WHAT WE CAN LEARN FROM ATMOSPHERIC NEUTRINOS

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Goals for the Future / Plan of Talk

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- Using atmospheric neutrinos to constrain new physics

Confirmation of Oscillations of Atmospheric Neutrinos

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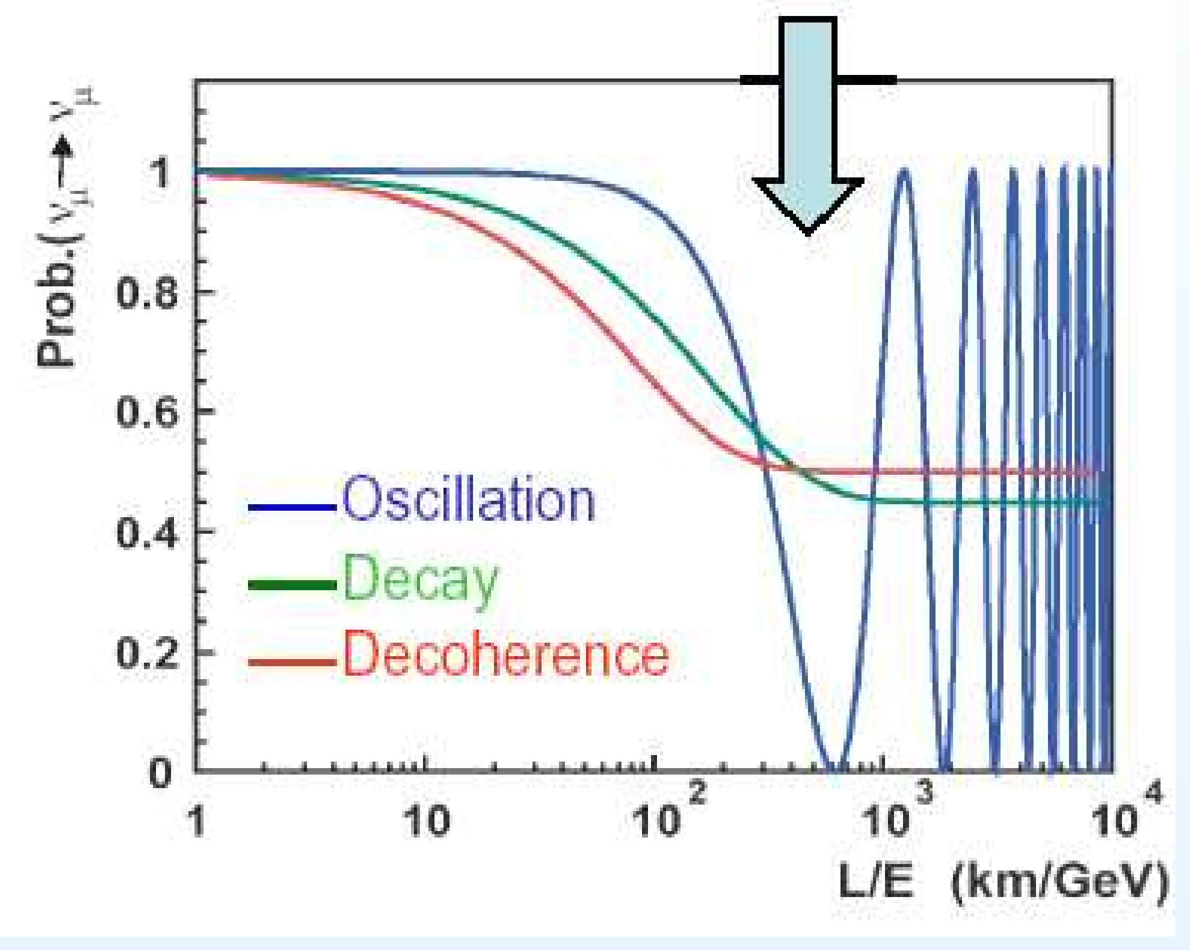
- Smoking Gun Signal for $\nu_\mu - \nu_\tau$ Oscillations



SK collab, Koshio talk, NANP '05

- Its important to observe the characteristic "dip" in L/E

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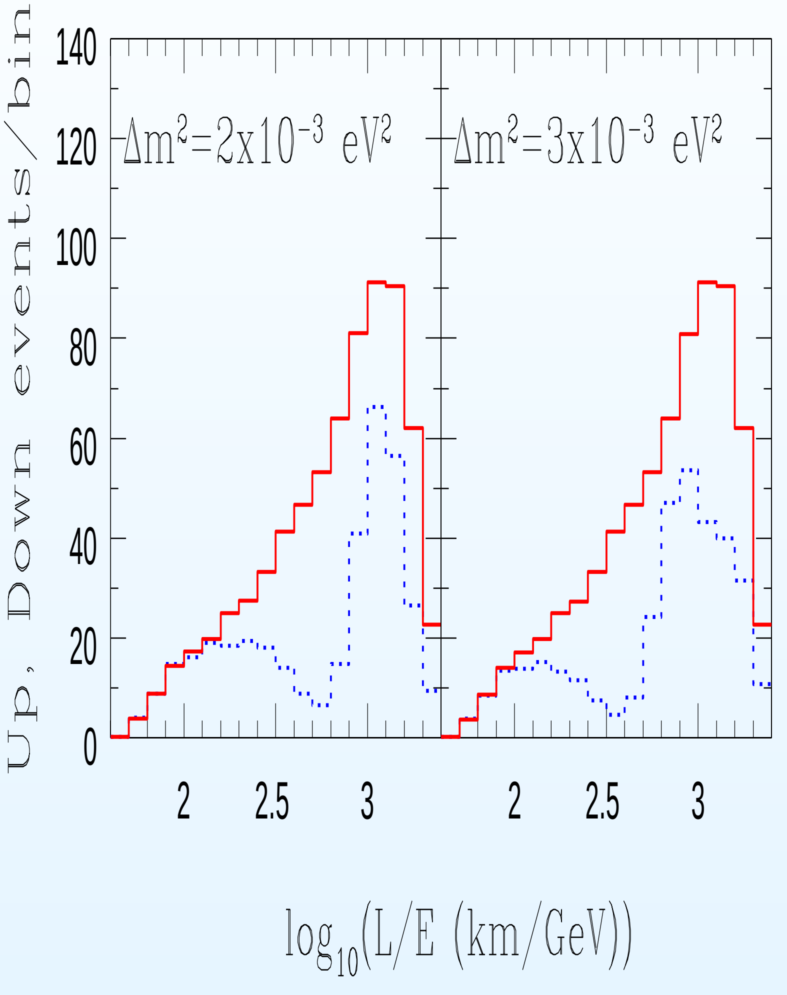

INO collaboration

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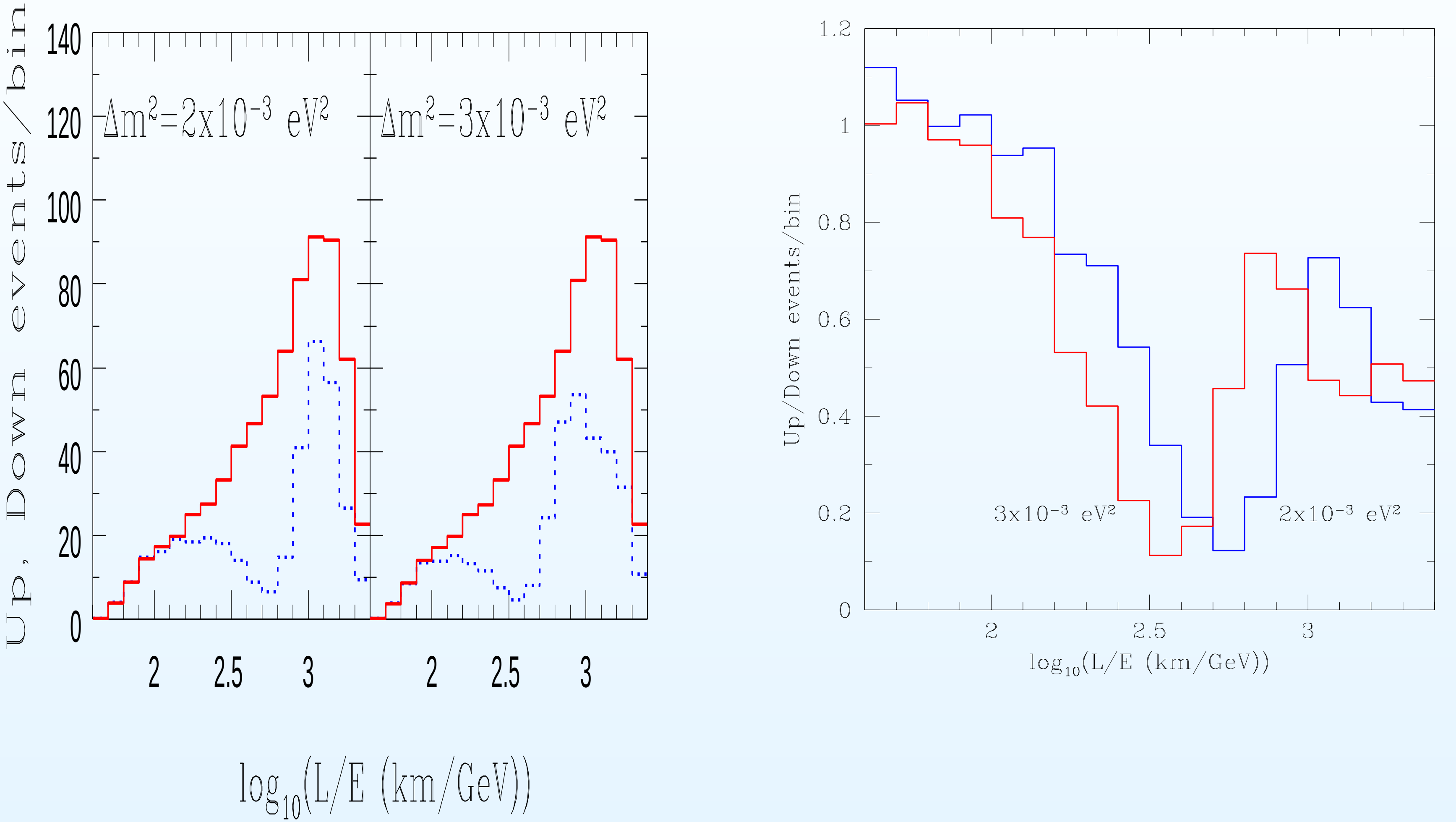

- The first oscillation dip should be clearly observable

INO collaboration

Precision Measurement of Δm^2_{31} and θ_{23}

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MINOS+CNGS	13%	38%
T2K (5 yrs)	6%	22%
NOνA (5 yrs)	13%	42%
Combination	4.5%	20%

Huber et al hep-ph/0403068

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Gonzalez-Garcia et al, hep-ph/0408170

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INO (250 kTy)	10%	30%

Huber et al hep-ph/0403068

Gonzalez-Garcia et al, hep-ph/0408170

INO Collaboration

Three Generation Oscillation Probabilities

Muon Neutrino Survival Probability

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

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

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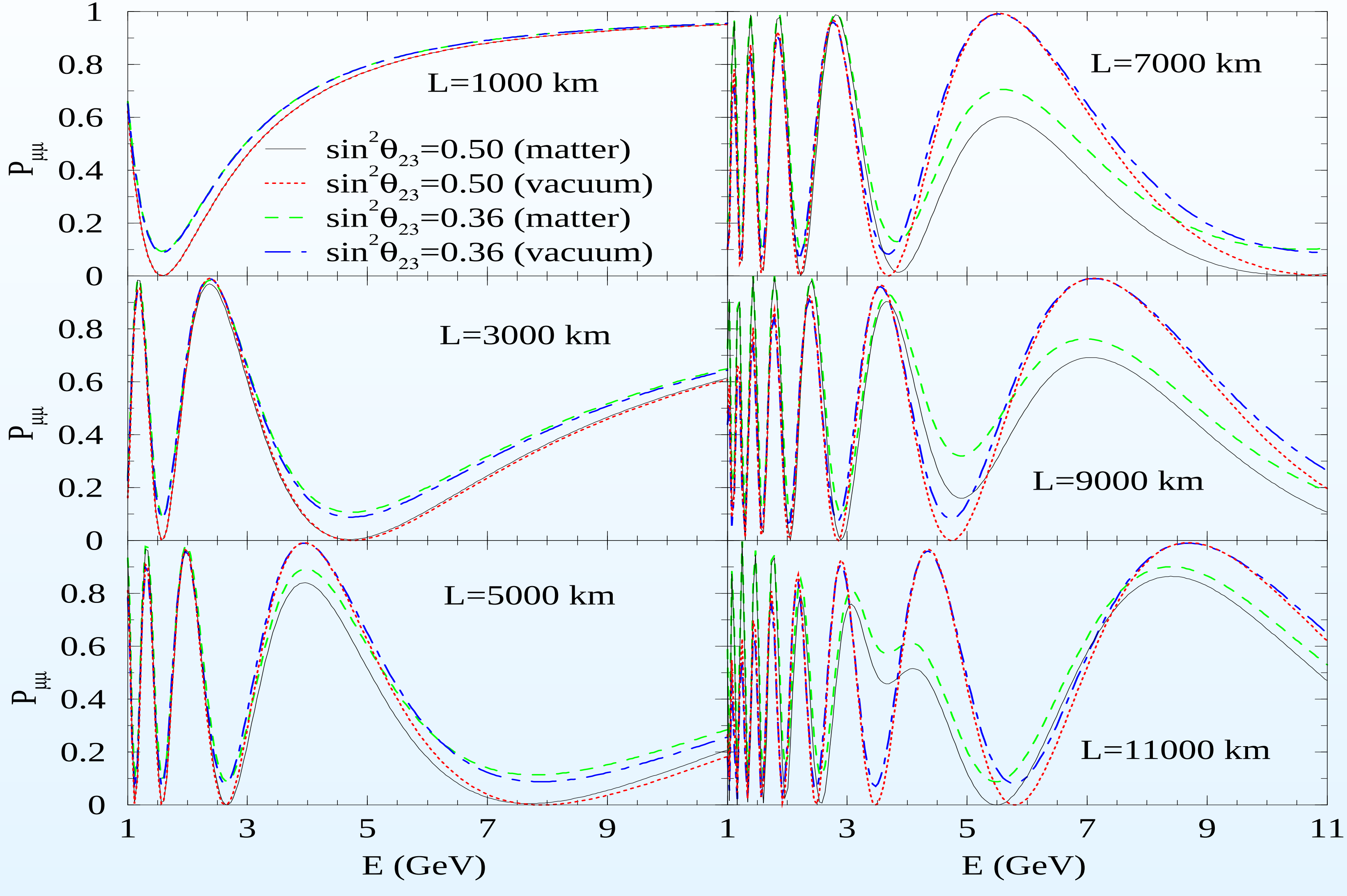
- Dependence on θ_{23} in the form $\sin^4\theta_{23}$
- Octant sensitivity is expected to be good

Large Matter Effects in ν_μ Survival Probability



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

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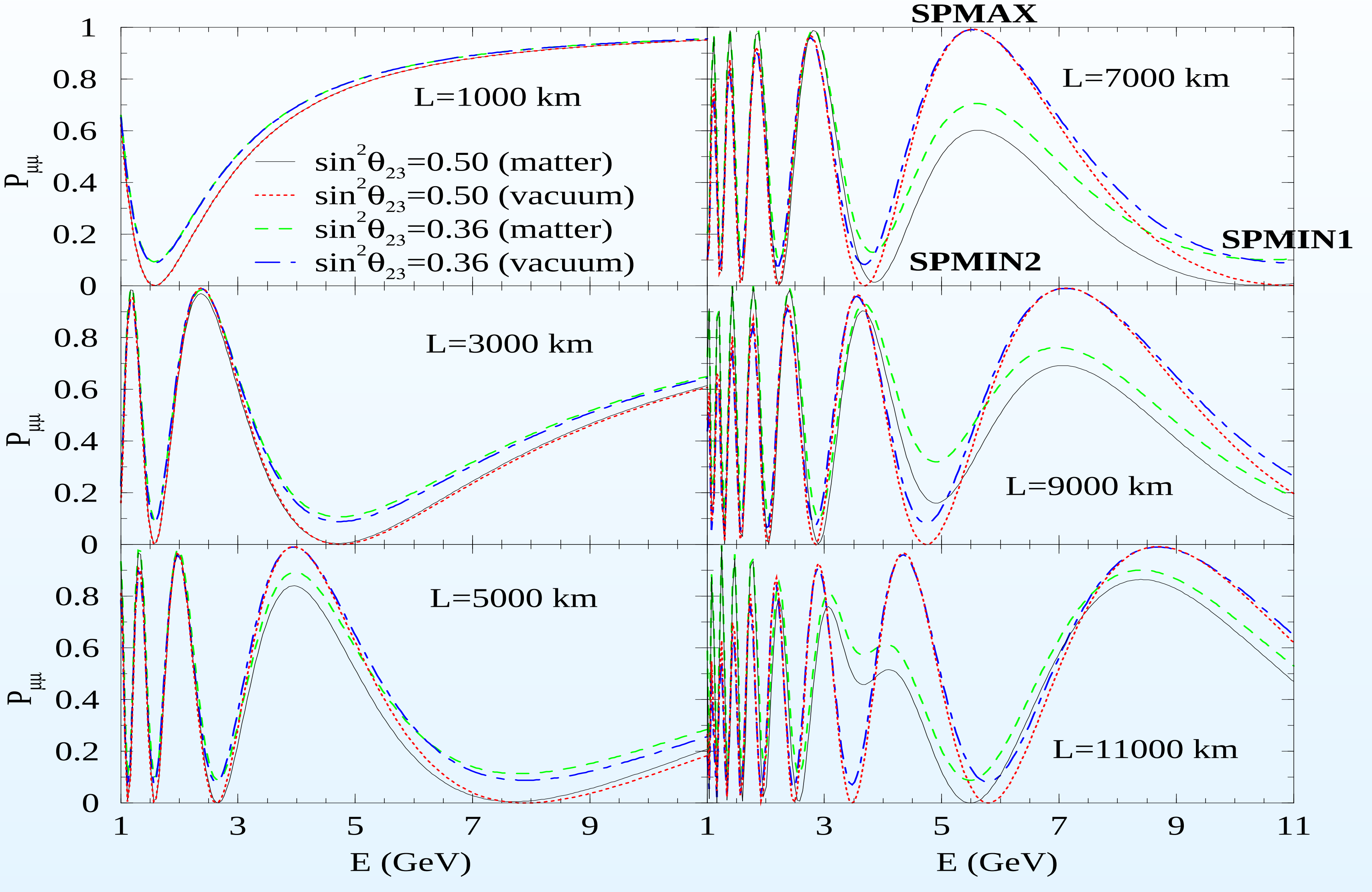

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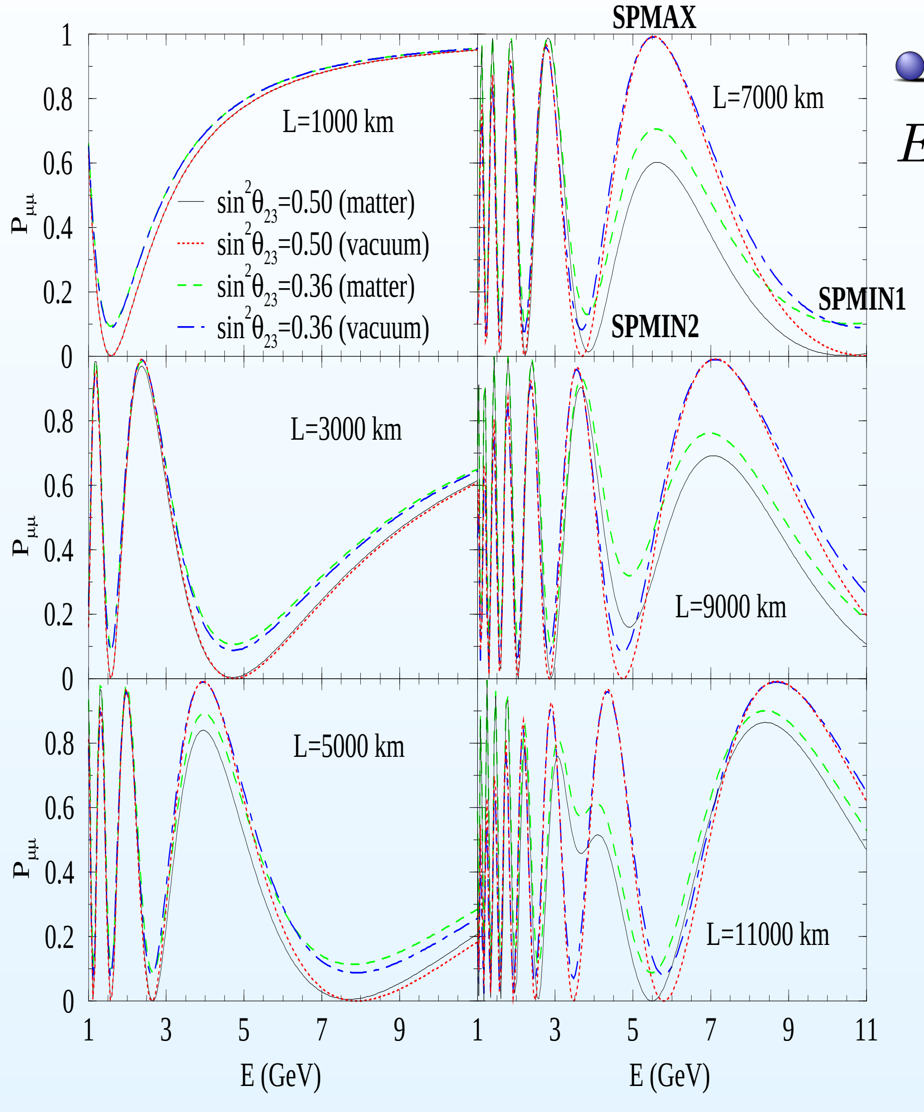

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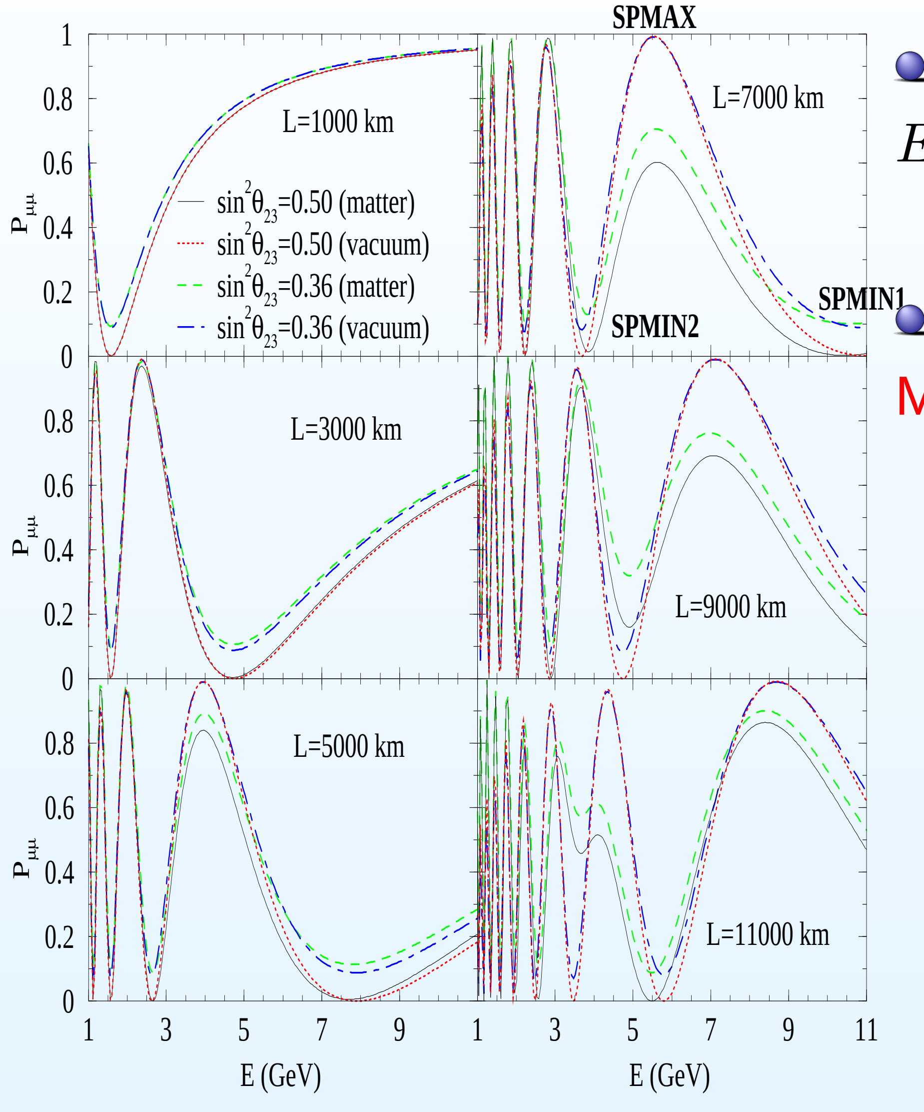

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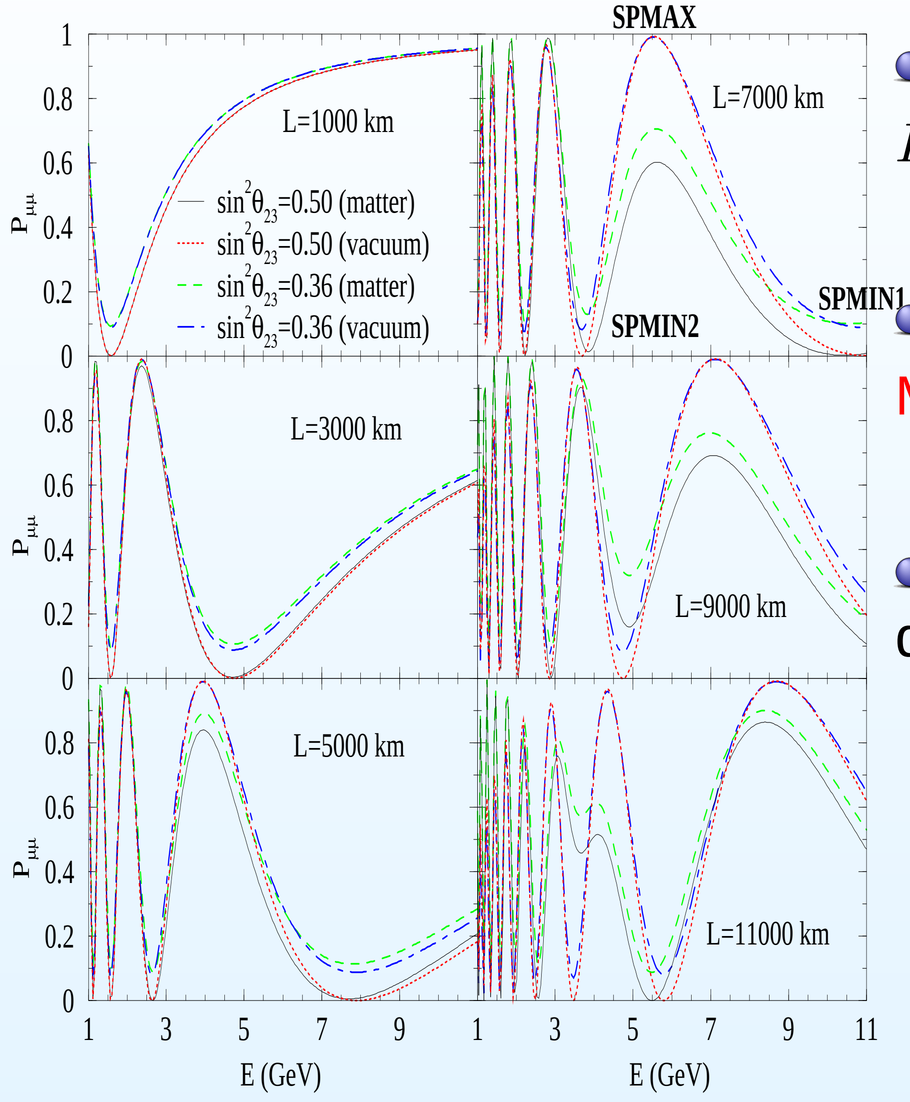

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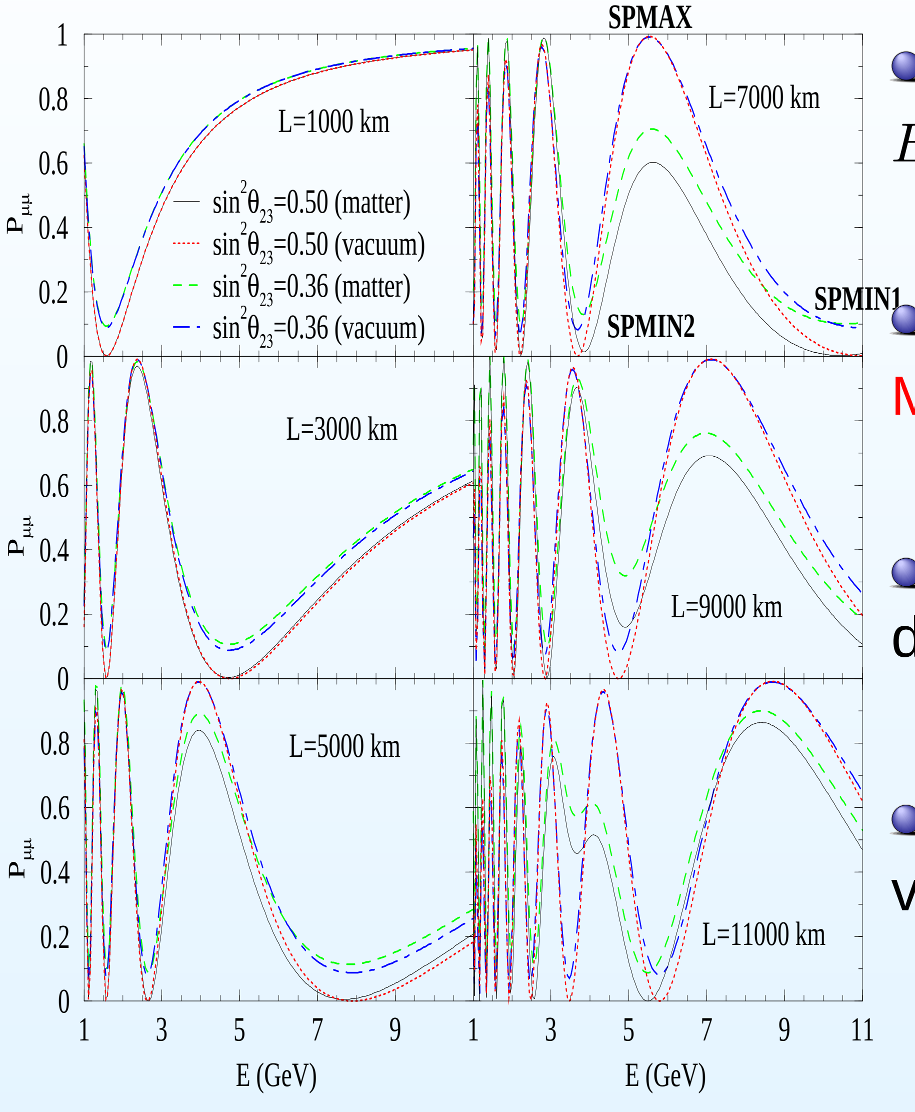

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- Sign of the earth matter effects depends on both E and L
- Matter effects depend on the value of $\sin^2\theta_{23}$

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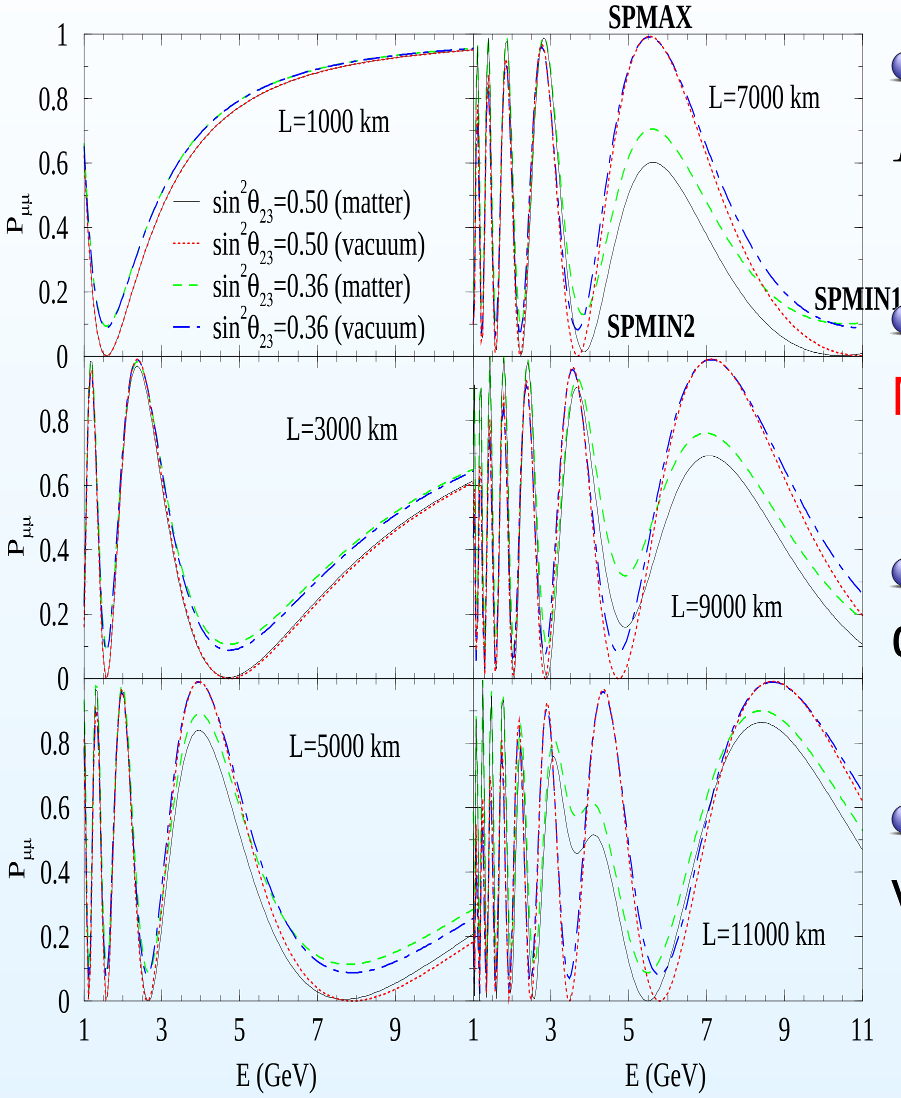

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- $P_{\mu\mu}$ decreases (increases) at SP-MAX (SPMIN) due to matter effects
- Sign of the earth matter effects depends on both E and L
- Matter effects depend on the value of $\sin^2\theta_{23}$
- Most important to choose the bins properly in both E and L

Very Large Matter Effects in $\nu_\mu \leftrightarrow \nu_e$ Probability

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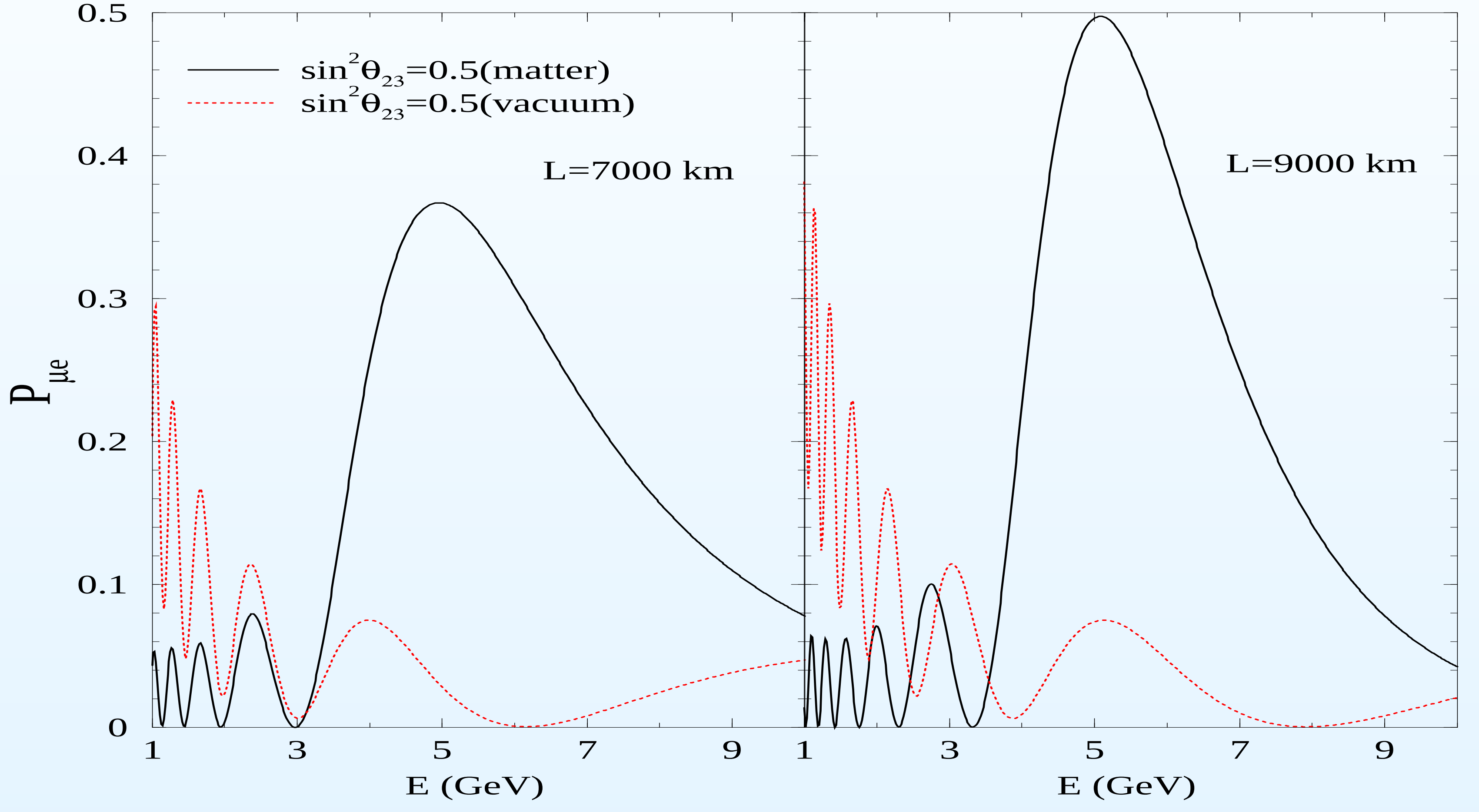

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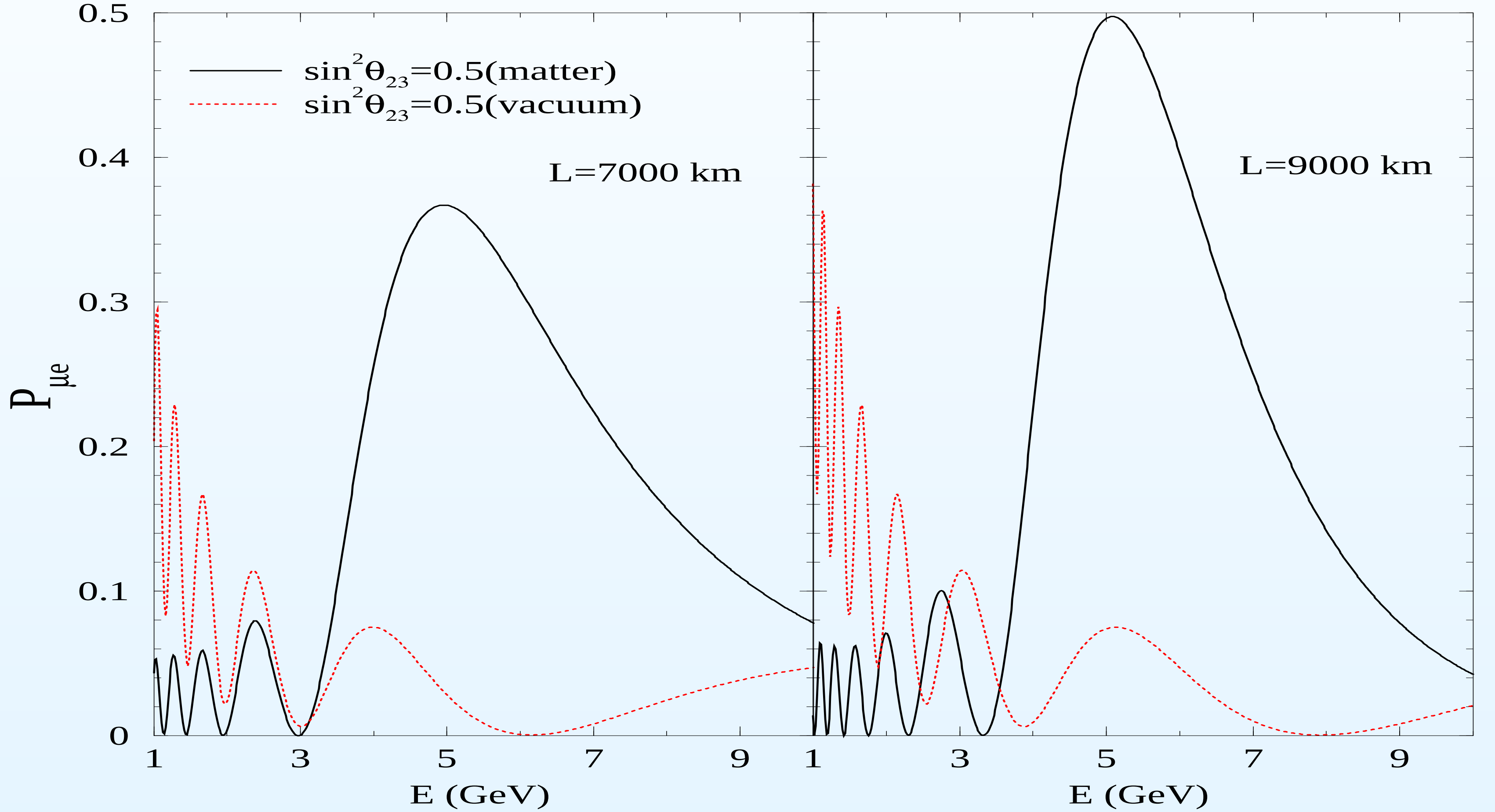

- Above ~ 3 GeV, matter effects increase $P_{\mu e}$ for all E and L

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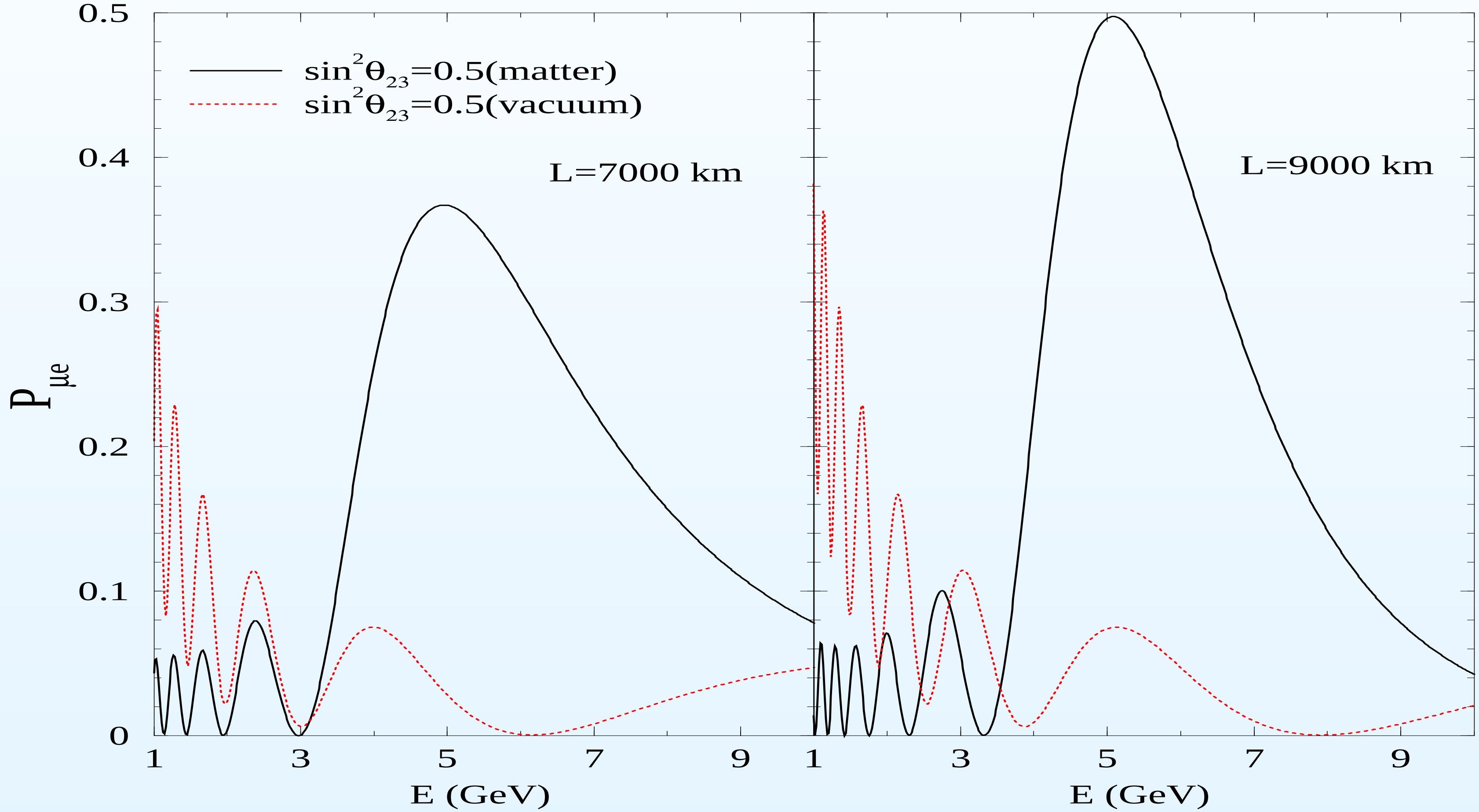

- Sub-dominant Δm^2_{21} oscillations in $P_{\mu e}$ is also crucial

Atmospheric Neutrino Events

Atmospheric Neutrino Events

Change in number of muon events:

$$\begin{aligned} N_\mu &= N_\mu^0 P_{\mu\mu} + N_e^0 P_{e\mu} \\ &= N_\mu^0 \left[P_{\mu\mu} + \frac{1}{r} P_{e\mu} \right]; \quad (\text{where } r = \frac{N_\mu^0}{N_e^0}) \end{aligned}$$

$$1 - \frac{N_\mu}{N_\mu^0} \simeq (P_{\mu\mu}^1 + P_{\mu\mu}^2) + (P_{\mu\mu}^3)' s_{23}^2 (s_{23}^2 - \frac{1}{r})$$

$$(P_{\mu\mu}^3)' = \sin^2 2\theta_{13}^M \sin^2 \frac{(\Delta m_{31}^2)^M}{4E} L$$

- Can be used to study maximality and octant of θ_{23}
- Can be used to study the neutrino mass hierarchy
- Δm_{21}^2 and δ_{CP} bring in small effects

Atmospheric Neutrino Events

Change in number of electron events:

$$\begin{aligned}
\frac{N_e}{N_e^0} - 1 \quad &\simeq \quad \sin^2 2\theta_{12}^M \sin^2\left(\frac{(\Delta m_{21}^2)^M L}{4E}\right) \times (r\cos^2\theta_{23} - 1) \\
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- θ_{13}-driven oscillation effect

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- θ_{13}-driven oscillation effect
- Reduces the excess (depletion) in the sub-GeV electron event sample for $\sin^2\theta_{23} < 0.5 (> 0.5)$ – thats the bad part!!

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- Can be used for studying the neutrino mass hierarchy

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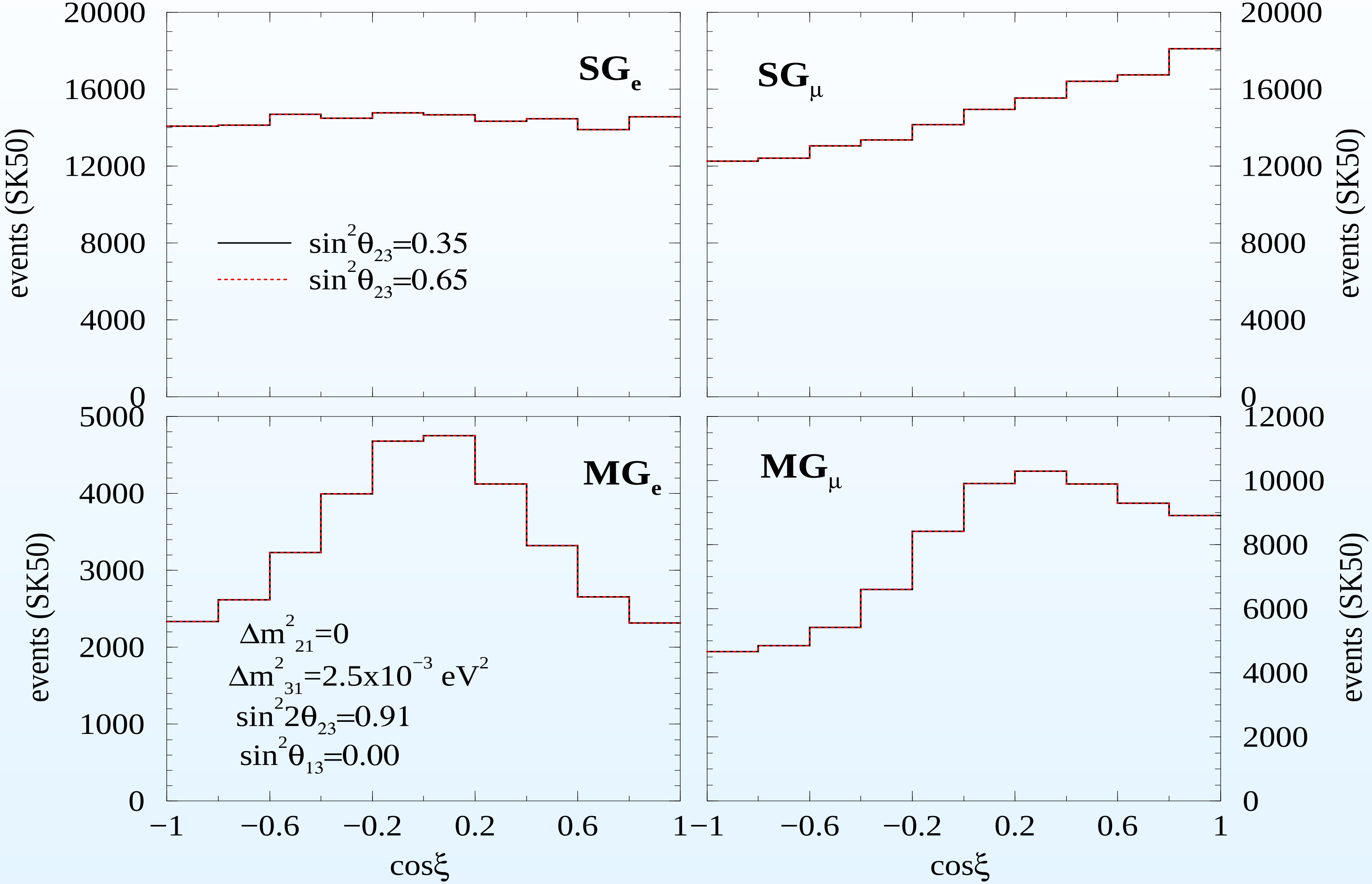
- “interference” term which depends on δ_{CP}
- It might cancel the effect of the Δm^2_{21} and θ_{13} terms depending on the value of δ_{CP} – bad bad bad...
- But it might tell us if $\delta_{CP} = 0$ or π (Fogli et al. hep-ph/0506083)

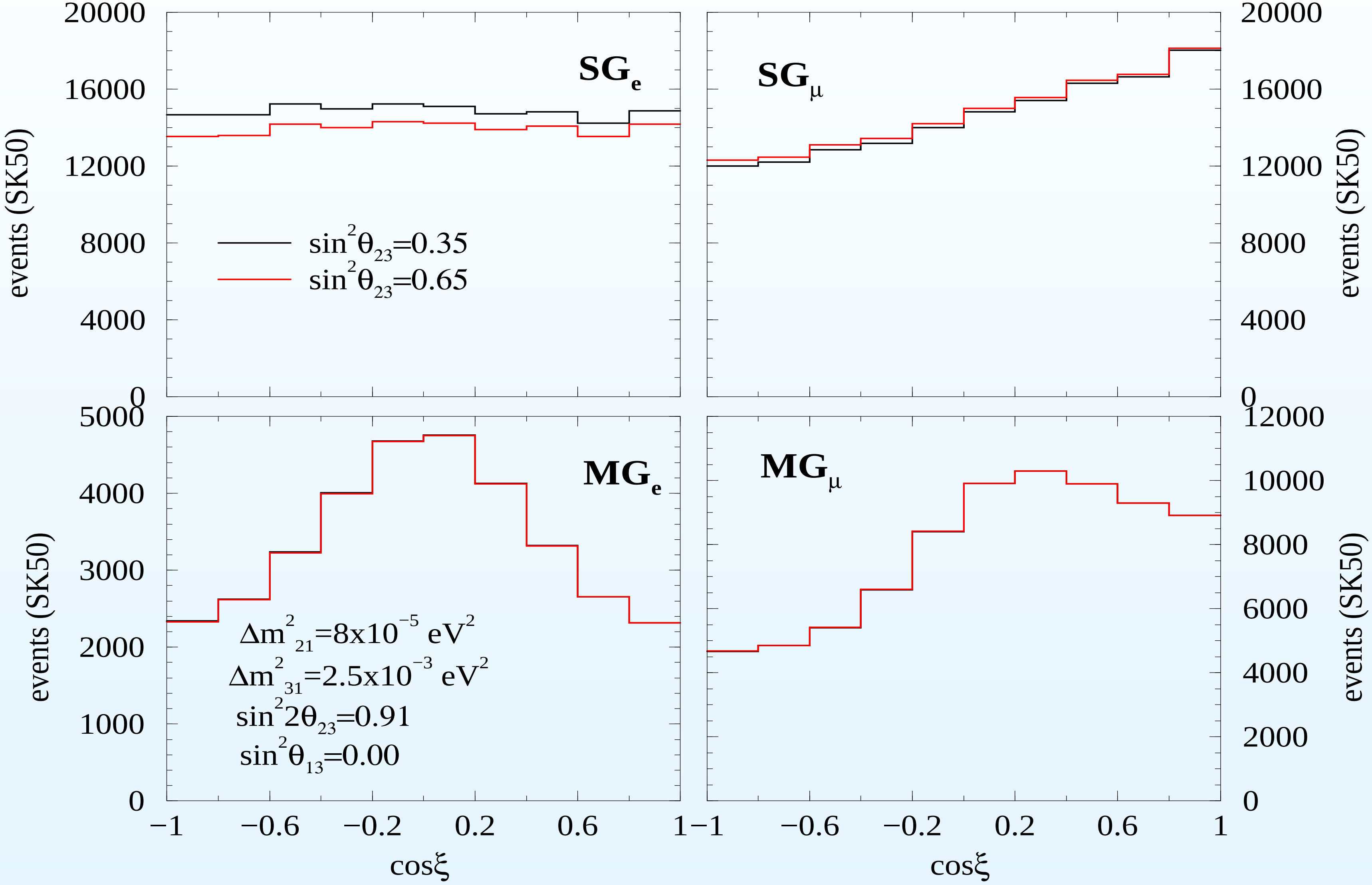
Atmospheric Neutrino Events in MTon Water Detector

Atmospheric Neutrino Events in MTon Water Detector



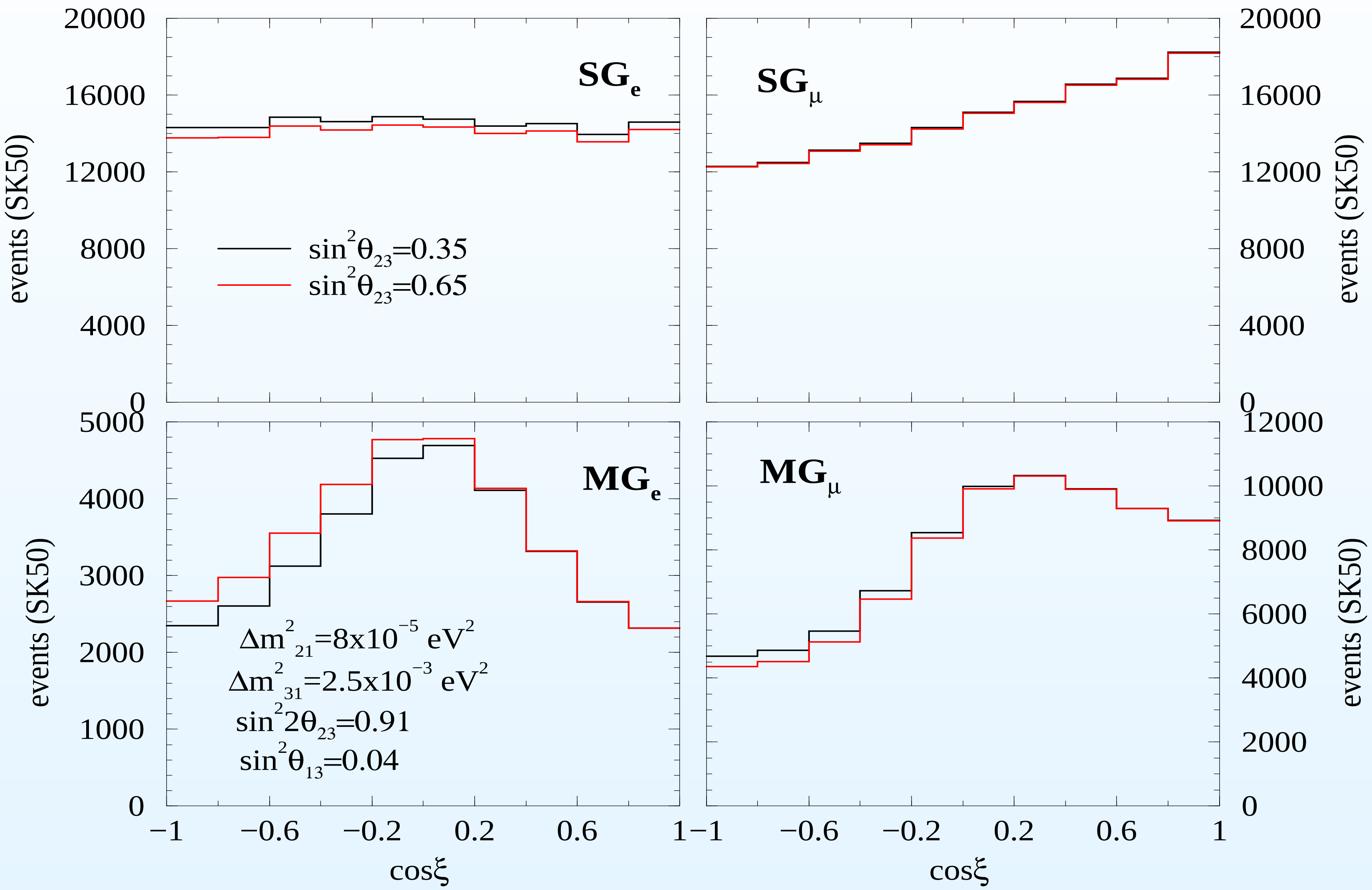
- These are just 2-gen $\nu_\mu \rightarrow \nu_\tau$ oscillations

Atmospheric Neutrino Events in MTon Water Detector



- Δm^2_{21}-driven oscillations bring in octant sensitivity in SGe events

Atmospheric Neutrino Events in MTon Water Detector



- θ_{13} brings in more octant sensitivity through matter effects

Atmospheric Neutrino Events in INO-ICAL

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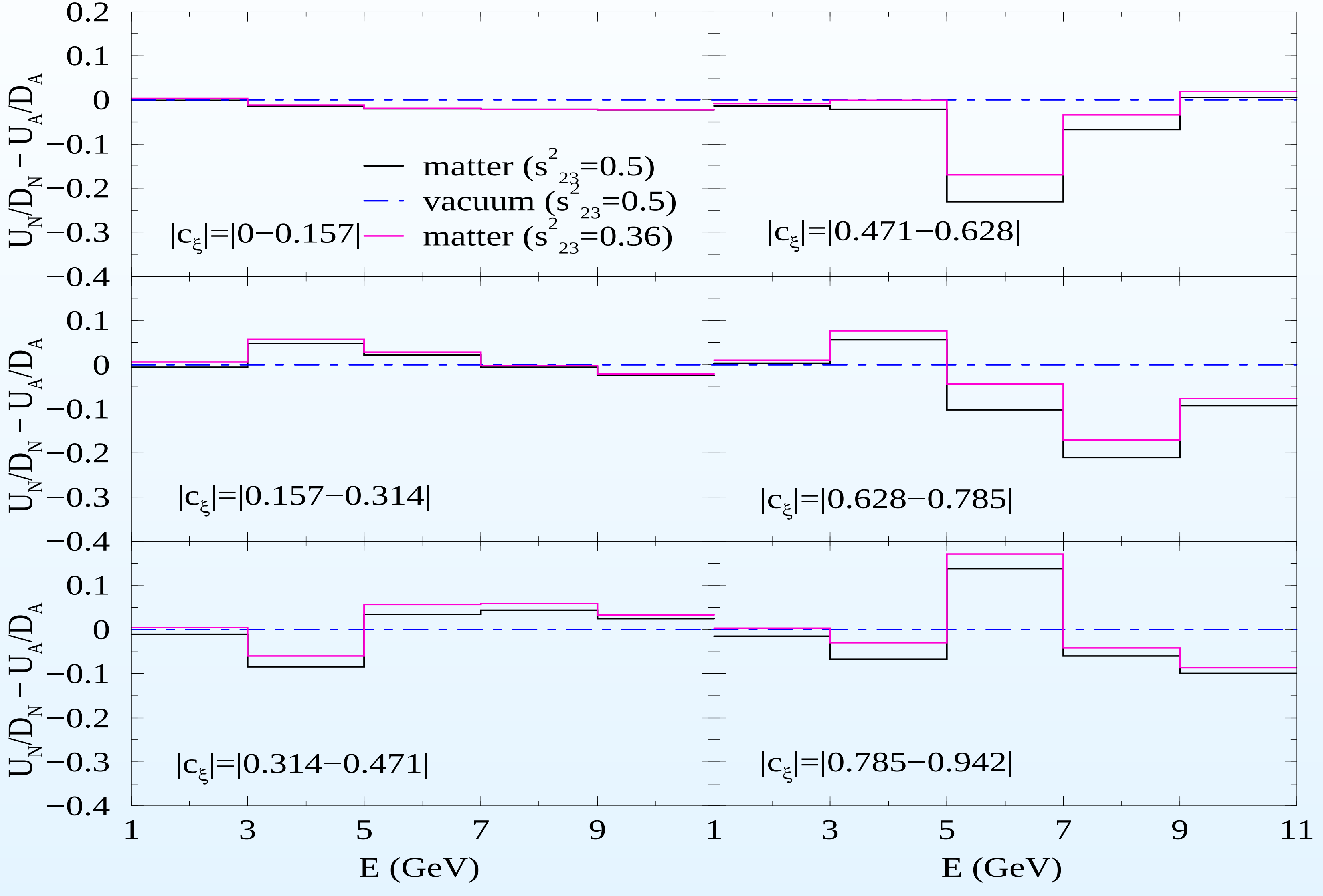

S.C and P. Roy hep-ph/0509197

Testing Maximality of θ_{23}

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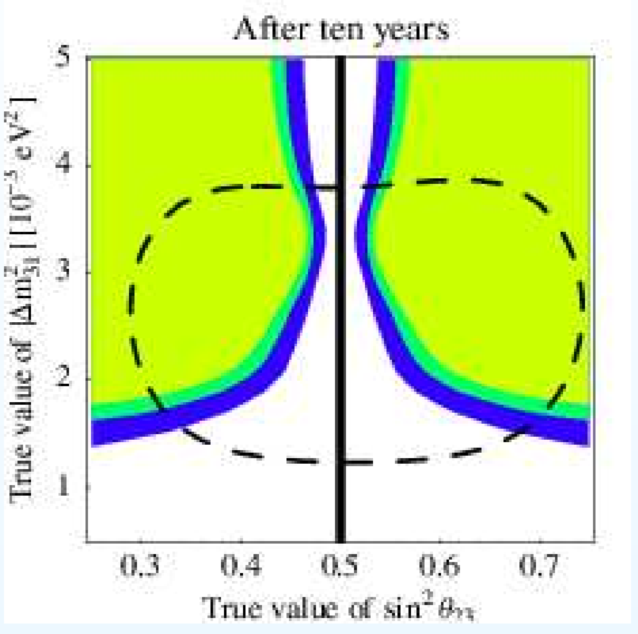

$|D|$ within 14%

LBL combined

Antusch, et al,

hep-ph/0404268

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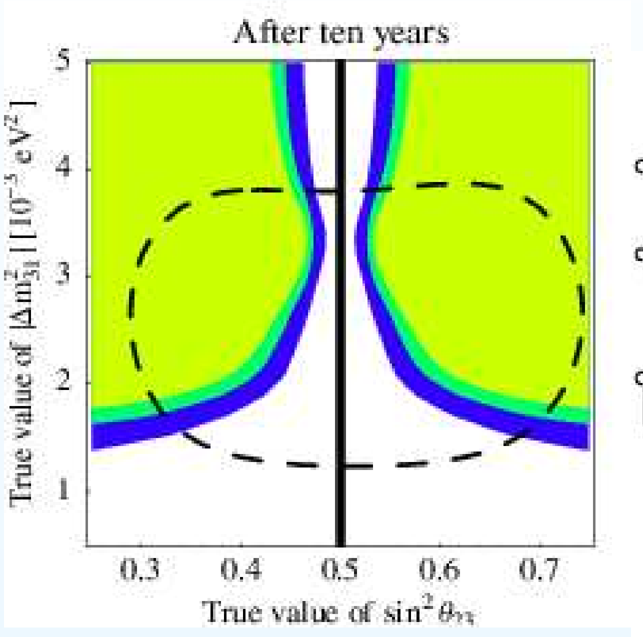

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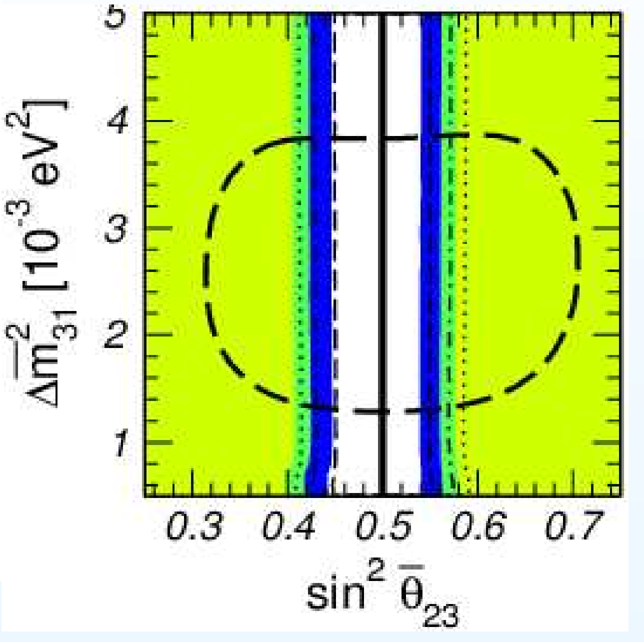

$|D|$ within 19%

SK50

Gonzalez-Garcia, et al,

hep-ph/0408170

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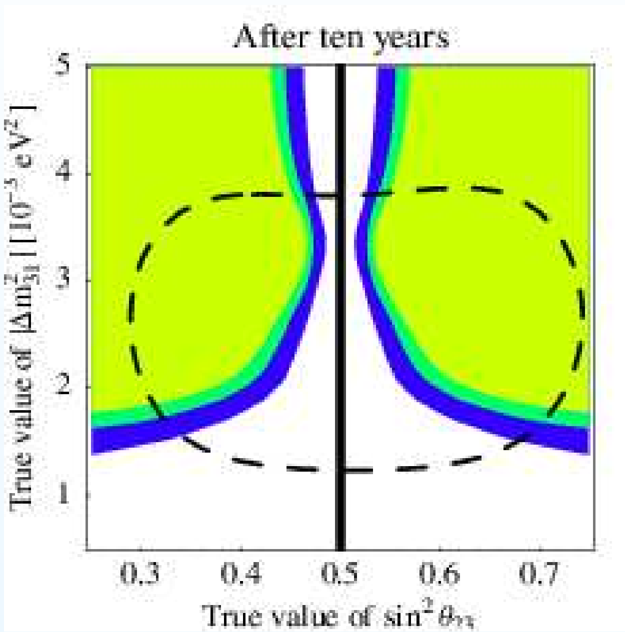

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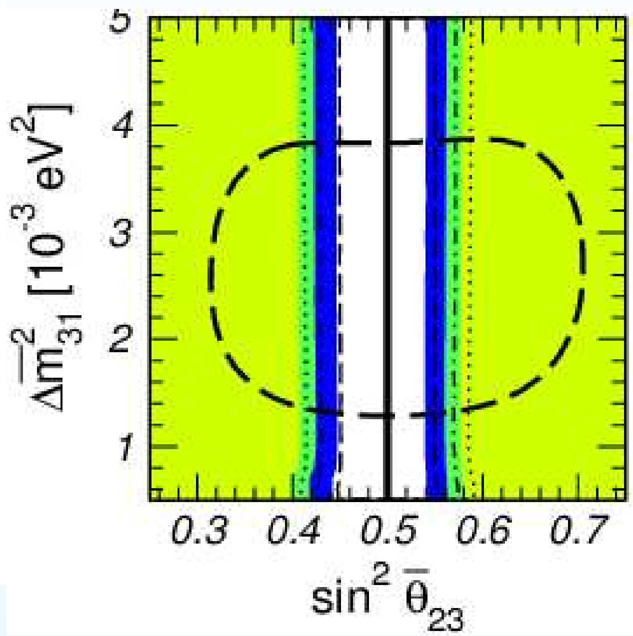

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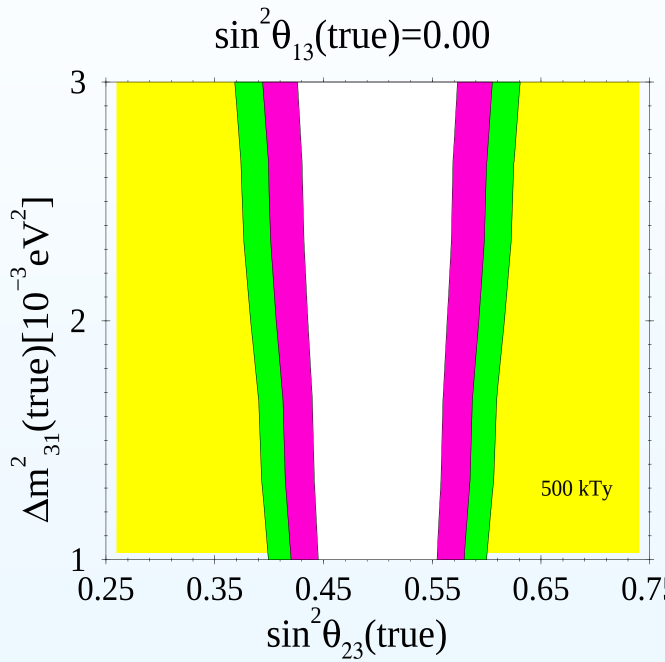

$|D|$ within 25%

INO-ICAL 500 kTy

S.C. and P. Roy,

hep-ph/0509197

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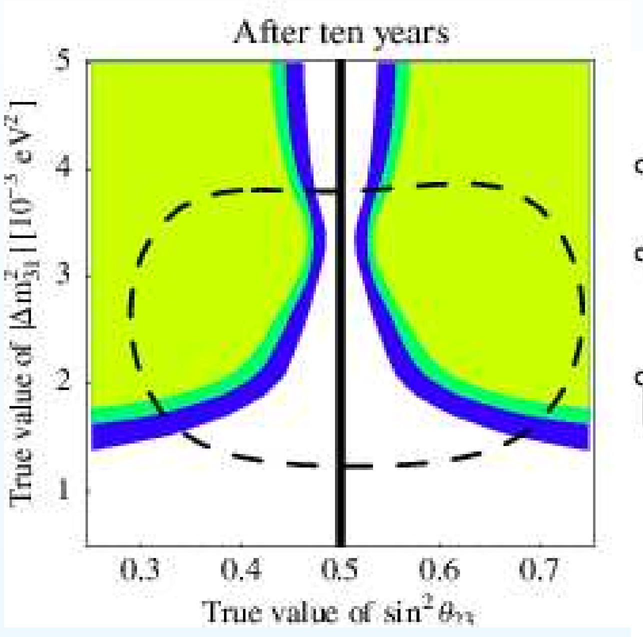

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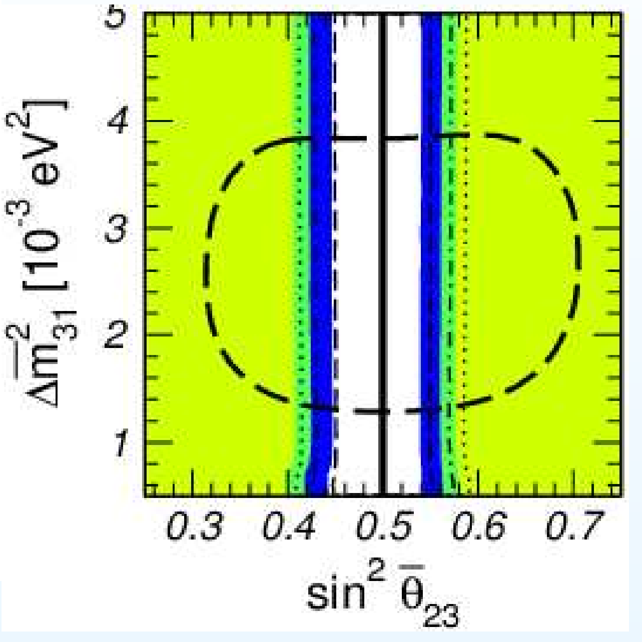
Antusch, et al,

hep-ph/0404268



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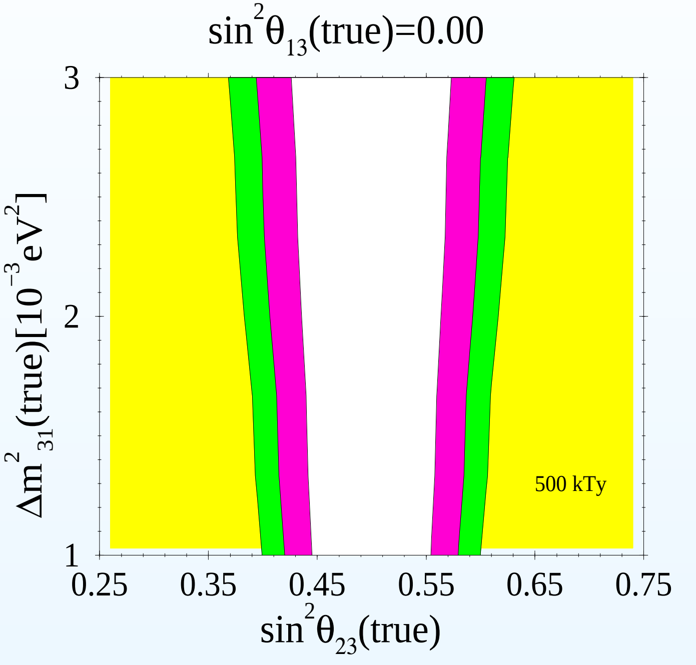

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S.C. and P. Roy,

hep-ph/0509197

- Sensitivity to $|D| \equiv |(\sin^2\theta_{23} - 0.5)|$ comparable to LBL expts

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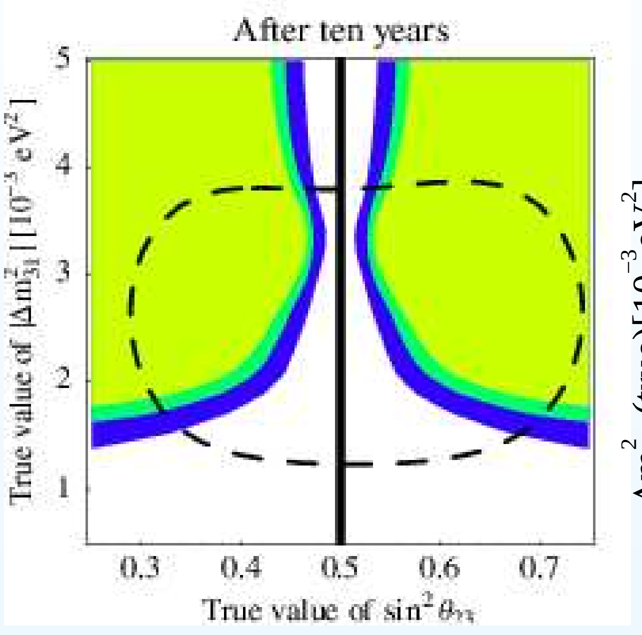

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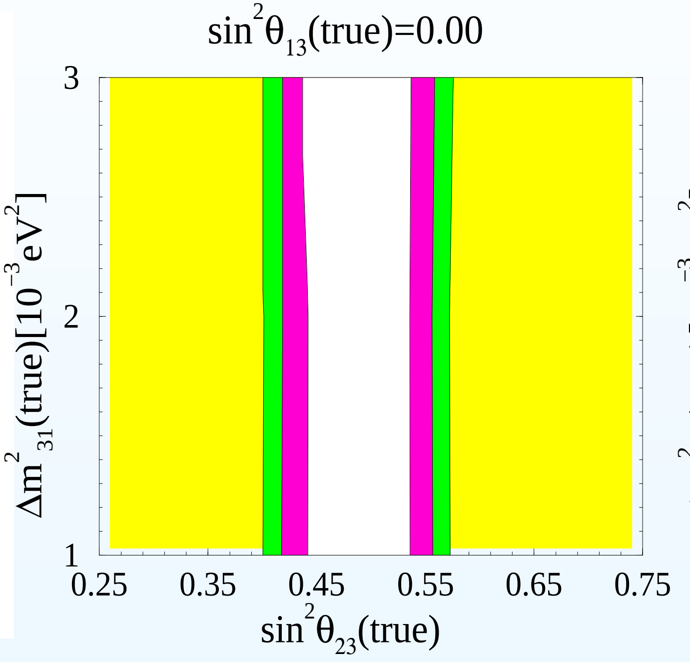
LBL combined

Antusch, et al,

hep-ph/0404268



$|D|$ within 20%

SK50

preliminary

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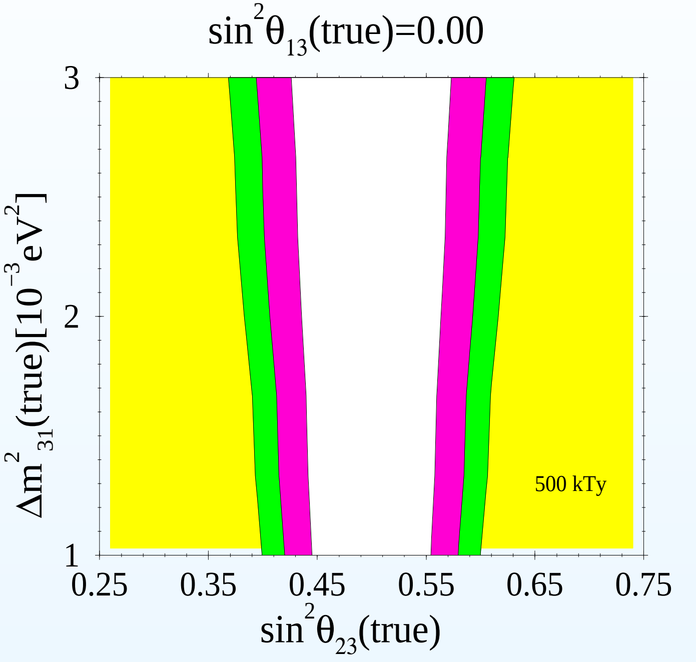

$|D|$ within 25%

INO-ICAL 500 kTy

S.C. and P. Roy,

hep-ph/0509197

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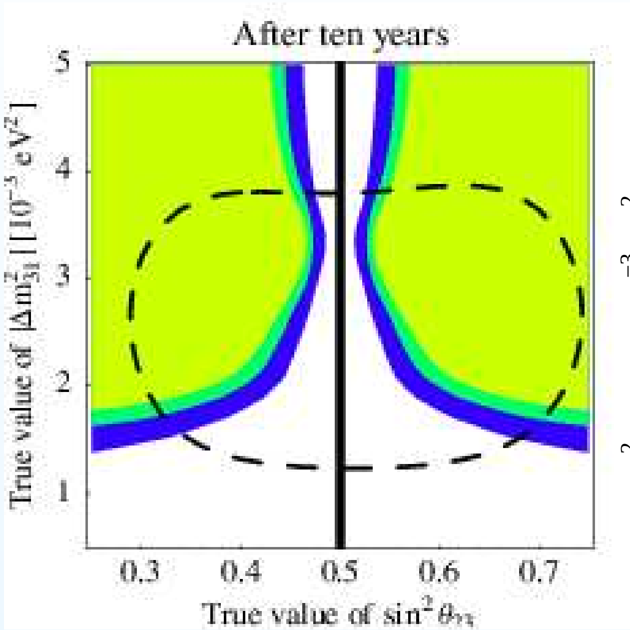
Testing Maximality of θ_{23}

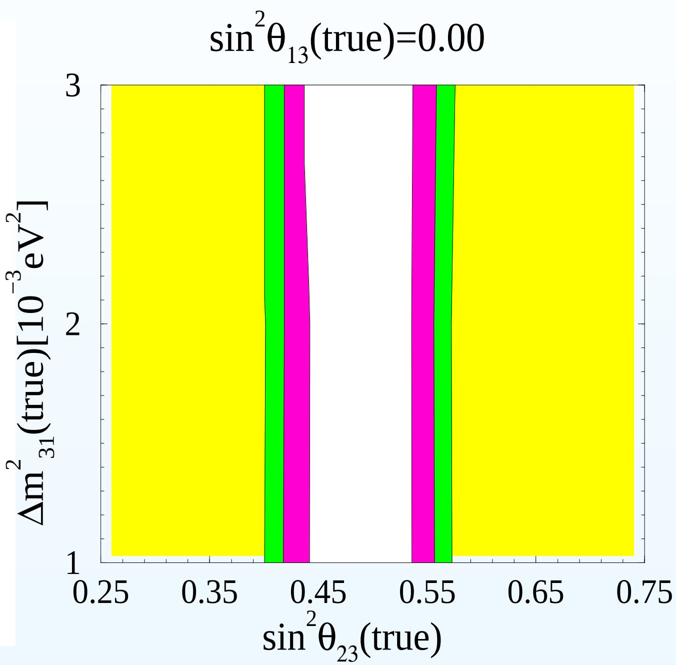


$|D|$ within 14%

LBL combined

Antusch, et al,

hep-ph/0404268

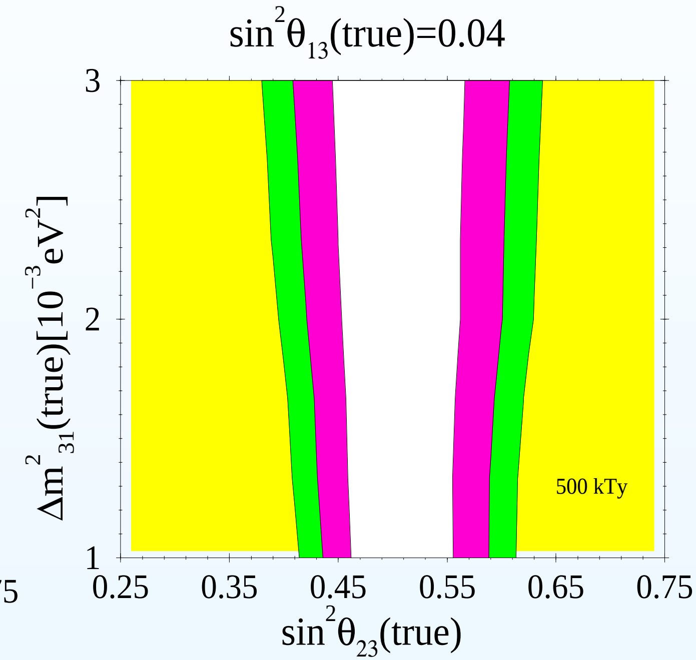


$|D|$ within 20%

SK50

preliminary

.



$|D|$ within 23%

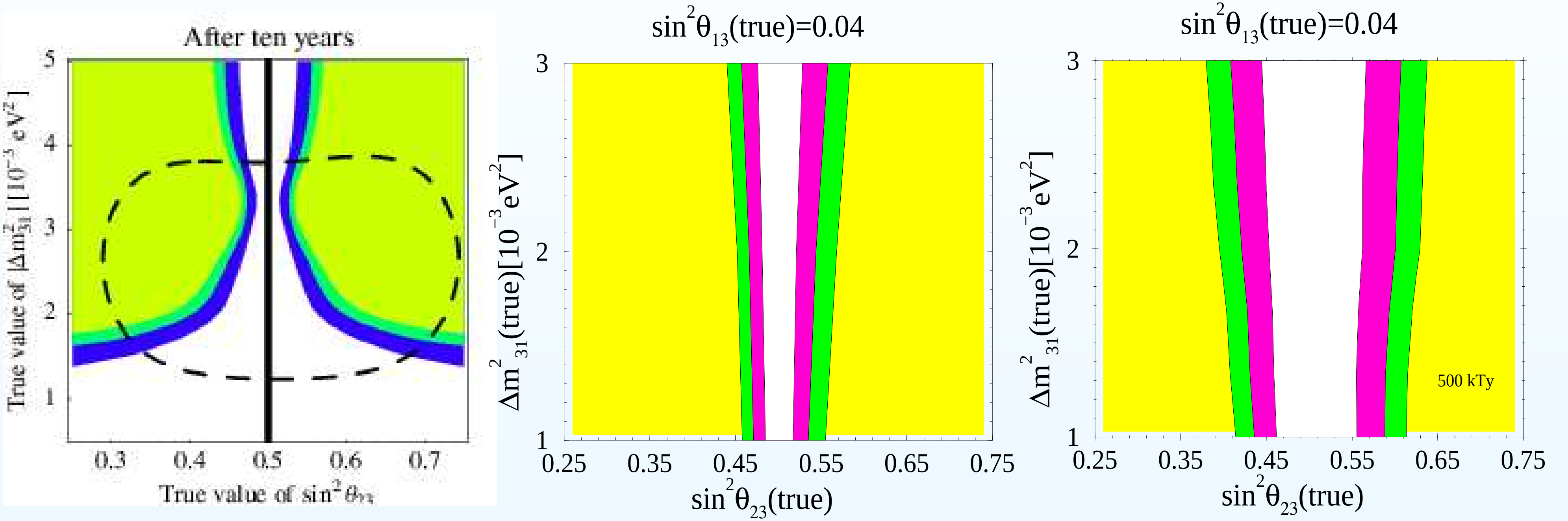
INO-ICAL 500 kTy

S.C. and P. Roy,

hep-ph/0509197

- Sensitivity to $|D|$ in INO-ICAL improves marginally with θ_{13}

Testing Maximality of θ_{23}



$|D|$ within 14%
LBL combined
Antusch, et al,
hep-ph/0404268

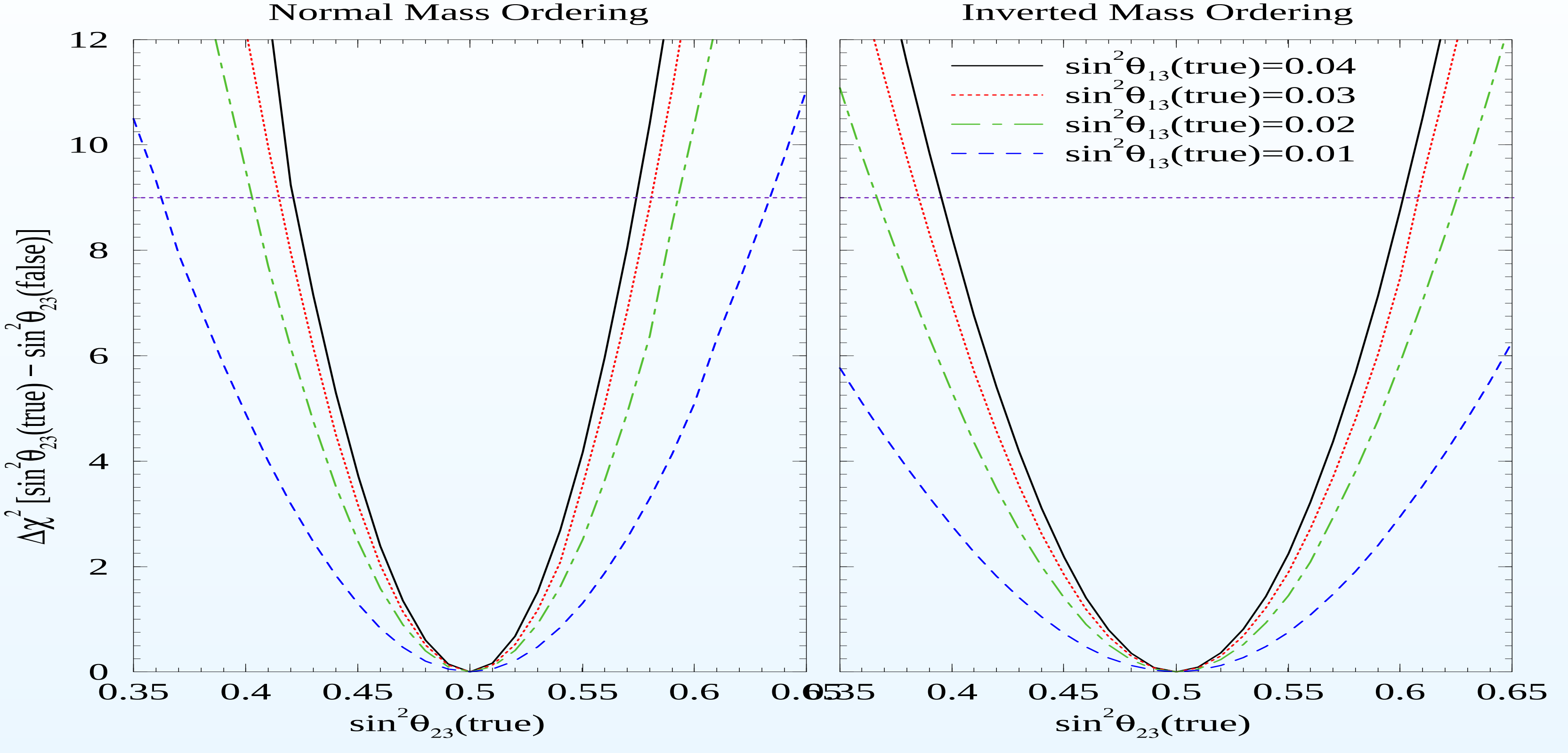
$|D|$ within 11%
SK50
preliminary
.

$|D|$ within 23%
INO-ICAL 500 kTy
S.C. and P. Roy,
hep-ph/0509197

- Sensitivity to $|D|$ in INO-ICAL improves marginally with θ_{13}
- Sensitivity to $|D|$ in SK50 improves remarkably with θ_{13}

Resolving the θ_{23} Octant Ambiguity

Resolving the θ_{23} Octant Ambiguity with INO-ICAL



1 MTonyr

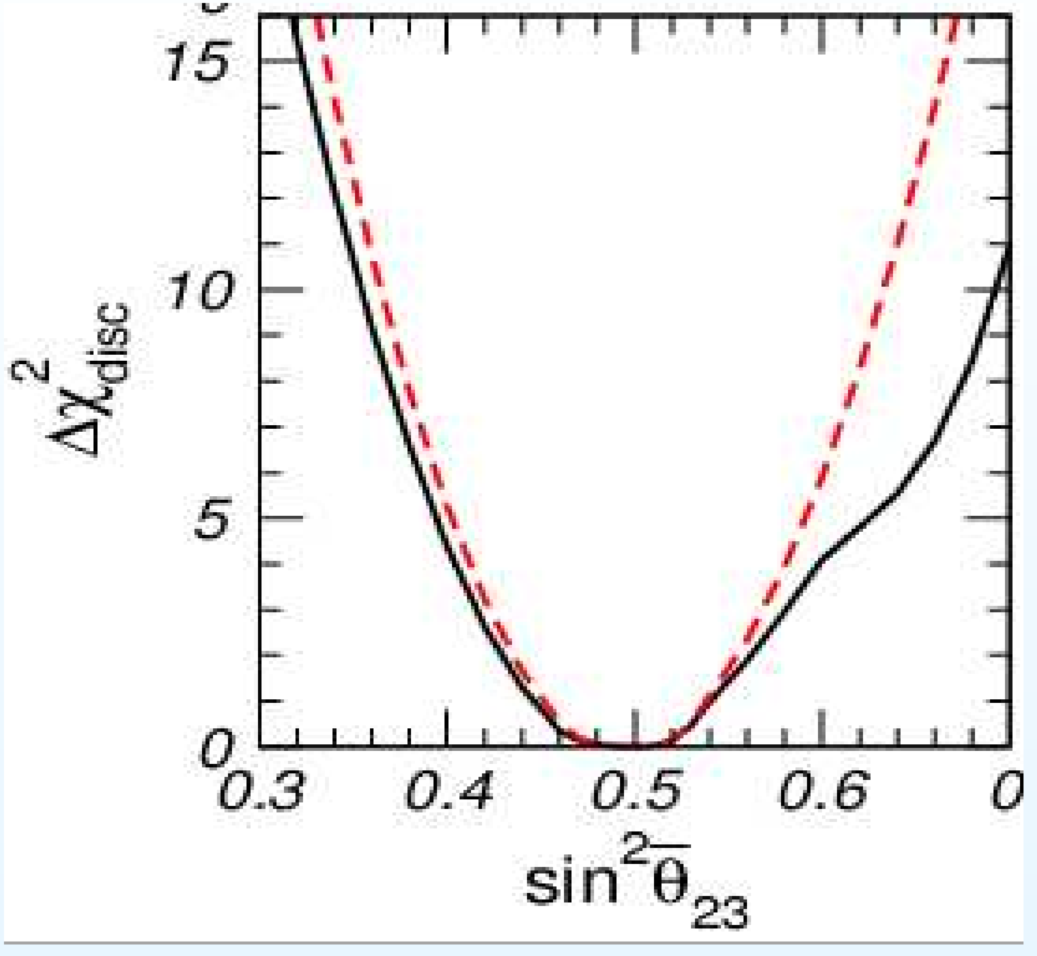
S.C and P. Roy hep-ph/0509197

- $\sin^2\theta_{23}$(false) can be excluded at 3σ if:

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

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

Resolving the θ_{23} Octant Ambiguity with SK50

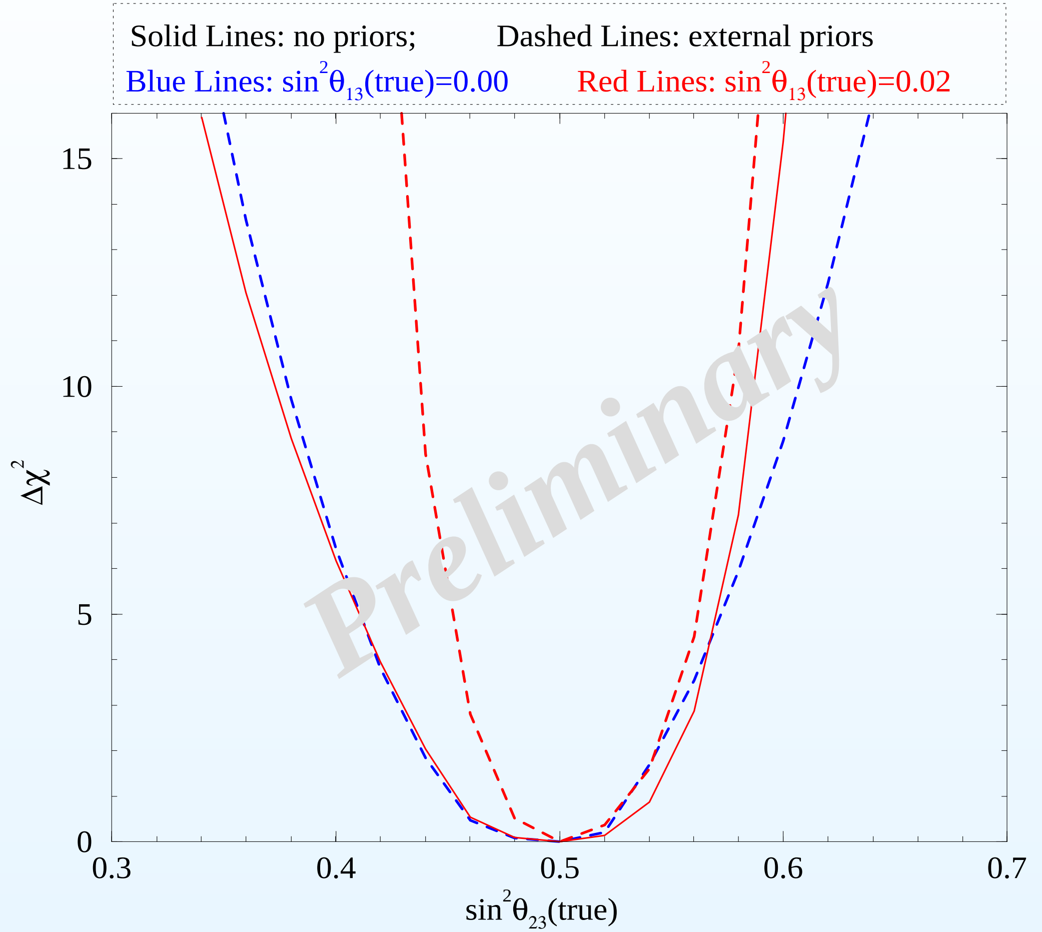


Gonzalez-Garcia et al, hep-ph/0408170

- $\sin^2\theta_{23}$(false) can be excluded at 3σ if:

  $\sin^2\theta_{23}(\text{true}) < 0.36$ or > 0.62 for $\sin^2\theta_{13}(\text{true}) = 0.00.$

Resolving the θ_{23} Octant Ambiguity with SK50

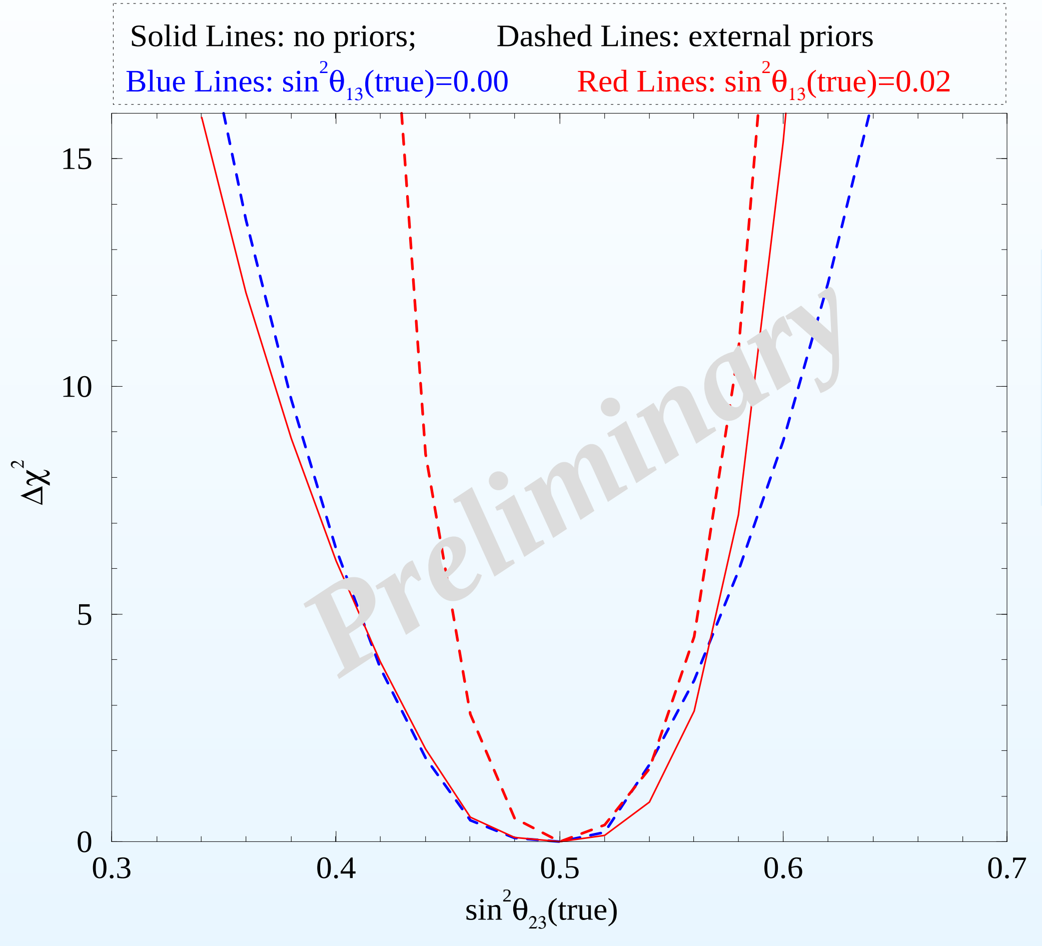


- $\sin^2\theta_{23}$(false) can be excluded at 3σ if:

  $\sin^2\theta_{23}(\text{true}) < 0.384$ or > 0.601 for $\sin^2\theta_{13}(\text{true}) = 0.00$.

  $\sin^2\theta_{23}(\text{true}) < 0.438$ or > 0.574 for $\sin^2\theta_{13}(\text{true}) = 0.02$.

Resolving the θ_{23} Octant Ambiguity with SK50



Sensitivity to octant of θ_{23} improves remarkably as θ_{13} increases from zero.

- $\sin^2\theta_{23}$(false) can be excluded at 3σ if:

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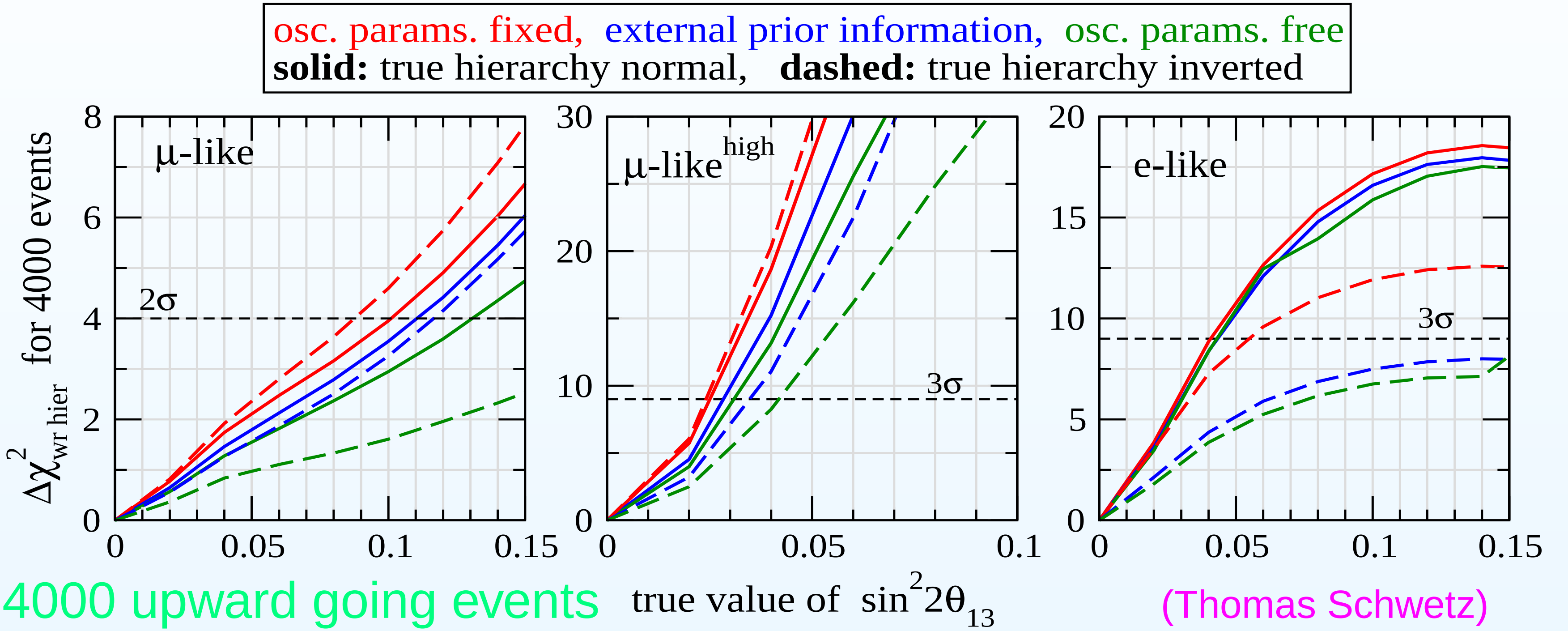
Resolving the $sgn(\Delta m^2_{31})$ Ambiguity

Resolving the $sgn(\Delta m^2_{31})$ Ambiguity with INO-ICAL



4000 upward going events

(Thomas Schwetz)
Petcov and Schwetz, hep-ph/0511277

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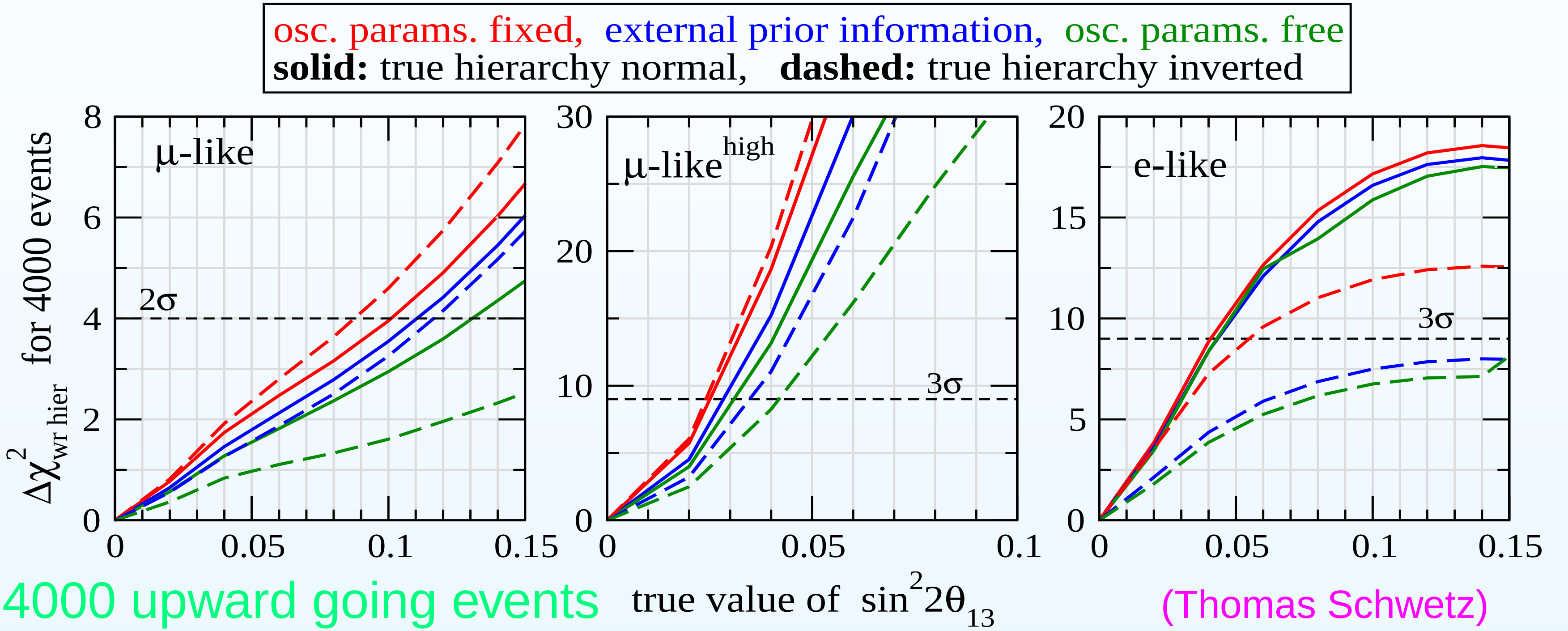

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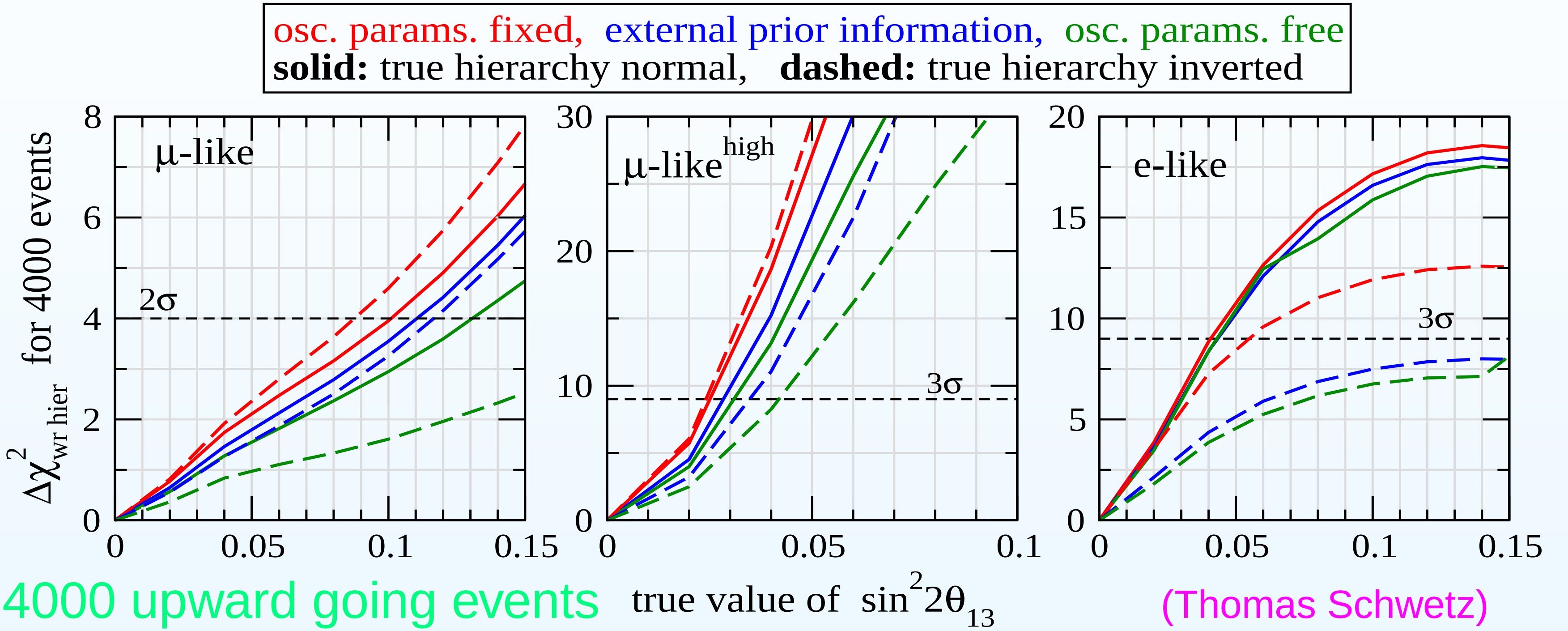

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Polamares-Ruiz,Petcov (2003)

Indumathi, Murthy (2004)

Ghoshal,Gandhi,Goswami,Mehta,UmaSankar (2004)

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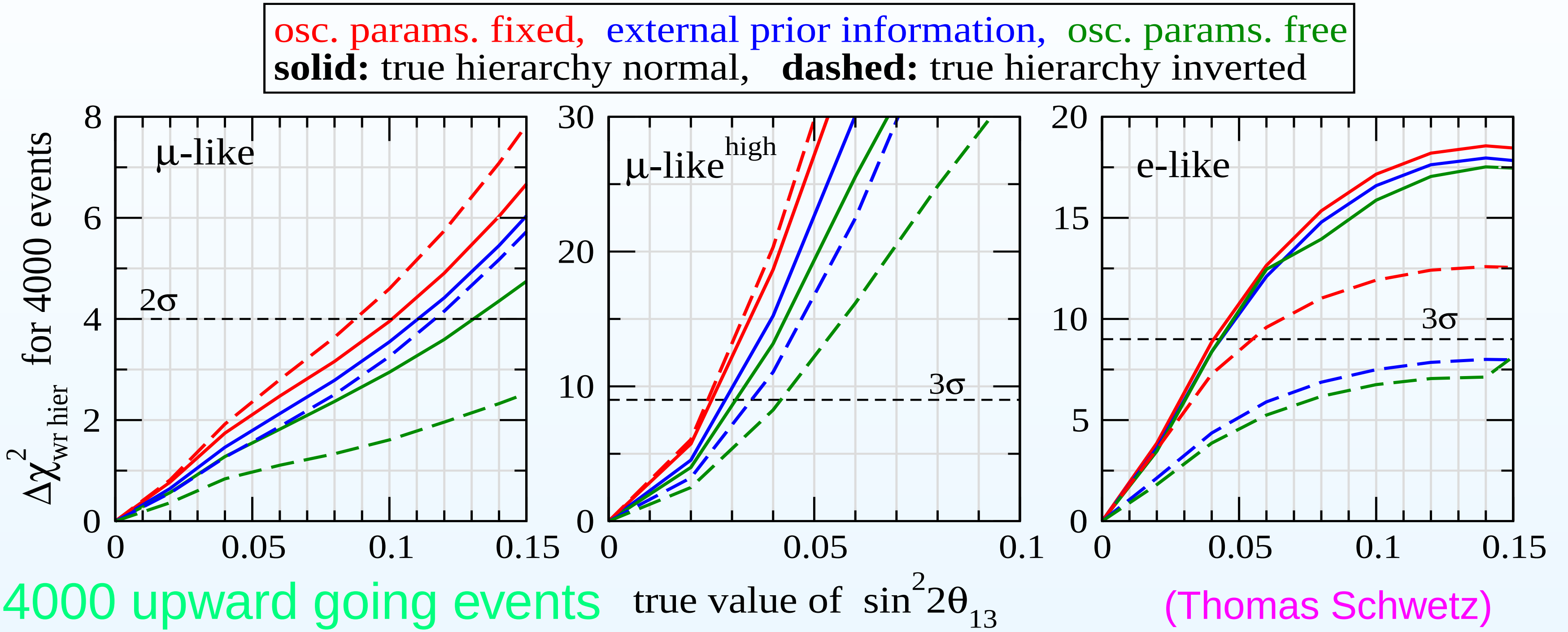

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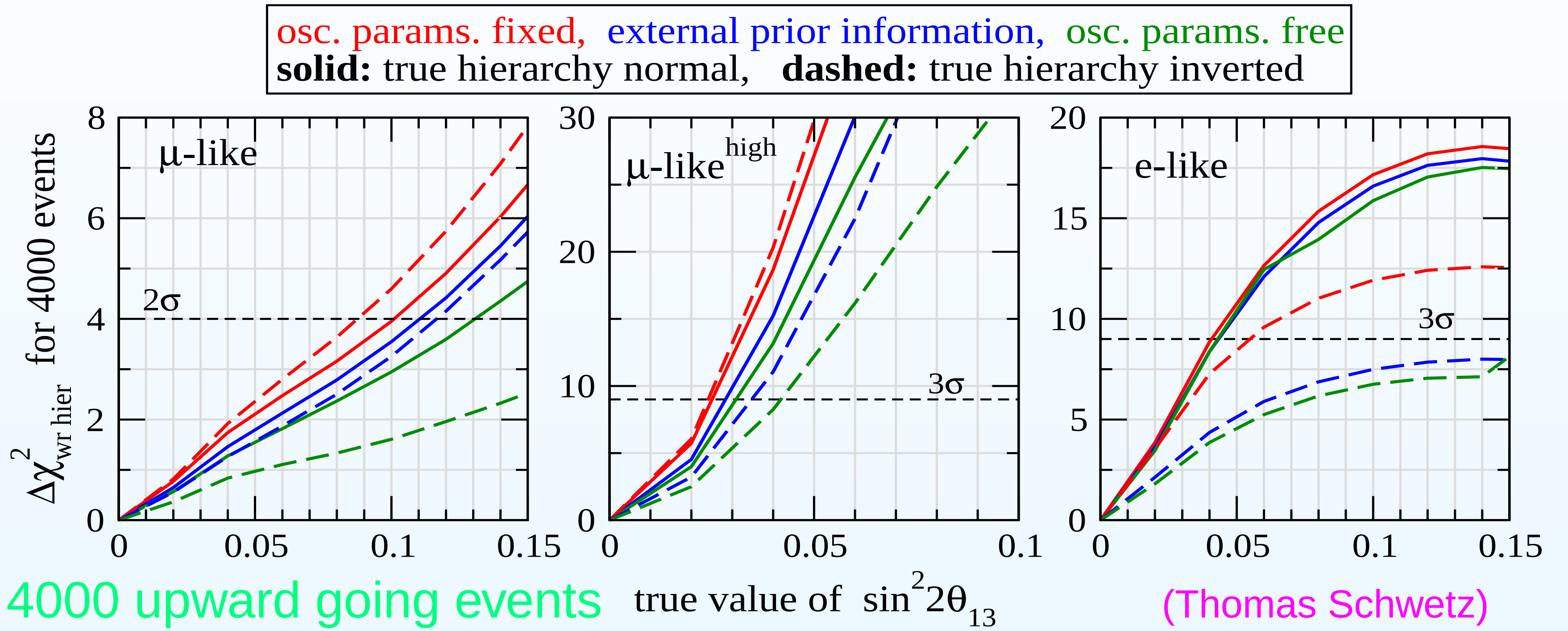

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- Sensitivity increases if it were possible to detect electrons

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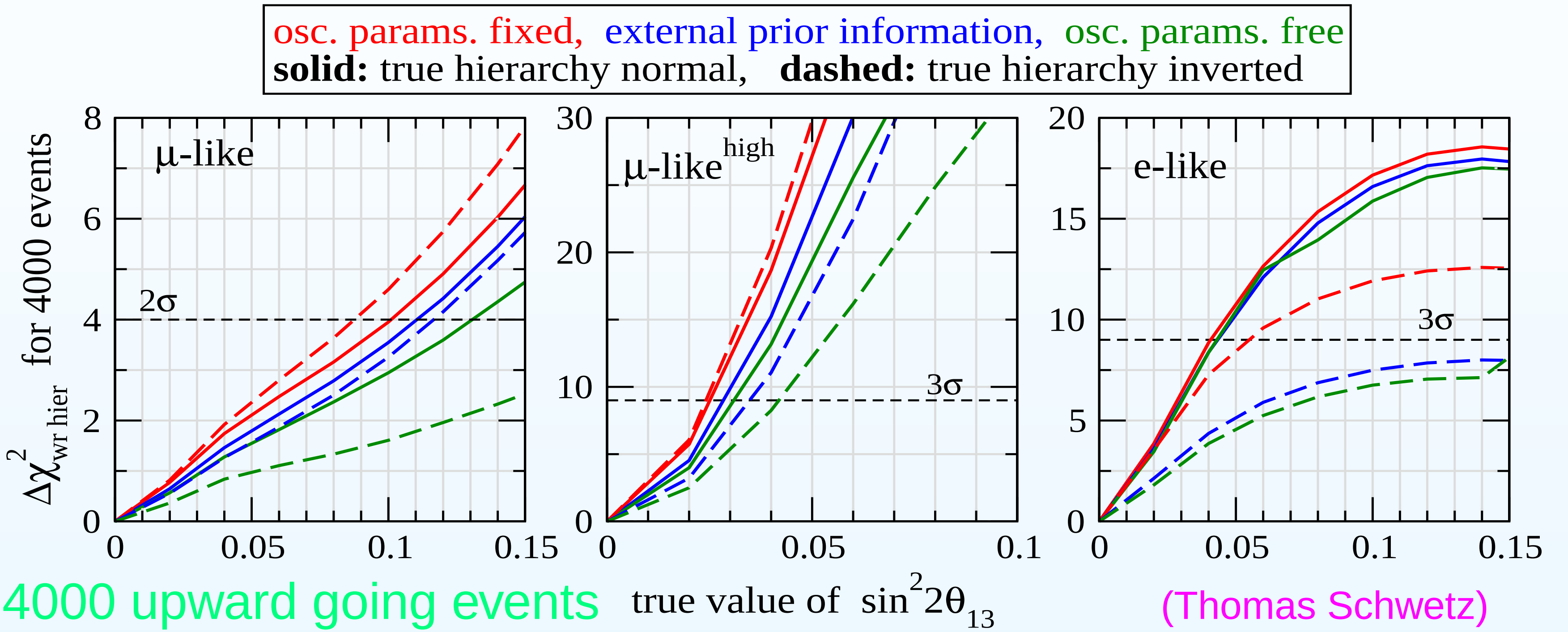

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Petcov and Schwetz, hep-ph/0511277

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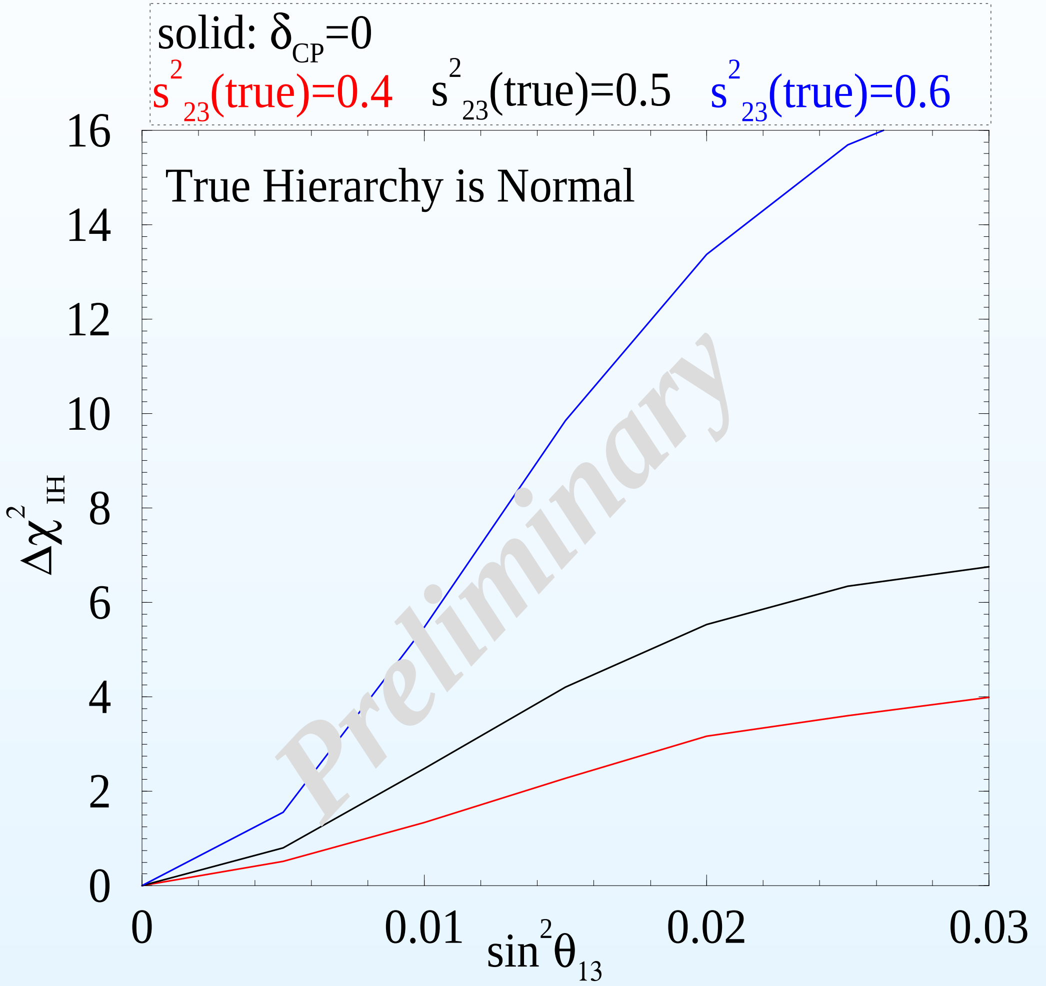

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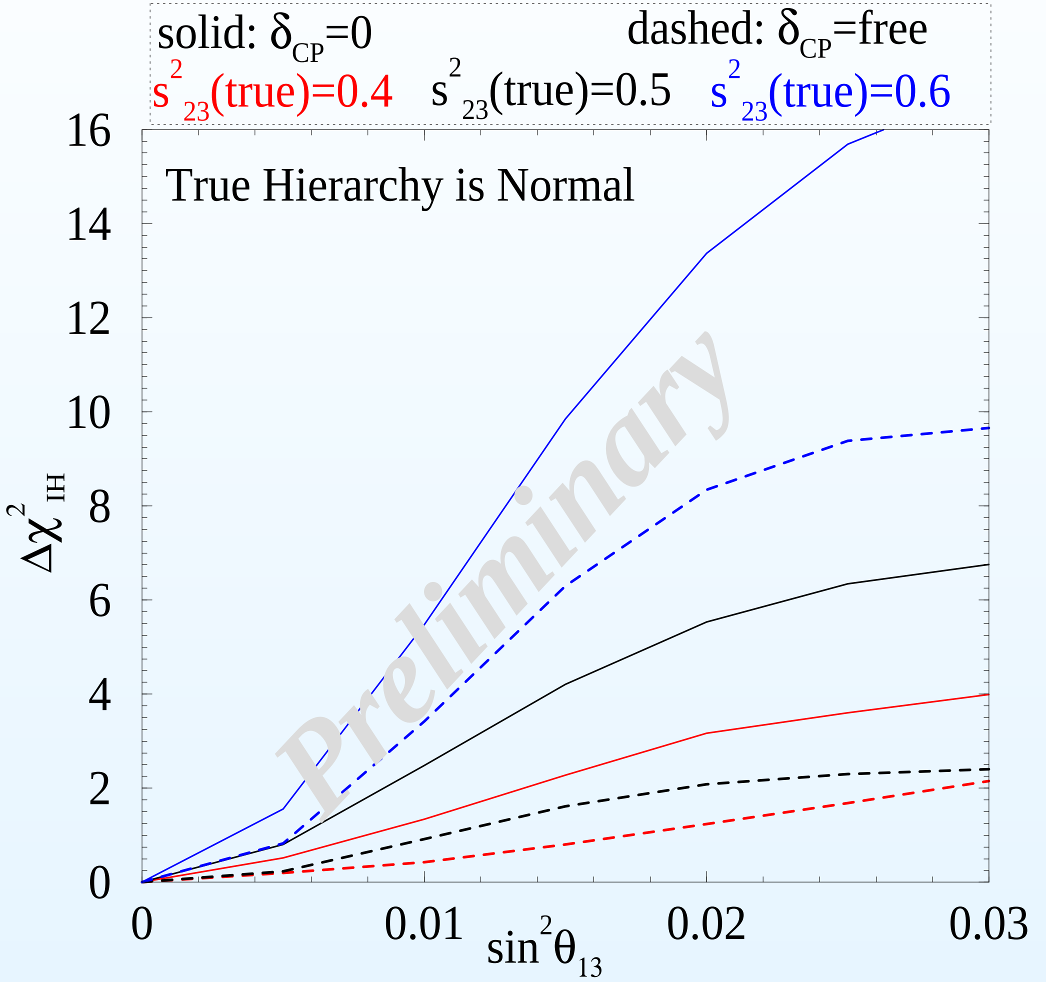

- Sensitivity drops appreciably due to δ_{CP}

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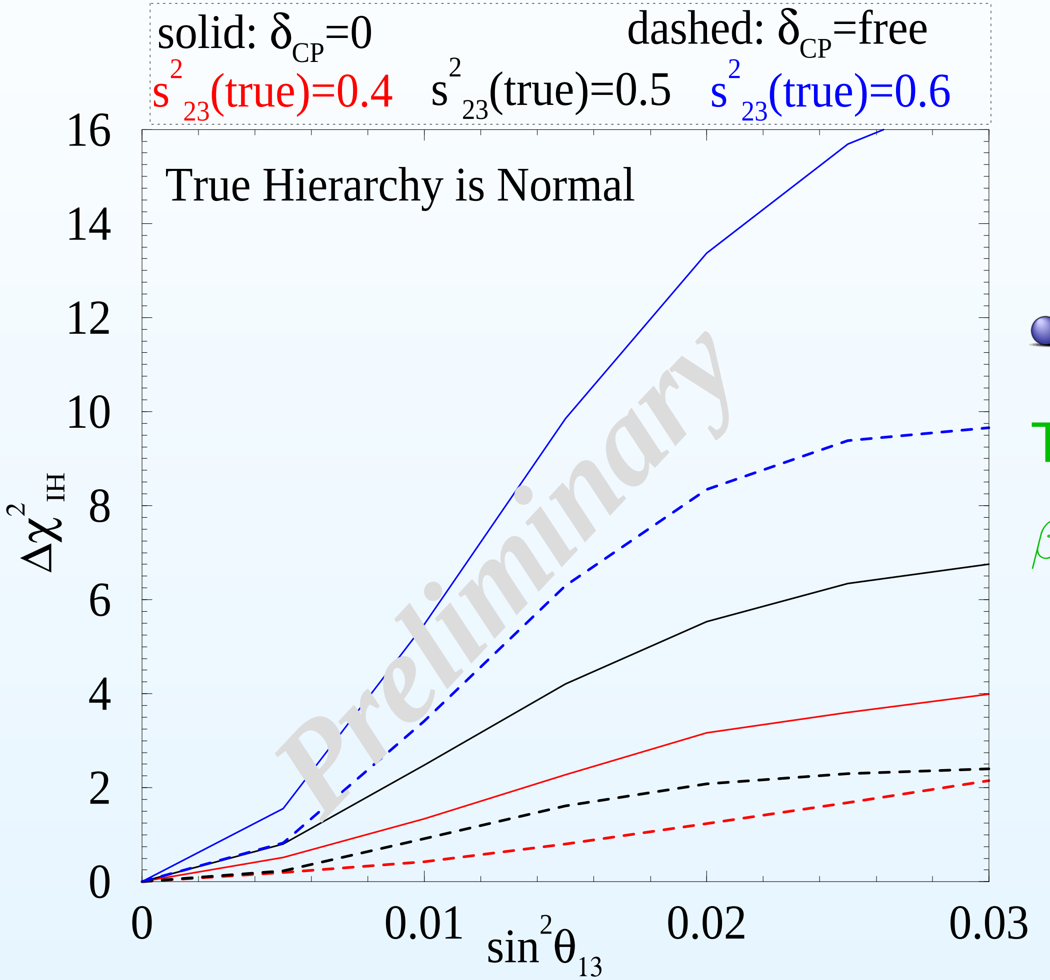

- Resolving param degen:

T2K+ATM:hep-ph/0501037

βbeams+ATM:hep-ph/0603172

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Searching for New Physics

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- Non-Standard neutrino-matter Interaction
- Violation of Equivalence Principle
- Lorentz Invariance Violation
- Violation of CPT Symmetry
- Neutrino Decay
- Quantum Decoherence

(This list is not exhaustive.)

Searching for New Physics in INO-ICAL/SK50 like Expts

- Non-Standard neutrino-matter Interaction
- Violation of Equivalence Principle
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- Quantum Decoherence

- Each one has a distinctive L/E behavior
- Oscillations go linearly as L/E
- Atmospheric neutrinos have a very wide range of L/E
- This L/E data can be used to probe new physics – INO-ICAL
- Comparison of contained events and upward going muons in water Cerenkov detectors can also be used

Searching for New Physics with Neutrino Telescopes

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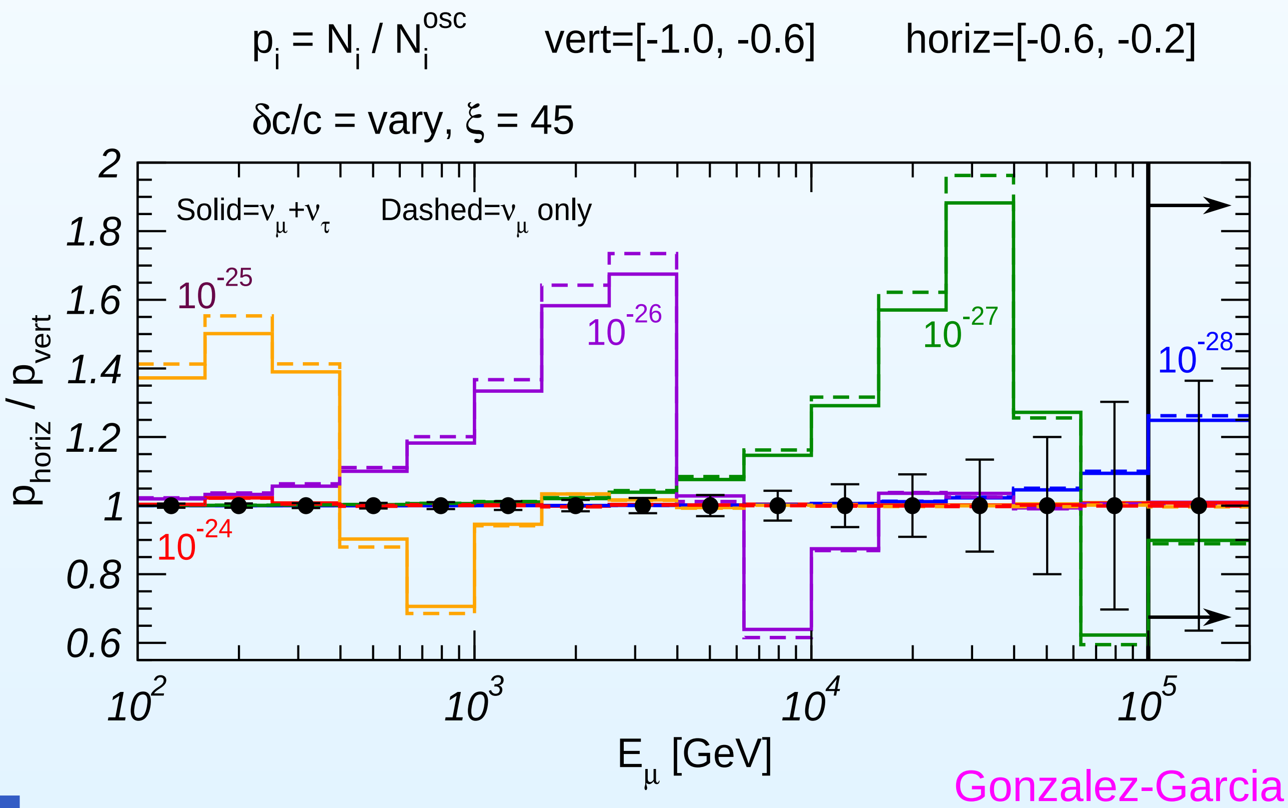

ICECUBE

Gonzalez-Garcia et al, hep-ph/0502223

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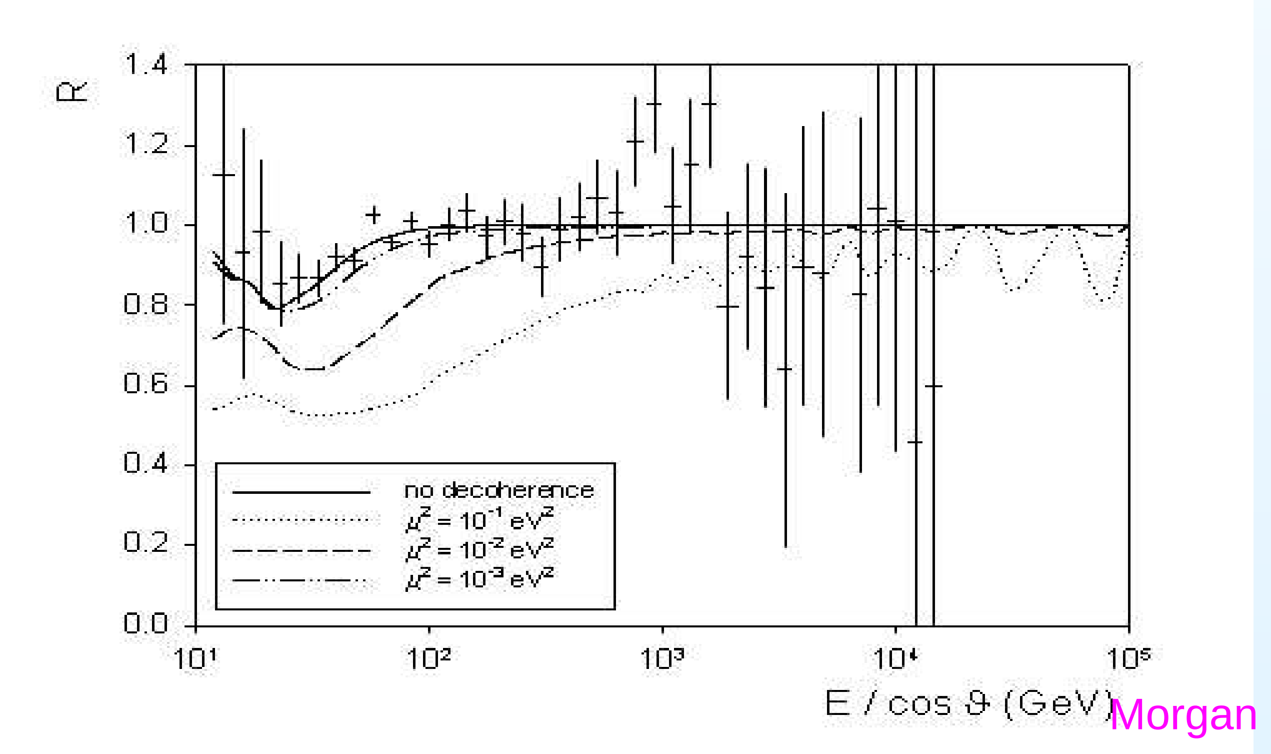

ANTARES

Morgan et al, astro-ph/0412618

Conclusions

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Thank You!!