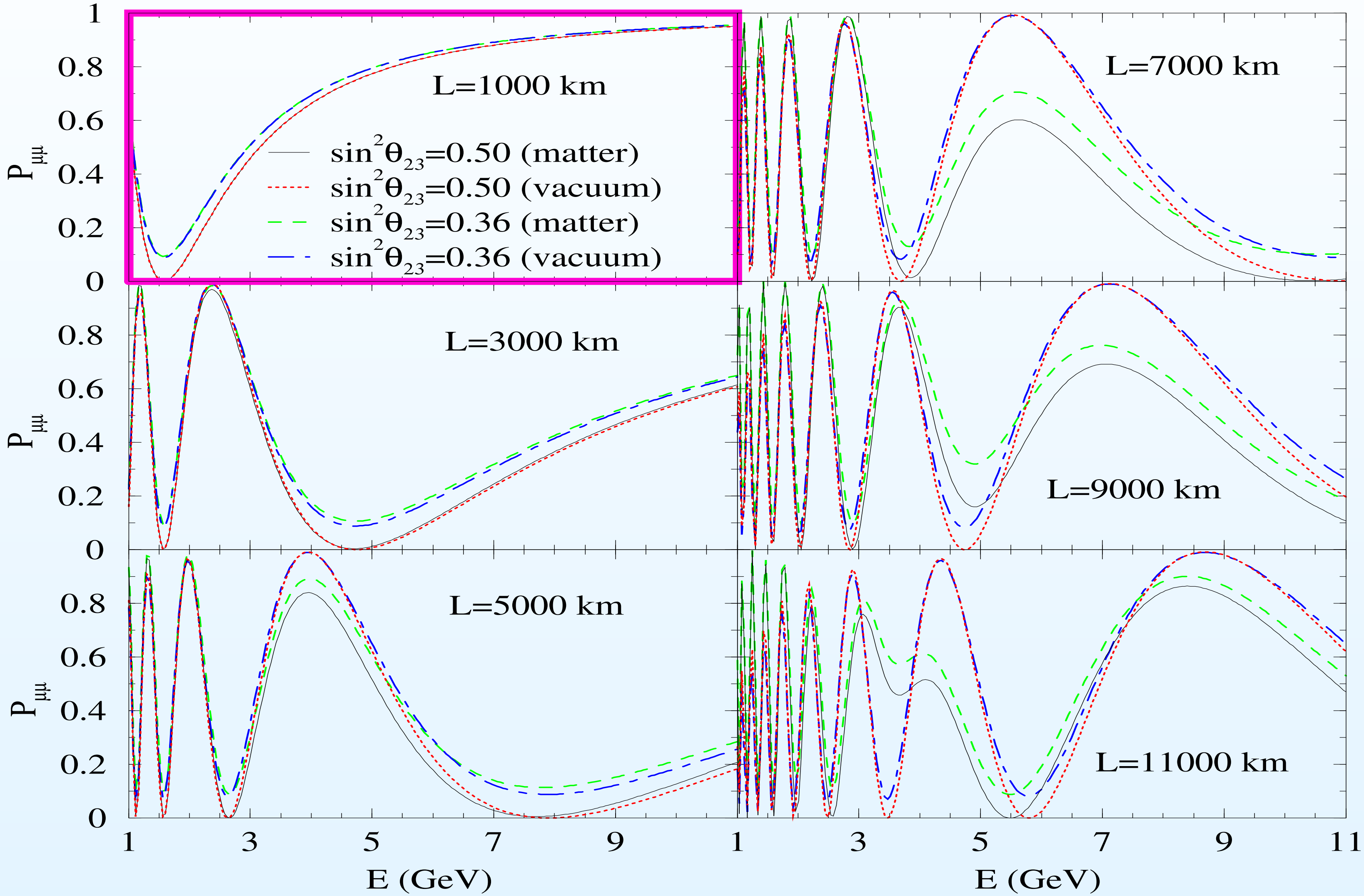
- $(\Delta \sin^2\theta)_{LMA} \sim \Delta P$; (good even if $\sin^2\theta \sim 0.5$)
- $(\Delta \sin^2\theta)_{VAC} \sim \frac{\Delta P}{-4\cos 2\theta < \sin^2 \frac{\Delta m^2 L}{4E} >}$;
- $(\Delta \sin^2\theta)_{SPMIN} \sim \frac{\Delta P}{-4\cos 2\theta}$; (best if $\cos 2\theta \gtrsim 0.25 (\sin^2\theta \lesssim 0.375)$)

Muon Neutrino Survival Probability



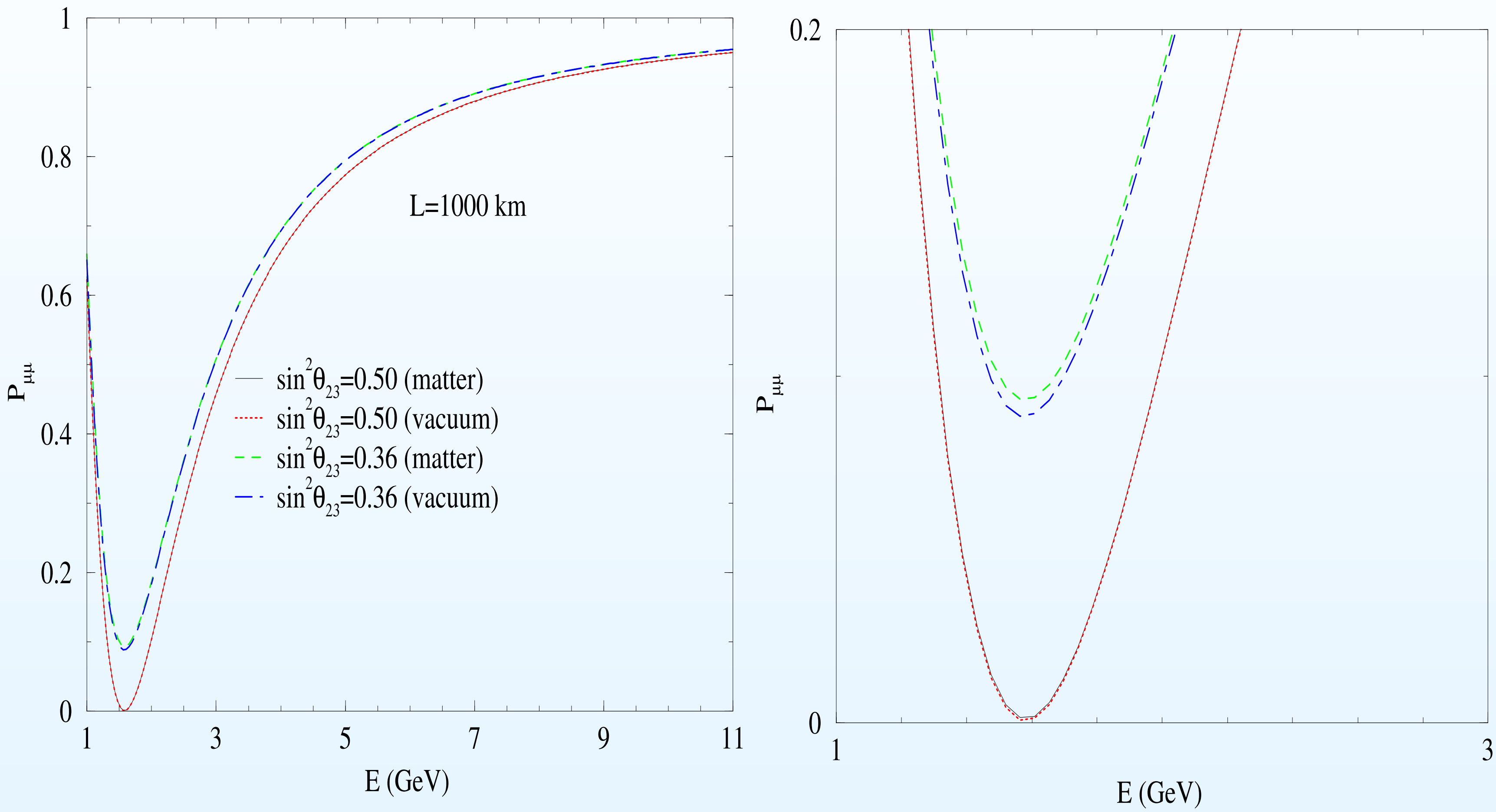
S.C. and P. Roy, hep-ph/0509197

Muon Neutrino Survival Probability



S.C. and P. Roy, hep-ph/0509197

Muon Disappearance in Long Baseline Experiments



- No matter effect for $\sin^2\theta_{23} = 0.5$
- Very small matter effects for $\sin^2\theta_{23} \neq 0.5$

Muon Disappearance in Long Baseline Experiments

- The ν_μ survival probability can be written as

$$P_{\mu\mu} = P_{\mu\mu}^{\rm vac} + 2|U_{e3}|^2|U_{\mu3}|^2(1-2|U_{\mu3}|^2)$$

$$A\left[4\Delta_{31}^{-1}\sin^2\frac{\Delta_{31}L}{2} - L\sin(\Delta_{31}L)\right] + \mathcal{O}(A^2)$$

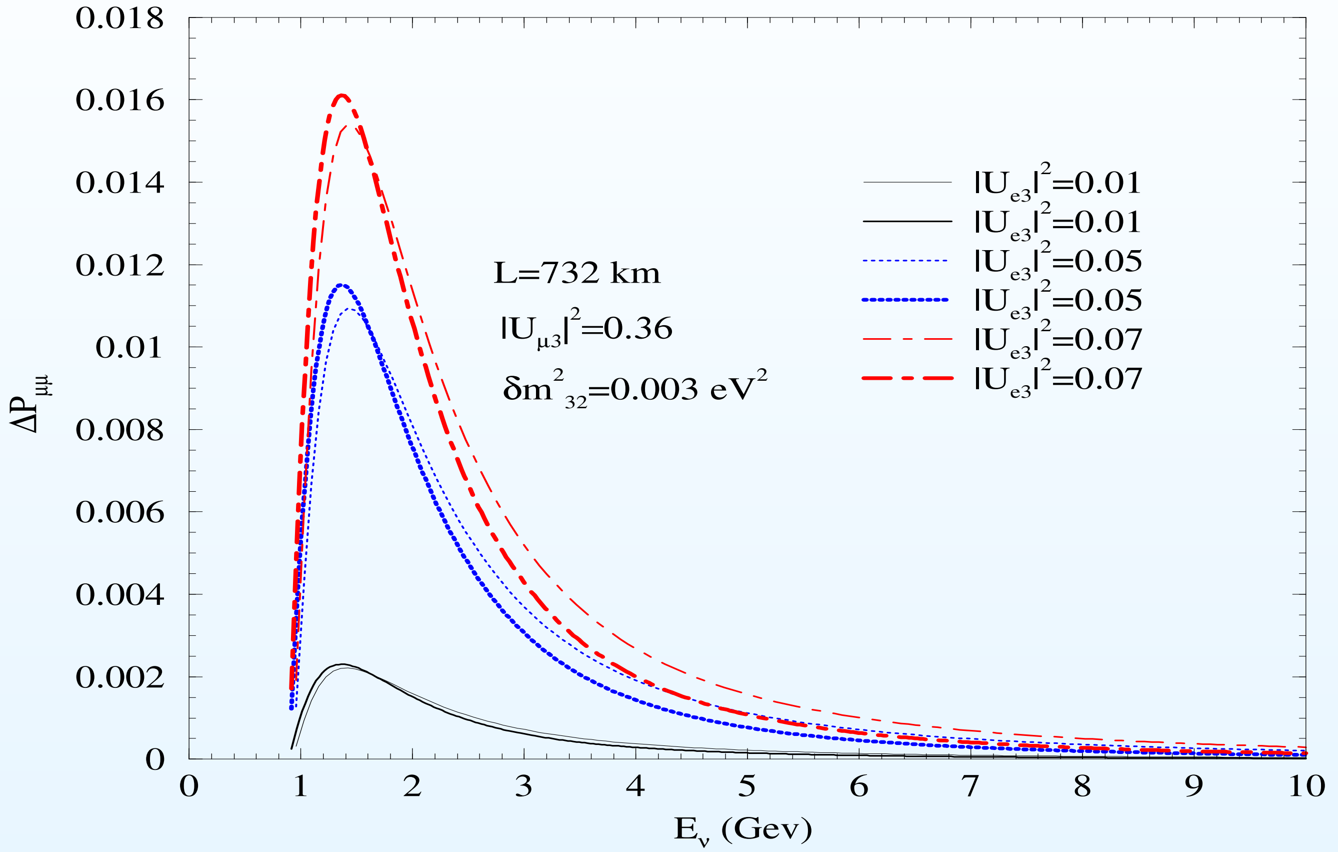
$$\Delta P_{\mu\mu} = 4|U_{e3}|^2|U_{\mu3}|^2(1-2|U_{\mu3}|^2)$$

$$A\left[4\Delta_{31}^{-1}\sin^2\frac{\Delta_{31}L}{2} - L\sin(\Delta_{31}L)\right]$$

$$+\mathcal{O}[(U_{e3}A)^3]$$

- $(\Delta_{31} = \Delta m_{31}^2/2E)$

Muon Disappearance in Long Baseline Experiments



S.C. and Roy, hep-ph/0310316

Not feasible to measure in any proposed experiment

Muon Disappearance in Long Baseline Experiments

- Survival probability in vacuum:

$$P_{\mu\mu} \simeq 1 - (c_{13}^2 \sin^2 2\theta_{23} + \sin^2 2\theta_{13} s_{23}^4) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

Muon Disappearance in Long Baseline Experiments

- Survival probability in vacuum:

$$P_{\mu\mu} \simeq 1 - (c_{13}^2 \sin^2 2\theta_{23} + \sin^2 2\theta_{13} s_{23}^4) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

- Dependence on θ_{23} in the form $\sin^2 2\theta_{23}$

Muon Disappearance in Long Baseline Experiments

- Survival probability in vacuum:

$$P_{\mu\mu} \simeq 1 - (c_{13}^2 \sin^2 2\theta_{23} + \sin^2 2\theta_{13} s_{23}^4) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

- Dependence on θ_{23} in the form $\sin^2 2\theta_{23}$
- Measurement expected to be harder near maximal mixing

Muon Disappearance in Long Baseline Experiments

- Survival probability in vacuum:

$$P_{\mu\mu} \simeq 1 - (c_{13}^2 \sin^2 2\theta_{23} + \sin^2 2\theta_{13} s_{23}^4) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

- Dependence on θ_{23} in the form $\sin^2 2\theta_{23}$
- Measurement expected to be harder near maximal mixing
- No octant dependence expected

Muon Disappearance in Long Baseline Experiments

- Survival probability in vacuum:

$$P_{\mu\mu} \simeq 1 - (c_{13}^2 \sin^2 2\theta_{23} + \sin^2 2\theta_{13} s_{23}^4) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

- Dependence on θ_{23} in the form $\sin^2 2\theta_{23}$
- Measurement expected to be harder near maximal mixing
- No octant dependence expected
- Best measurements on $|D|$ expected near SPMIN where $\sin^2 \frac{\Delta m_{31}^2 L}{4E} \to 1$

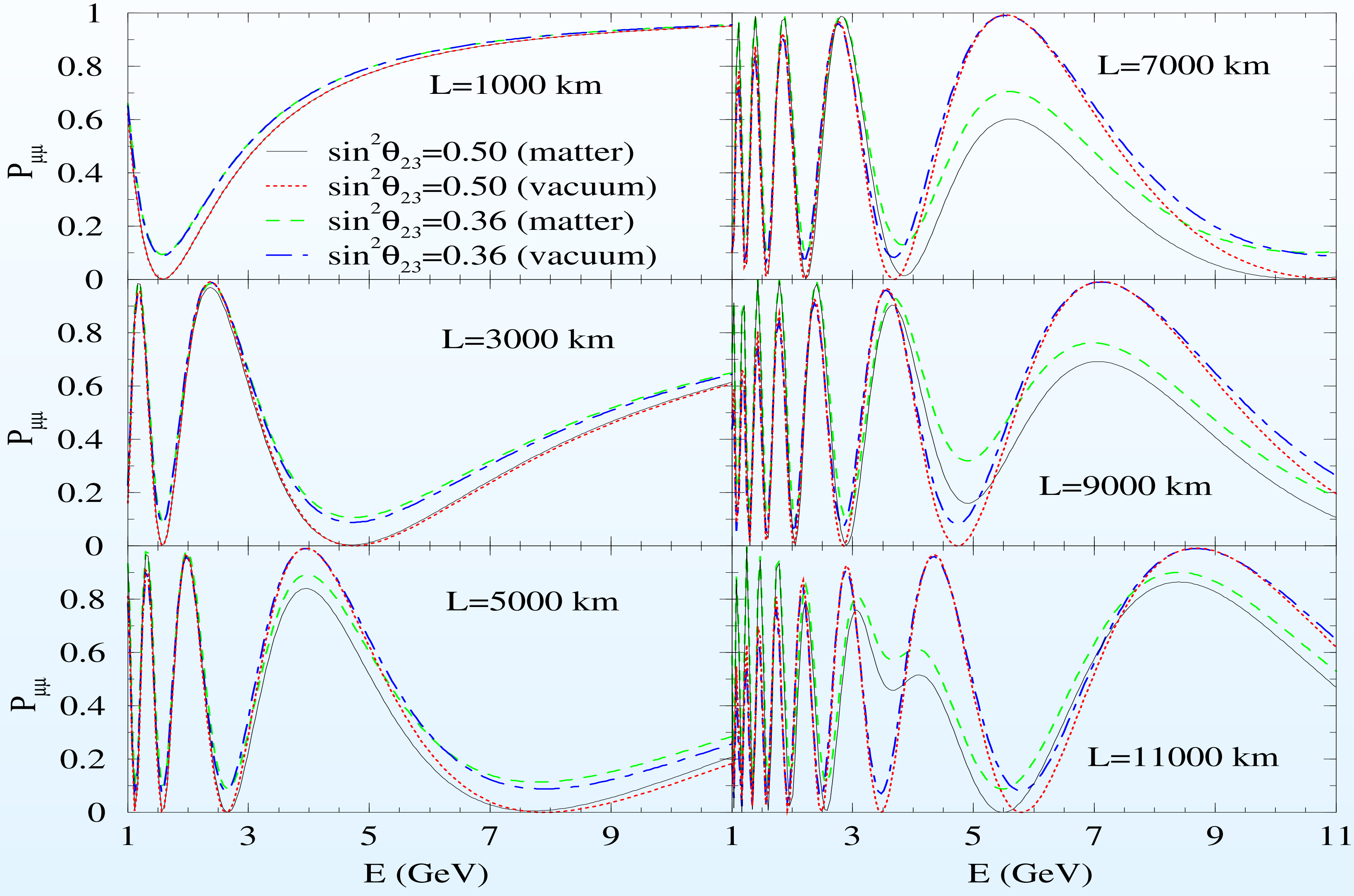
Muon Disappearance in Long Baseline Experiments

- Survival probability in vacuum:

$$P_{\mu\mu} \simeq 1 - (c_{13}^2 \sin^2 2\theta_{23} + \sin^2 2\theta_{13} s_{23}^4) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

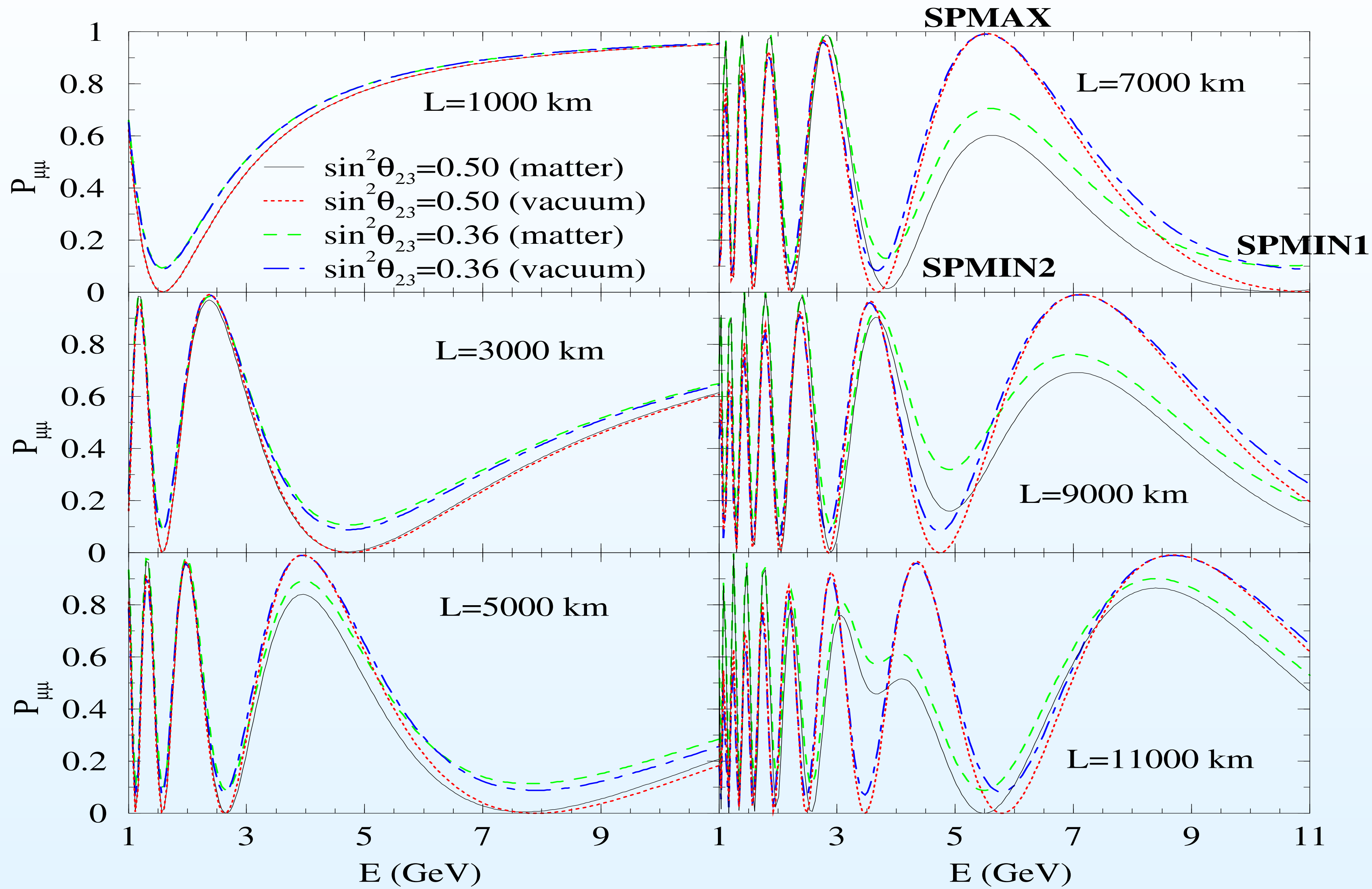
- Dependence on θ_{23} in the form $\sin^2 2\theta_{23}$
- Measurement expected to be harder near maximal mixing
- No octant dependence expected
- Best measurements on $|D|$ expected near SPMIN where $\sin^2 \frac{\Delta m_{31}^2 L}{4E} \to 1$
- For a given L and E, measurement sensitive to Δm_{31}^2(true)

Large Matter Effects in ν_μ Survival Probability



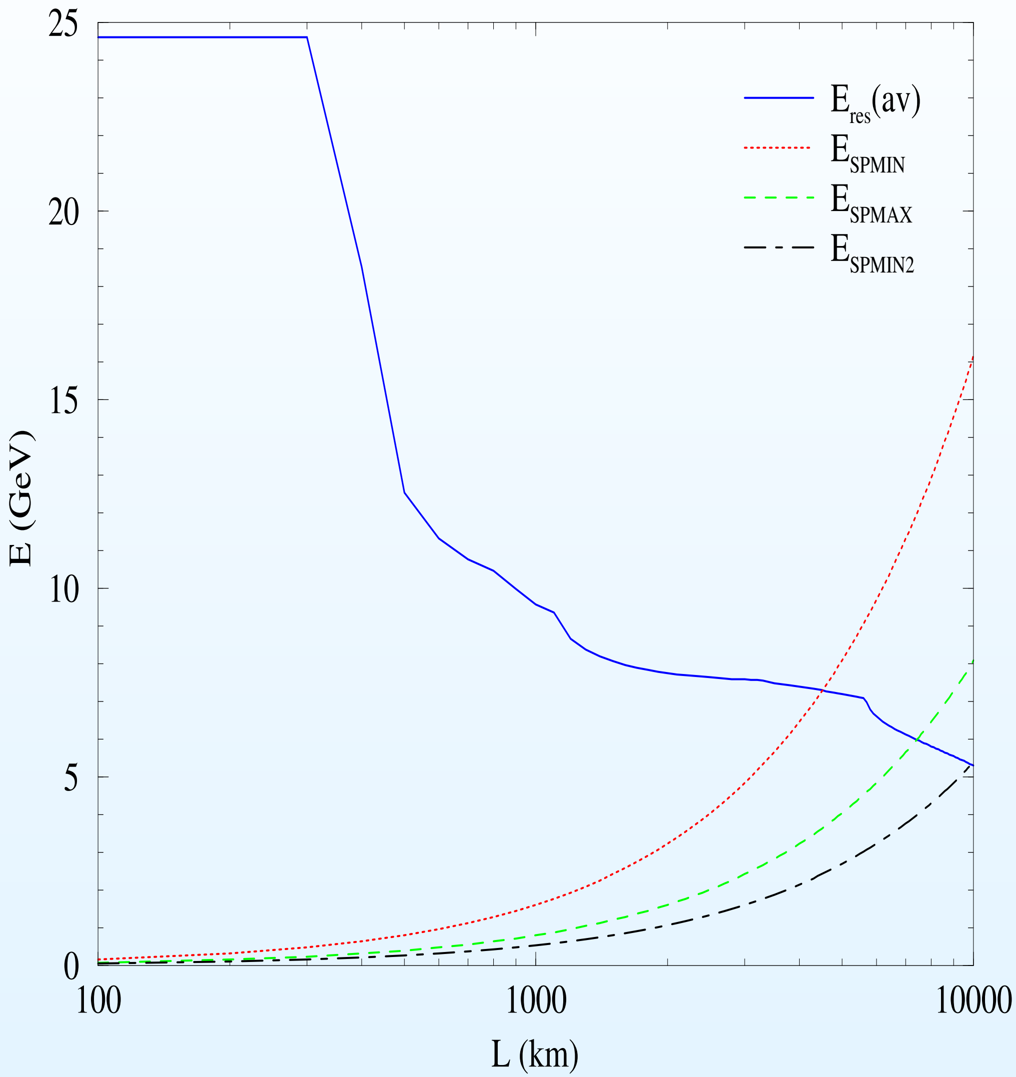
S.C. and P. Roy, hep-ph/0509197

Large Matter Effects in ν_μ Survival Probability



S.C. and P. Roy, hep-ph/0509197

Large Matter Effects in ν_μ Survival Probability



S.C. and P. Roy, hep-ph/0509197

- $E_{\rm res} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$
- $E_{\rm SPMINn} = \frac{2}{2n-1}(1.27)\Delta m^2_{31} L,$
- $E_{\rm SPMAXn} = \frac{2}{2n}(1.27)\Delta m^2_{31} L$

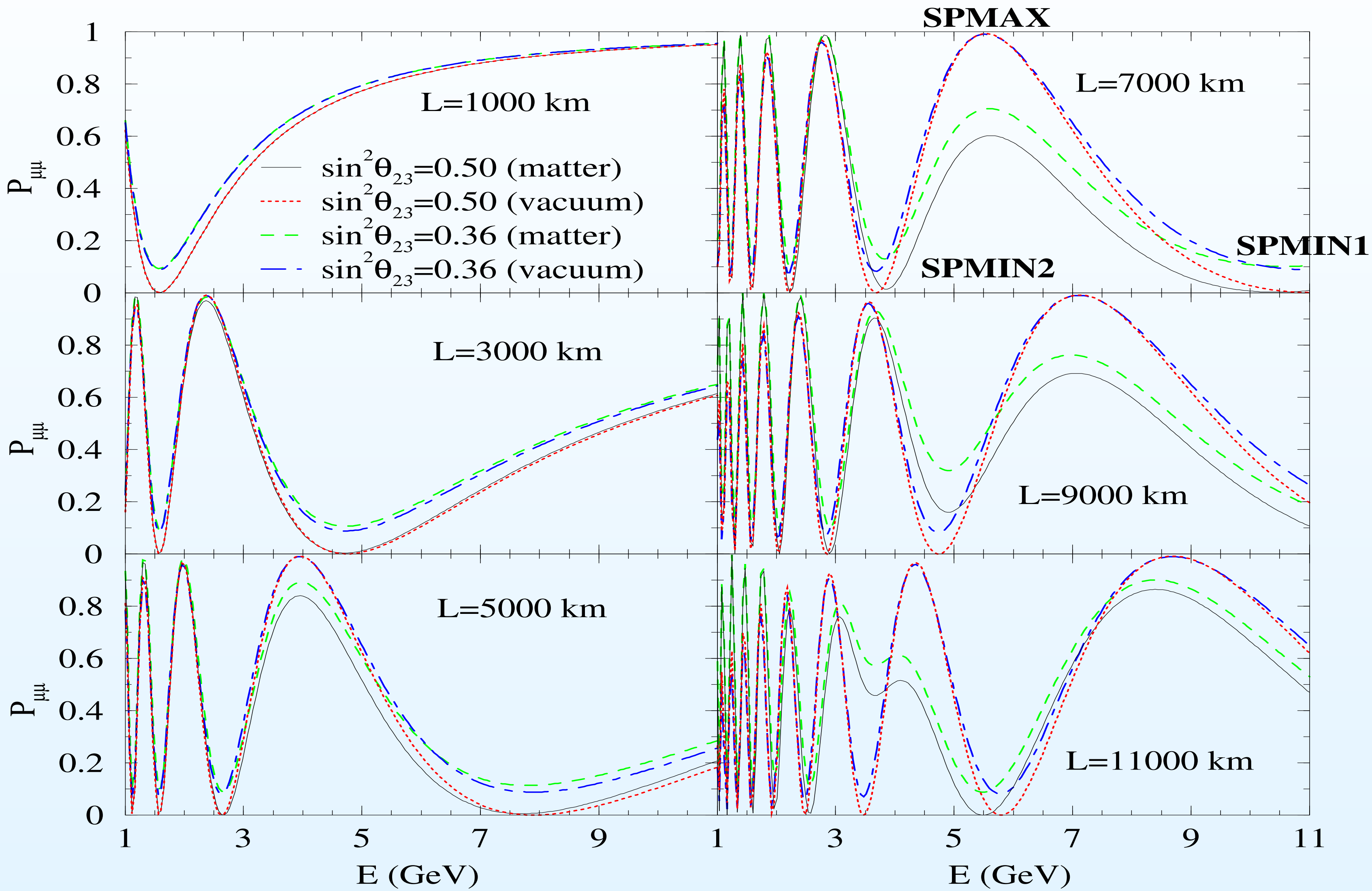
- $E_{\rm res} \simeq E_{\rm SPMIN1}$ for $L \simeq 4500$ km
- $E_{\rm res} \simeq E_{\rm SPMIN2}$ for $L \simeq 9700$ km
- $E_{\rm res} \simeq E_{\rm SPMAX}$ for $L \simeq 7400$ km

Polamares-Ruiz&Petcov

Indumathi&Murthy

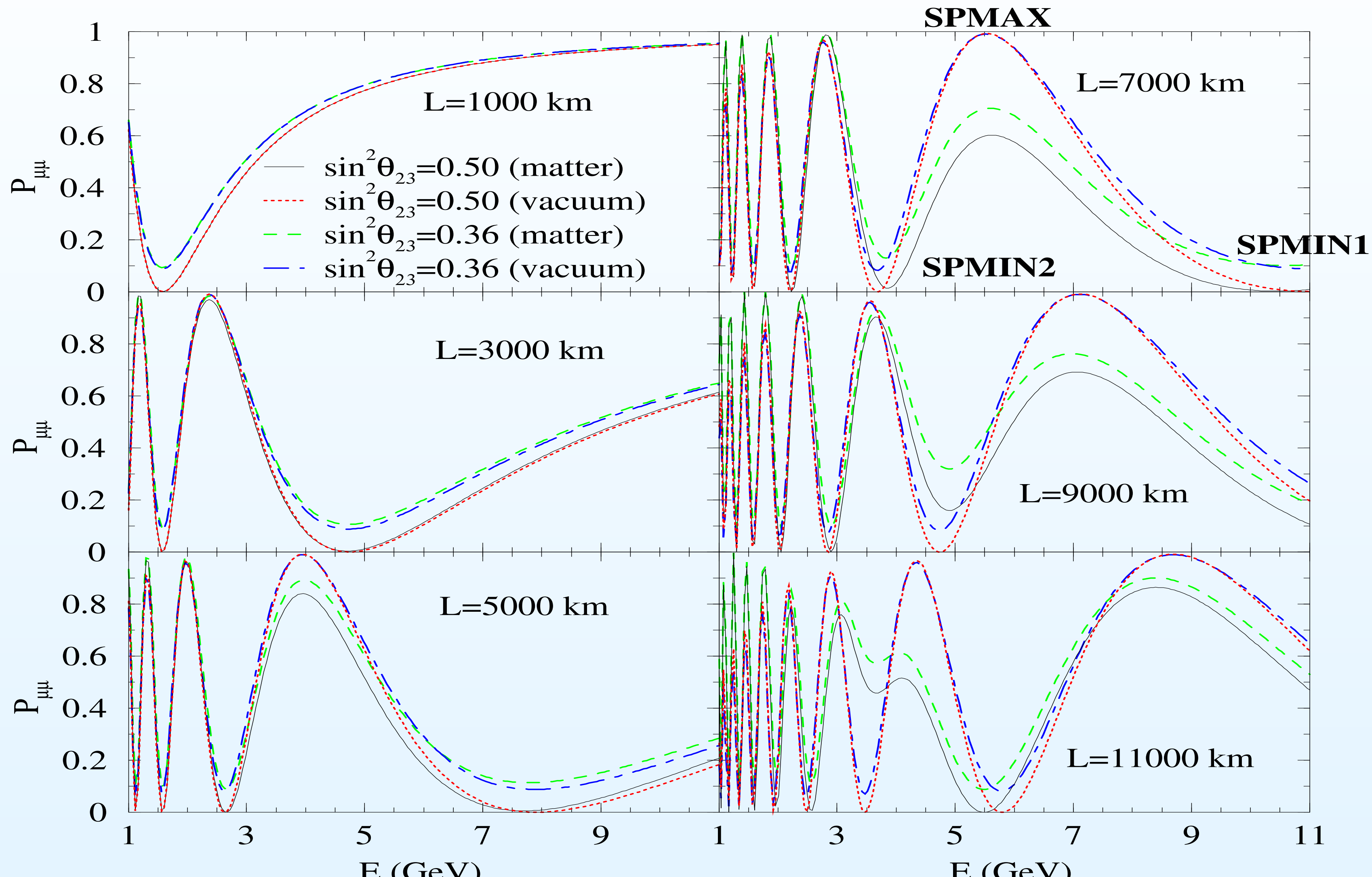
Gandhi et al

Large Matter Effects in ν_μ Survival Probability



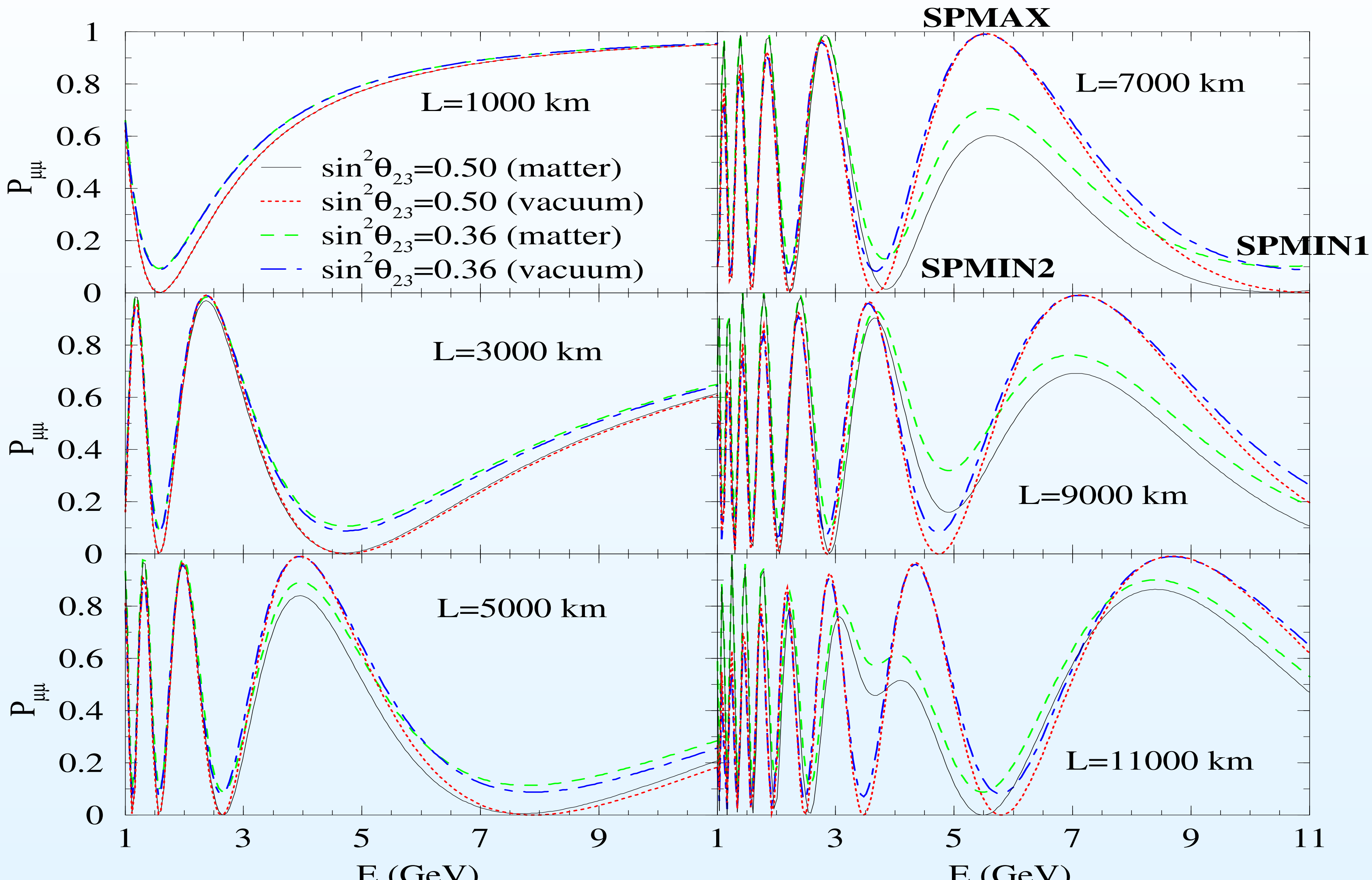
- Largest effect for $L \simeq 7000$ km and $E \simeq 5$ GeV $\Rightarrow$ $(E_{\rm SPMAX} \simeq E_{\rm res})$

Large Matter Effects in ν_μ Survival Probability



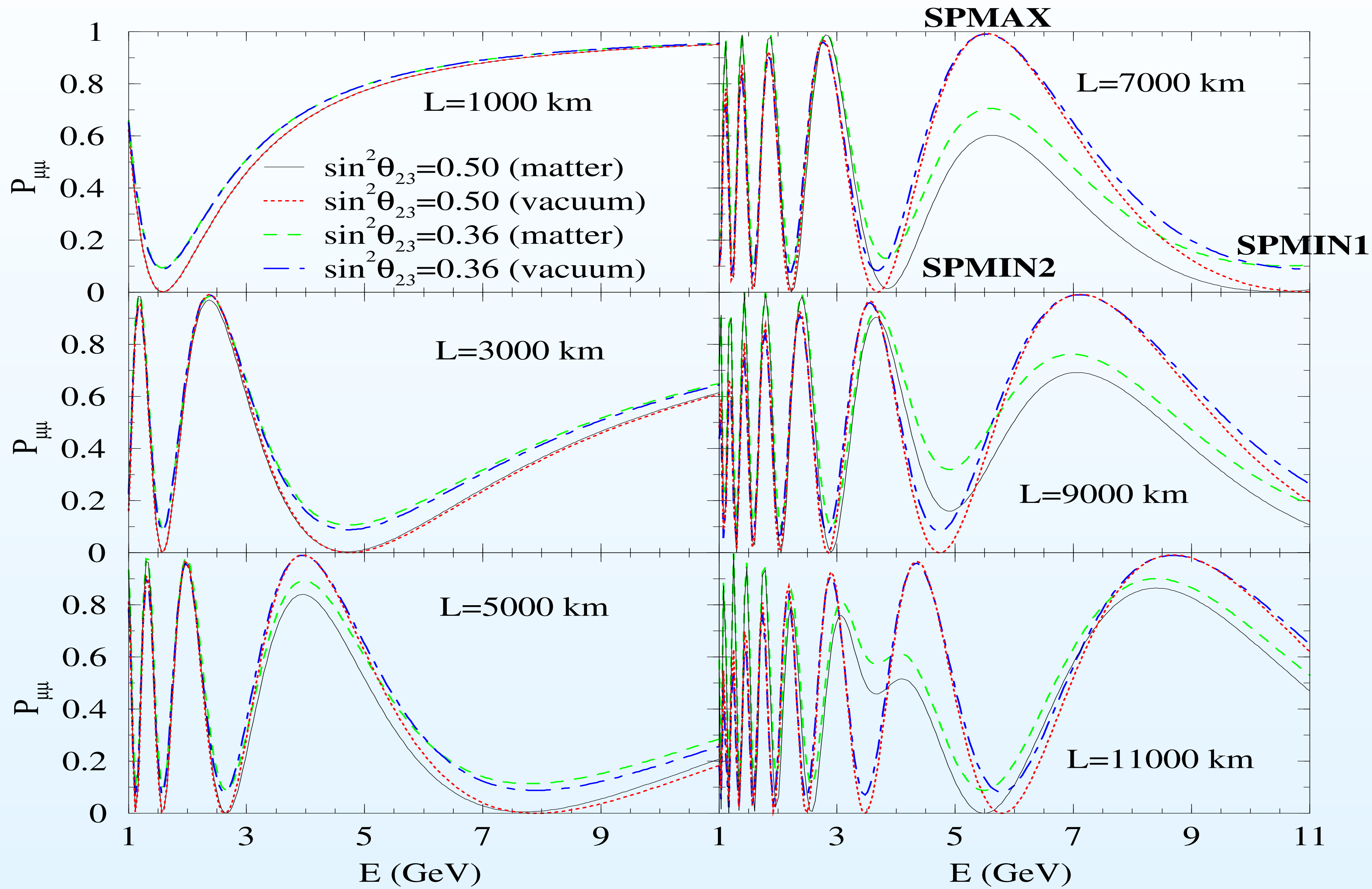
- $P_{\mu\mu}$ decreases (increases) at SPMAX (SPMIN) due to matter effects
- The spectral shape changes due to earth matter effects

Large Matter Effects in ν_μ Survival Probability



- Sign of the earth matter effects depends on both E and L
- Most important to choose the bins properly in both E and L

Large Matter Effects in ν_μ Survival Probability



- Matter effects depend on the value of $\sin^2\theta_{23}$

Muon Neutrino Survival Probability

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu\mu}(L) = 1 - P^1_{\mu\mu}(L) - P^2_{\mu\mu}(L) - P^3_{\mu\mu}(L)$$

$$P^1_{\mu\mu}(L) = \sin^2\theta^M_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31}(\tilde{A}+1) - (\Delta m^2_{31})^M}{8E} L$$

$$P^2_{\mu\mu}(L) = \cos^2\theta^M_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31}(\tilde{A}+1) + (\Delta m^2_{31})^M}{8E} L$$

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

Muon Neutrino Survival Probability

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu\mu}(L) = 1 - P^1_{\mu\mu}(L) - P^2_{\mu\mu}(L) - P^3_{\mu\mu}(L)$$

$$P^1_{\mu\mu}(L) = \sin^2 \theta^M_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31}(\tilde{A}+1) - (\Delta m^2_{31})^M}{8E} L$$

$$P^2_{\mu\mu}(L) = \cos^2 \theta^M_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31}(\tilde{A}+1) + (\Delta m^2_{31})^M}{8E} L$$

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

- Dependence on θ_{23} in the form $\sin^4 \theta_{23}$
- Octant sensitivity is expected to be good

Muon Neutrino Survival Probability

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu\mu}(L) = 1 - P^1_{\mu\mu}(L) - P^2_{\mu\mu}(L) - P^3_{\mu\mu}(L)$$

$$P^1_{\mu\mu}(L) = \sin^2\theta^M_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31}(\tilde{A}+1) - (\Delta m^2_{31})^M}{8E} L$$

$$P^2_{\mu\mu}(L) = \cos^2\theta^M_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31}(\tilde{A}+1) + (\Delta m^2_{31})^M}{8E} L$$

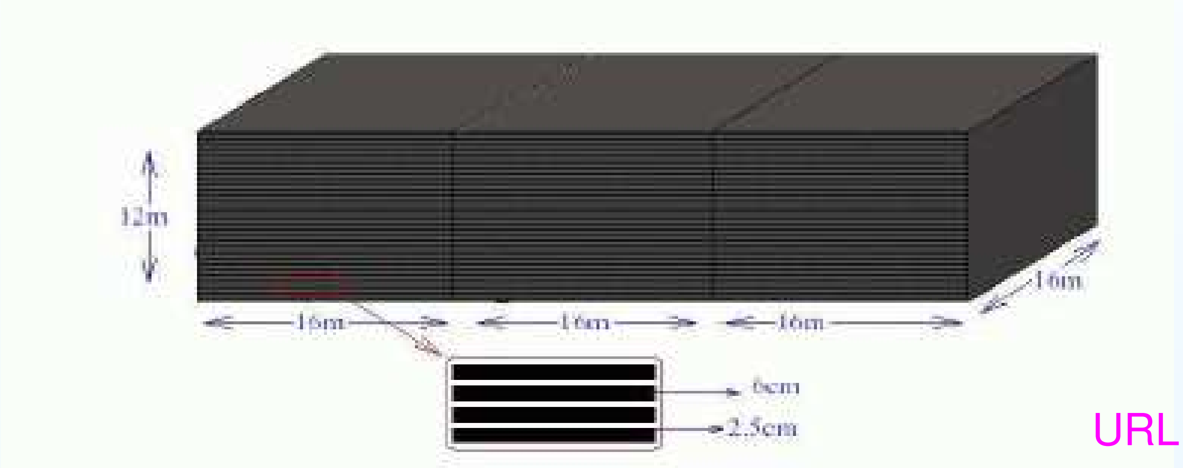
$$P^3_{\mu\mu}(L) = \sin^2 2\theta^M_{13} \sin^4\theta_{23} \sin^2 \frac{(\Delta m^2_{31})^M}{4E} L$$

- Dependence on θ_{23} in the form $\sin^4\theta_{23}$
- Octant sensitivity is expected to be good
- Need an experimental set-up that can see the matter effects

Atmospheric ν_μ in Large Magnetised Iron Calorimeter

Atmospheric ν_μ in Large Magnetised Iron Calorimeter

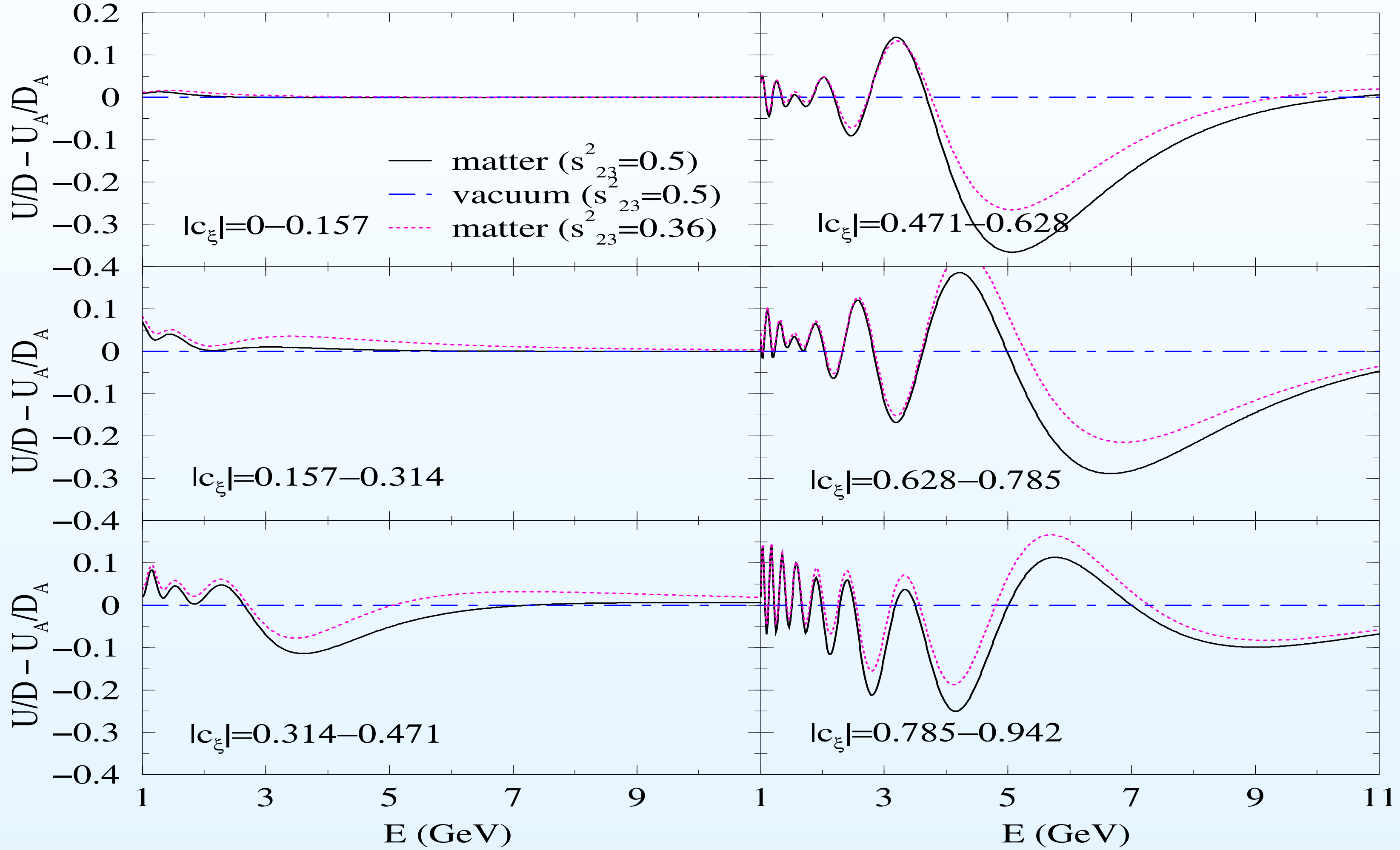
India-based Neutrino Observatory



URL:http://www.imsc.res.in/~ino

- ~2200 meters underground
- 50 kton detector
- Very good energy and angle resolution
$\Rightarrow$ fine binning possible in both energy and zenith angle
- It will be magnetized $\Rightarrow$ ν_μ can be distinguished from $\bar{\nu}_\mu$
- Best place to look for matter effects in $P_{\mu\mu}$

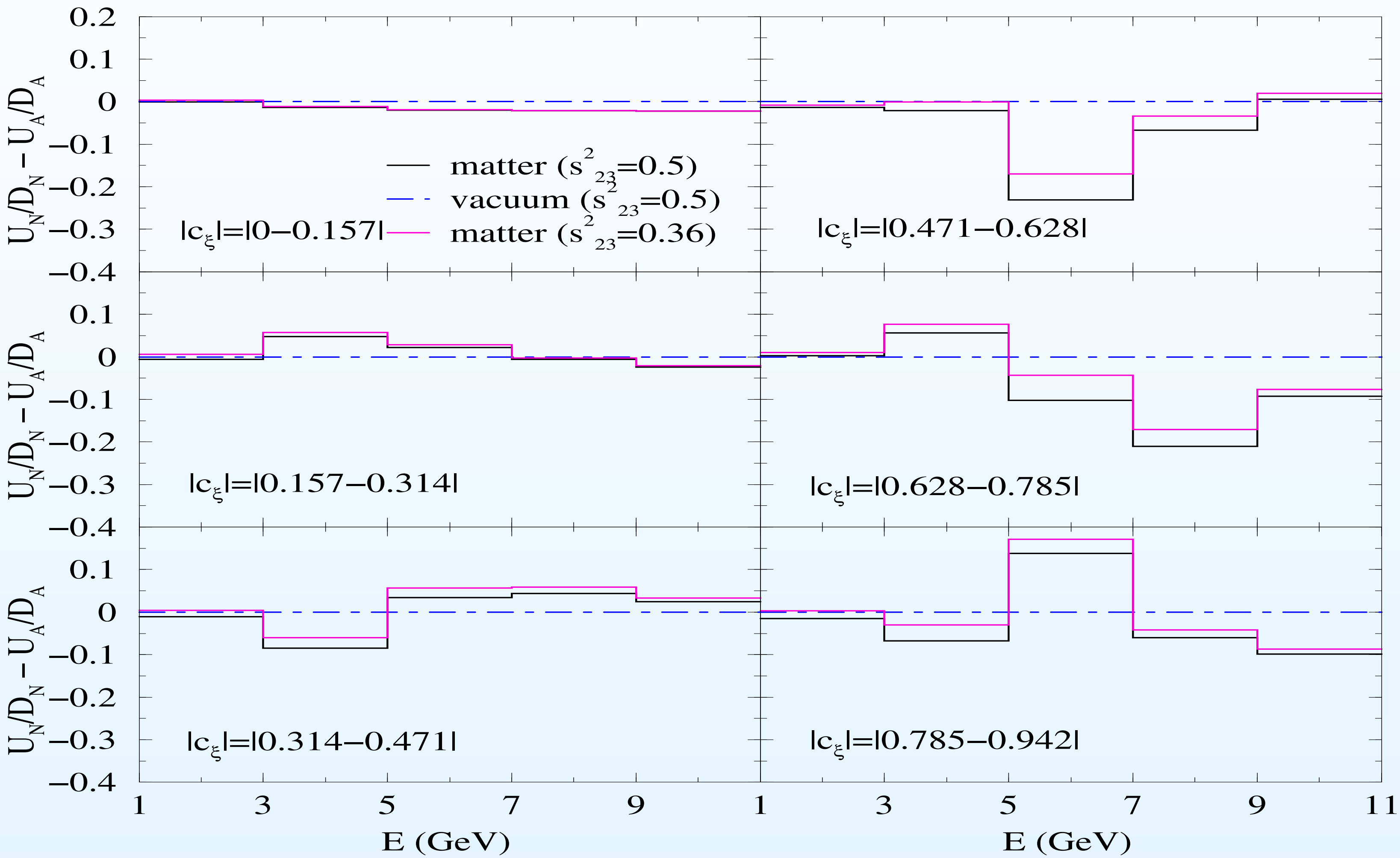
Atmospheric ν_μ in Large Magnetised Iron Calorimeter



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

- Large matter effects in $P_{\mu\mu}$
- Matter effects are $\sin^2\theta_{23}$ dependent

Atmospheric ν_μ in Large Magnetised Iron Calorimeter

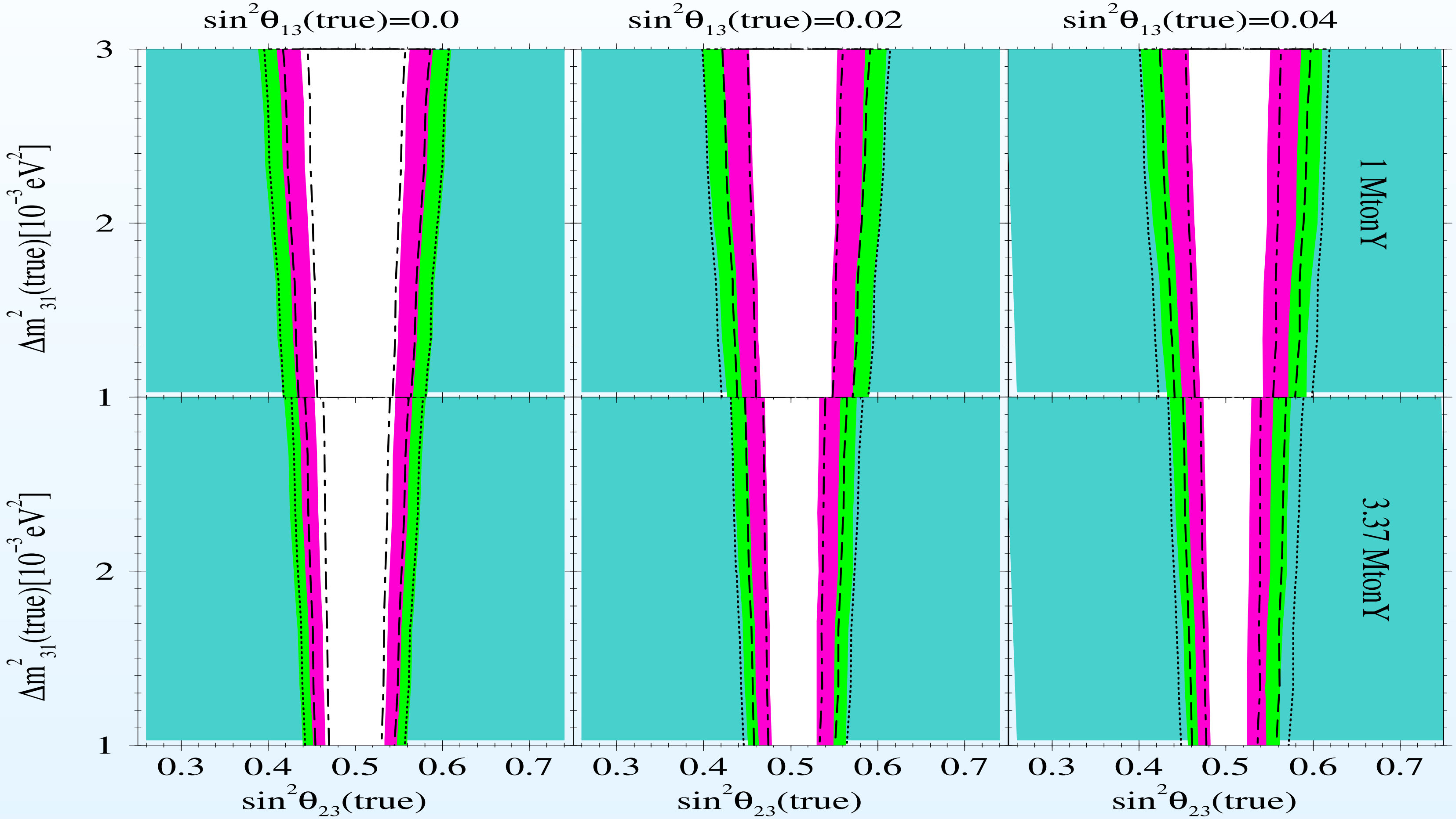


- Matter effects survive after the binning S.C and P. Roy hep-ph/0509197
- 60+60 bins of data
- define a χ^2 taking all errors

Is the Atmospheric Mixing Maximal?

Is the Atmospheric Mixing Maximal?

√ Using atmospheric neutrino data in INO

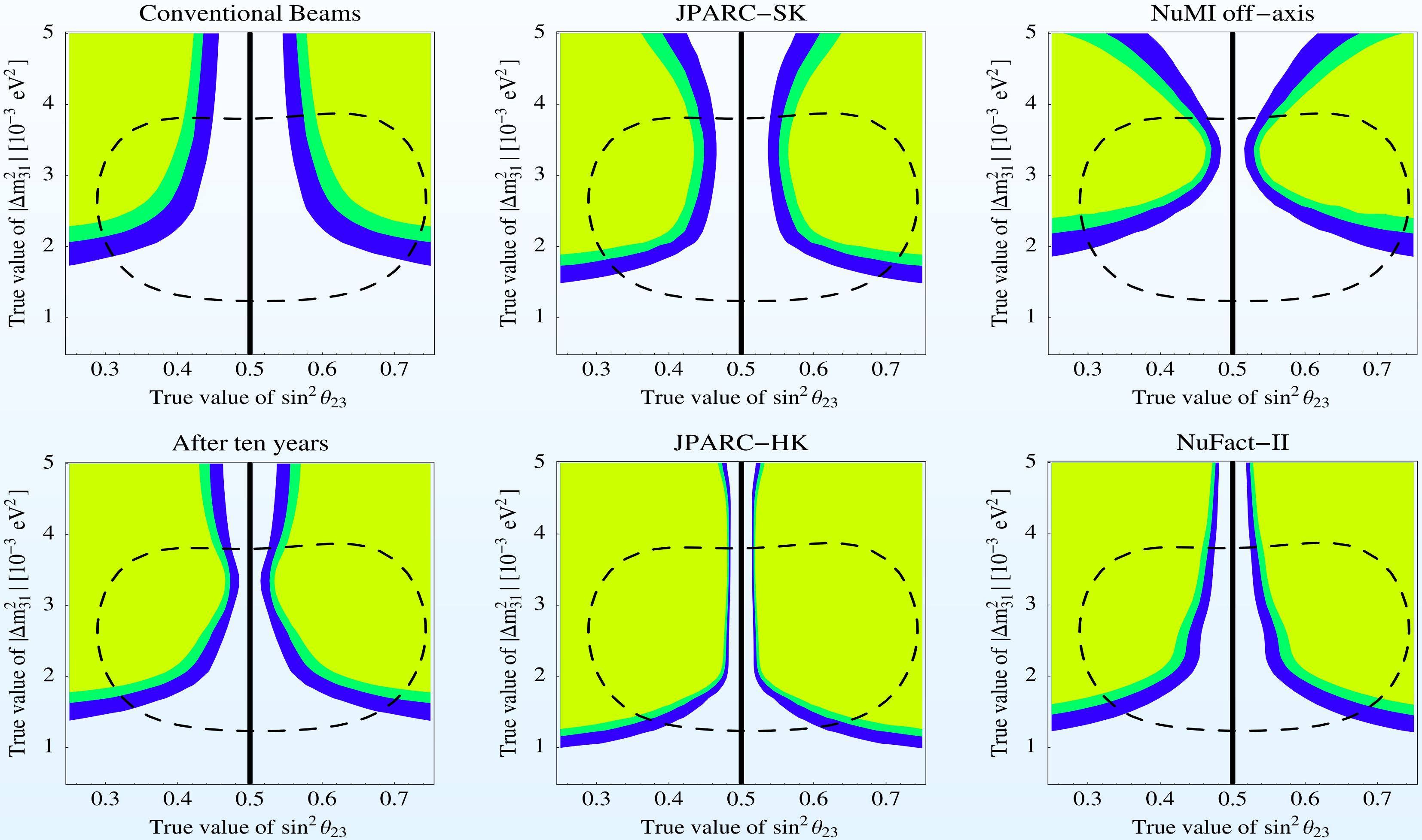


S.C. and P. Roy hep-ph/0509197

- $|D|$ 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

Is the Atmospheric Mixing Maximal?

√ Using long baseline experiments

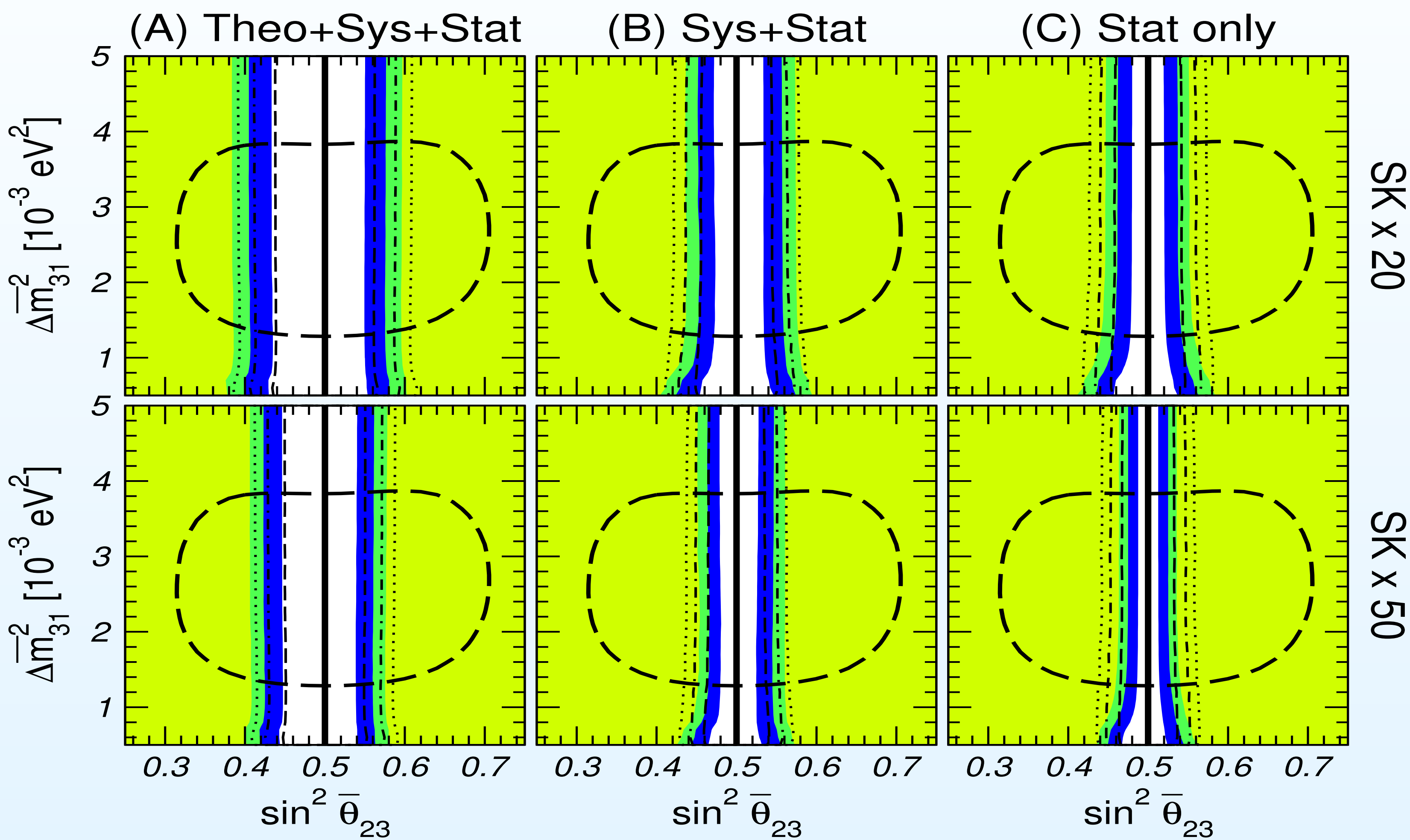


Antusch, et al, hep-ph/0404268

- $|D|$ can be measured to $\sim 14\%$ at 3σ for $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2

Is the Atmospheric Mixing Maximal?

√ Using atmospheric neutrino data in SK-like detector



Gonzalez-Garcia et al, hep-ph/0408170

- $|D|$ can be measured to $\sim 19\%(23\%)$ at 3σ with SK50(SK20)

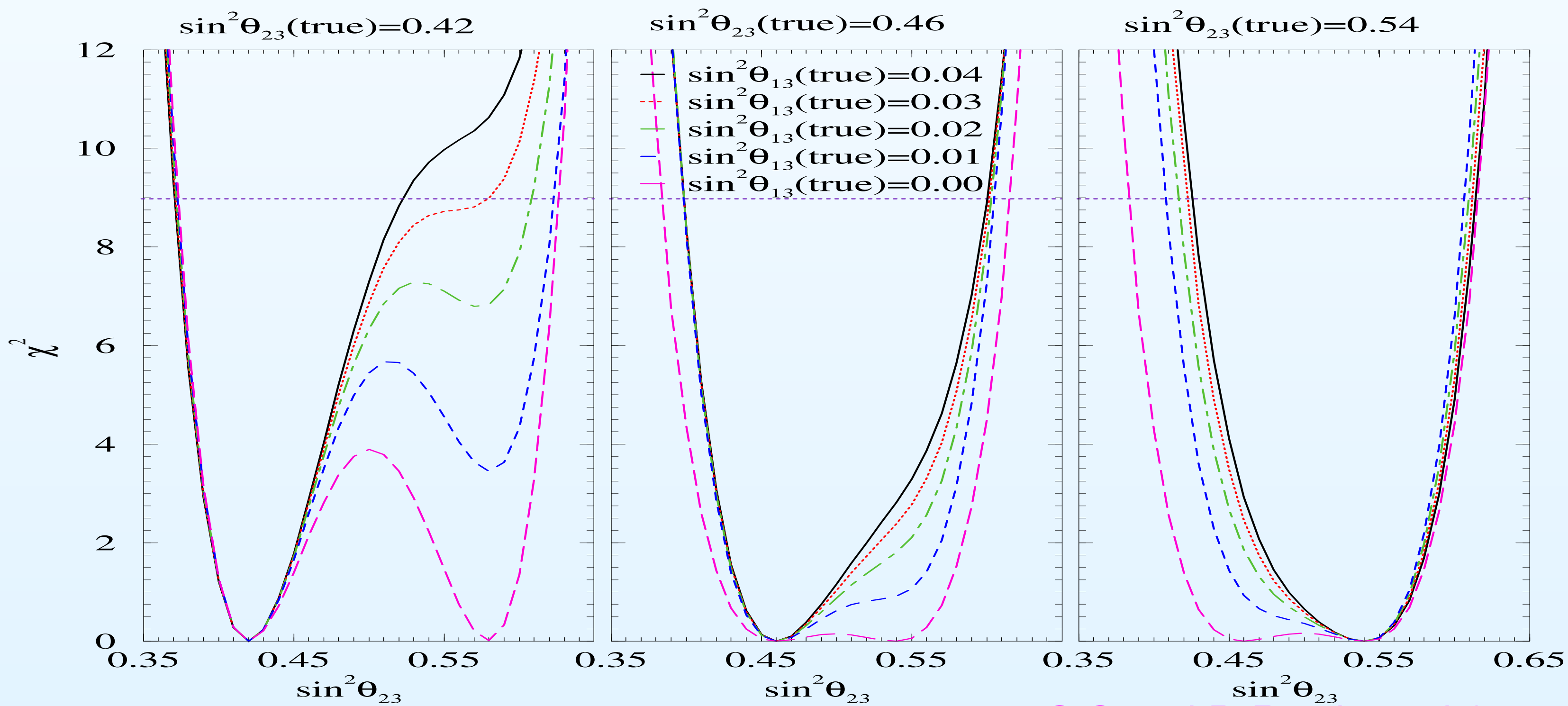
Resolving the Octant Ambiguity

Resolving the Octant Ambiguity

- For every nonmaximal $\sin^2\theta_{23}$(true), there exists a $\sin^2\theta_{23}$(false)

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

- Atmospheric neutrinos in magnetized iron detector



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

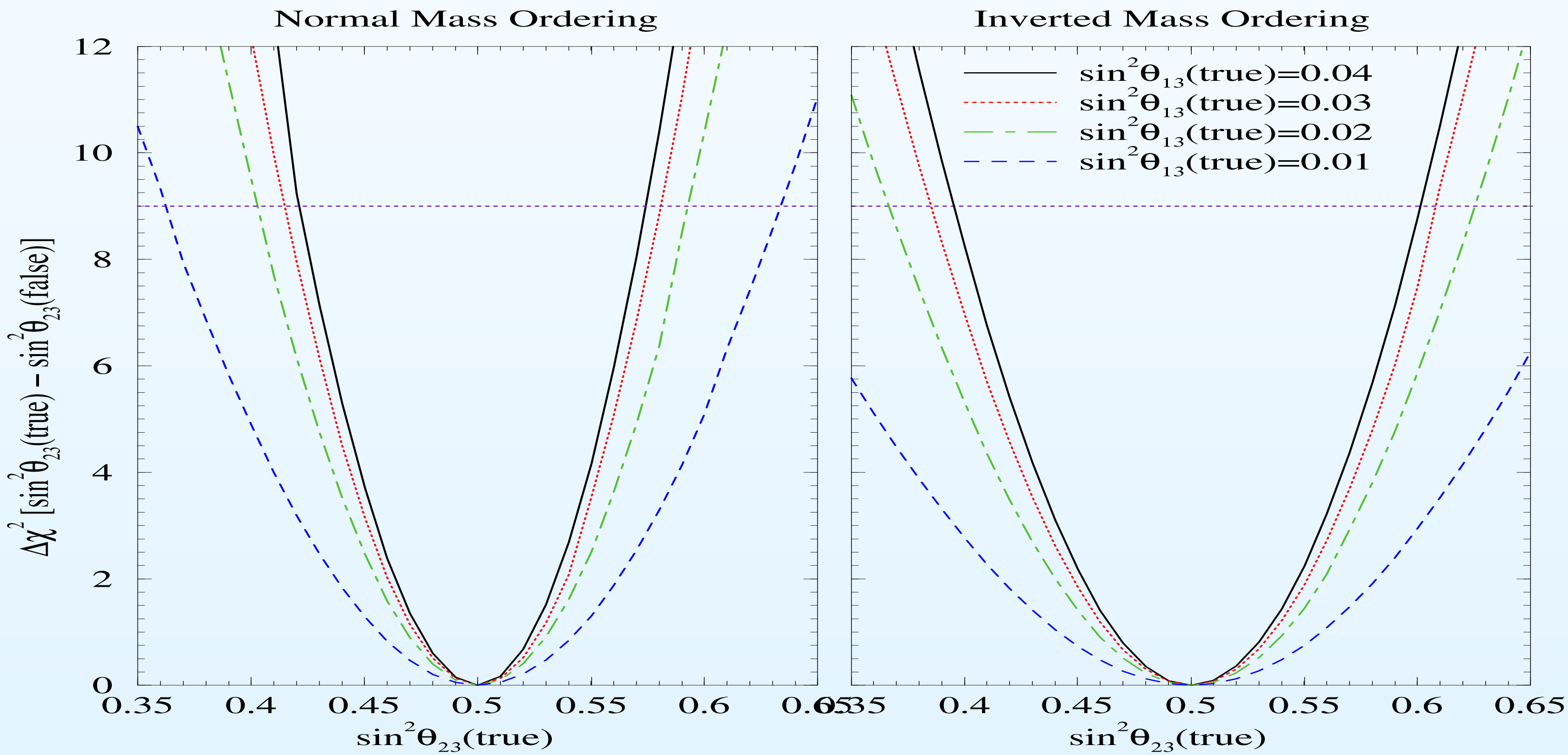
Resolving the Octant Ambiguity

$$\begin{aligned}\Delta\chi^2 &\equiv \chi^2(\sin^2\theta_{23}(\mathrm{false}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\mathrm{true})) \\ &-\chi^2(\sin^2\theta_{23}(\mathrm{true}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\mathrm{true}))\end{aligned}$$

Resolving the Octant Ambiguity

$$\Delta\chi^2 \equiv \chi^2(\sin^2\theta_{23}(\text{false}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\text{true})) - \chi^2(\sin^2\theta_{23}(\text{true}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\text{true}))$$

- Atmospheric neutrinos in magnetized iron detector

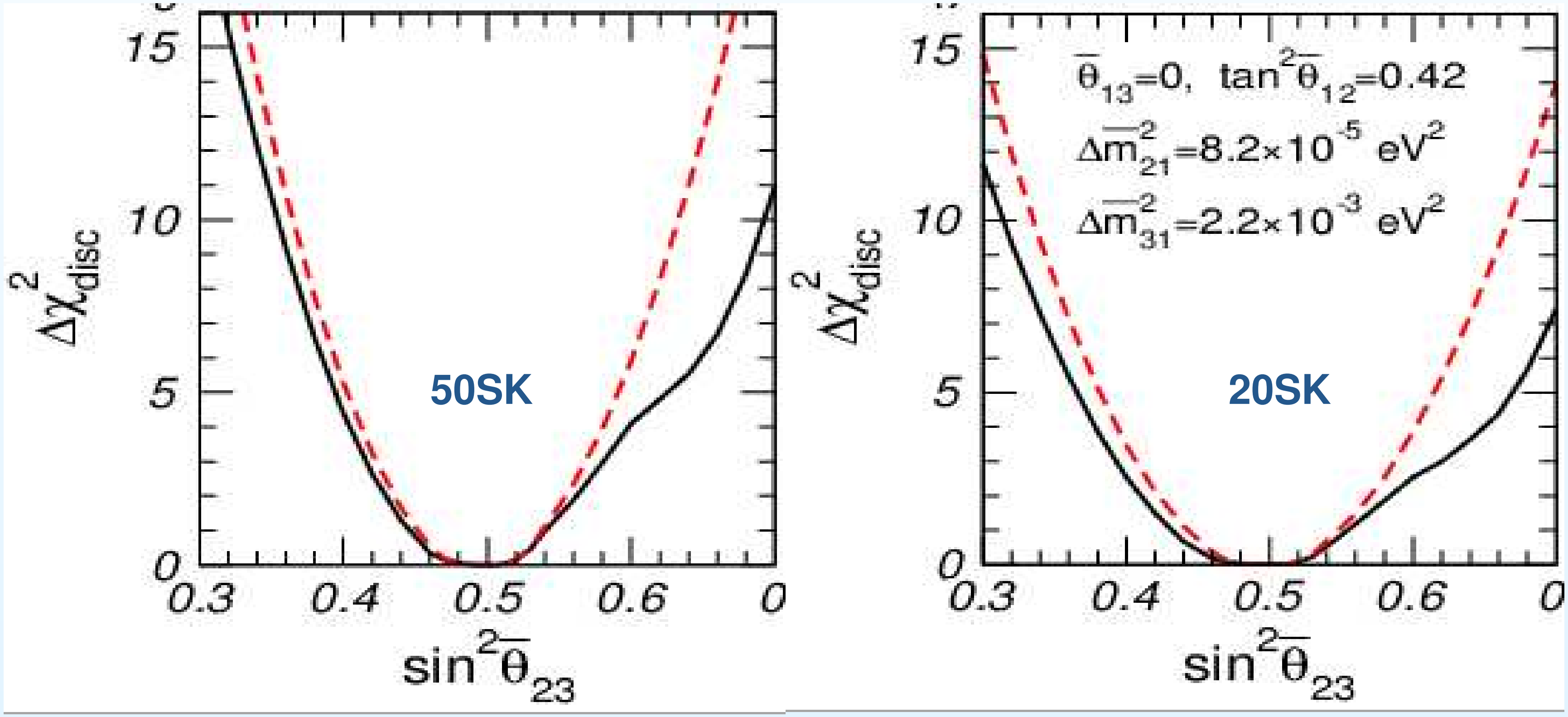


S.C and P. Roy hep-ph/0509197

Resolving the Octant Ambiguity

$$\Delta\chi^2 \equiv \chi^2(\sin^2\theta_{23}(\text{false}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\text{true})) - \chi^2(\sin^2\theta_{23}(\text{true}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\text{true}))$$

- Atmospheric neutrinos in water Cerenkov detector

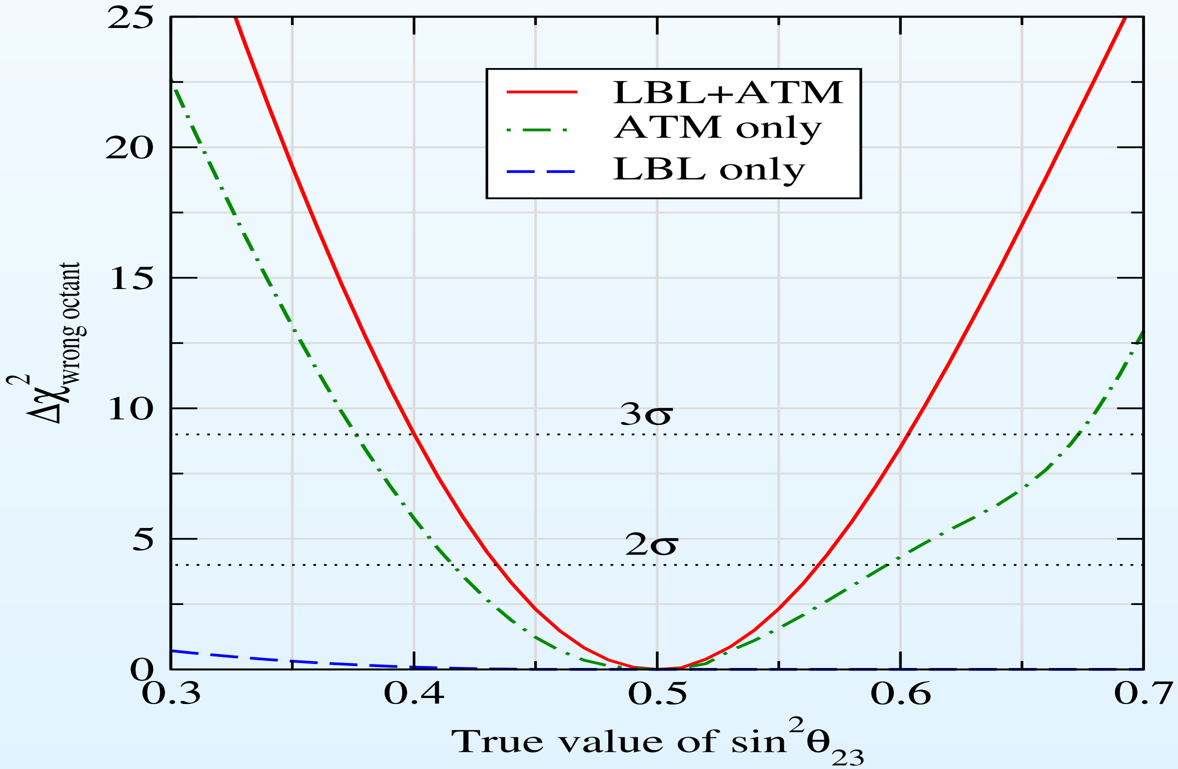


Gonzalez-Garcia et al, hep-ph/0408170

Resolving the Octant Ambiguity

$$\Delta\chi^2 \equiv \chi^2(\sin^2\theta_{23}(\text{false}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\text{true})) - \chi^2(\sin^2\theta_{23}(\text{true}), \sin^2\theta_{13}, \Delta m^2_{31}, \Delta m^2_{21}, \sin^2\theta_{12}|\omega(\text{true}))$$

- Long baseline experiments with accelerator (super)beam



Huber et al hep-ph/0501037

Comparing the Octant Sensitivity of the Experiments

- Long baseline experiments
  - ⋆ No sensitivity at all
- Atmospheric neutrinos in water Cerenkov detectors
  - ⋆ $\sin^2\theta_{23}$(false) can be excluded at 3σ if:

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

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

$$\sin^2\theta_{23}(\text{true}) < 0.361 \text{ or } > 0.633 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.01,$$

$$\sin^2\theta_{23}(\text{true}) < 0.402 \text{ or } > 0.592 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.02,$$

$$\sin^2\theta_{23}(\text{true}) < 0.415 \text{ or } > 0.580 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.03,$$

$$\sin^2\theta_{23}(\text{true}) < 0.421 \text{ or } > 0.573 \text{ for } \sin^2\theta_{13}(\text{true}) = 0.04.$$

Conclusions

Conclusions

- Earth matter effects in atmospheric $P_{\mu\mu}$ depends on θ_{23}

Conclusions

- Earth matter effects in atmospheric $P_{\mu\mu}$ depends on θ_{23}
- Binning in both energy and zenith angle is essential

Conclusions

- Earth matter effects in atmospheric $P_{\mu\mu}$ depends on θ_{23}
- Binning in both energy and zenith angle is essential
- It is also very important to distinguish neutrinos from anti-neutrinos

Conclusions

- Earth matter effects in atmospheric $P_{\mu\mu}$ depends on θ_{23}
- Binning in both energy and zenith angle is essential
- It is also very important to distinguish neutrinos from anti-neutrinos
- Large magnetized iron detectors can achieve both

Conclusions

- Earth matter effects in atmospheric $P_{\mu\mu}$ depends on θ_{23}
- Binning in both energy and zenith angle is essential
- It is also very important to distinguish neutrinos from anti-neutrinos
- Large magnetized iron detectors can achieve both
- Sensitivity to $|D|$ in INO comparable to 20SK/50SK and LBL experiments

Conclusions

- Earth matter effects in atmospheric $P_{\mu\mu}$ depends on θ_{23}
- Binning in both energy and zenith angle is essential
- It is also very important to distinguish neutrinos from anti-neutrinos
- Large magnetized iron detectors can achieve both
- Sensitivity to $|D|$ in INO comparable to 20SK/50SK and LBL experiments
- Octant resolution can be done best in INO if $\sin^2\theta_{13} \geq 0.01$