Physics with India-based Neutrino Observatory

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Plan of Talk

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- The India-based Neutrino Observatory (INO)
  - INO Proposal
  - ICAL Detector
- Physics with INO using Atmospheric Neutrinos
  - Confirming Neutrino Oscillations
  - Determining Δm^2_{31} and $\sin^2\theta_{23}$ precisely
  - Determining $sgn(\Delta m^2_{31})$
  - Determining the “octant” of θ_{23}
- Physics with INO using ν beams from factories
  - Using the Golden Channel
  - Turning on the INO “Magic”
  - Determining θ_{13} and $sgn(\Delta m^2_{31})$
  - Helping in CP violation Discovery

INO – The Proposal

- **Goal:** To build an underground facility which can be used mainly as a neutrino physics laboratory due to the low cosmic background

- **Detector Requirement:** A large mass detector with charge indentification capability.

- **Detector Choice:** The accepted choice was to build a large magnetized Iron CALorimeter – called the ICAL.

- **Detector Choice Based on:**
  - Existing/Planned detectors elsewhere
  - Expertise on detector technology
  - Modular design
  - Cost

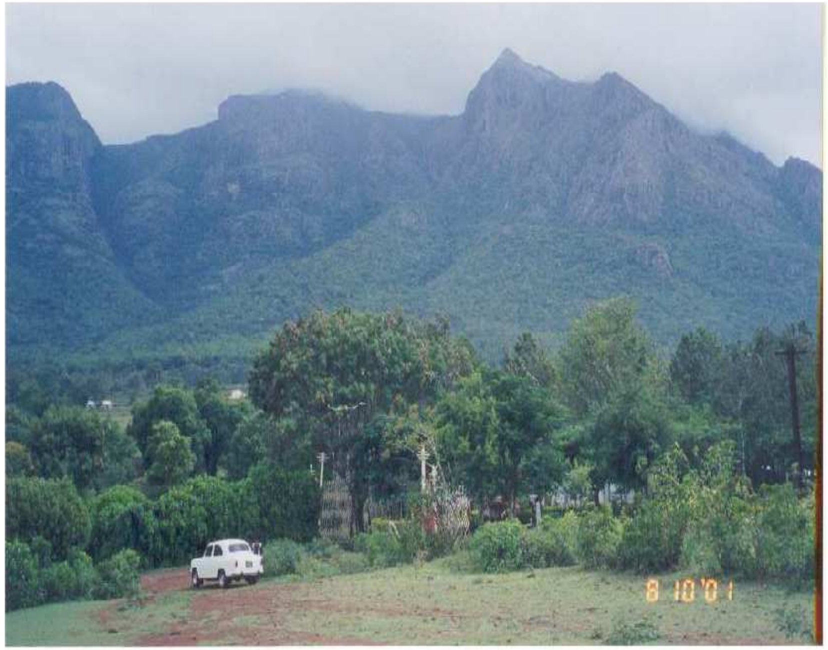
INO – The Proposal

The Phased Approach

- **R & D and Construction of Detector:**
  - Phase I: Detector choice, Site selection, Clearances, Human resource development, Detector R & D, Prototype, Physics studies
  - Phase II: Construction of the INO lab and the ICAL detector

- **Operation of the Detector:**
  - Phase I: Physics with atmospheric neutrinos
  - Phase II: Physics with neutrinos from a factory of muon decay and/or beta decay

INO – The Site

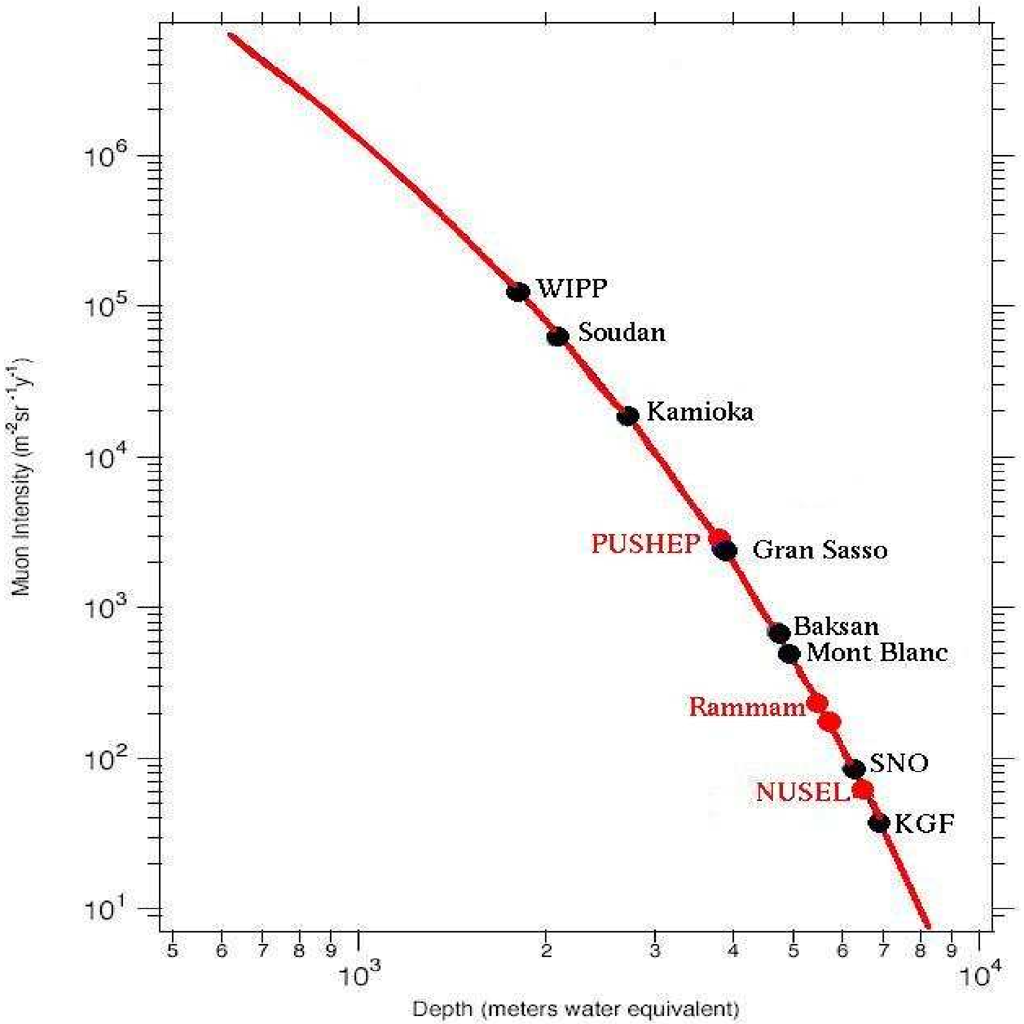


PUSHEP Site (Lat: N11.5°, Long: E76.6°)

PUSHEP-Bangalore: 250km

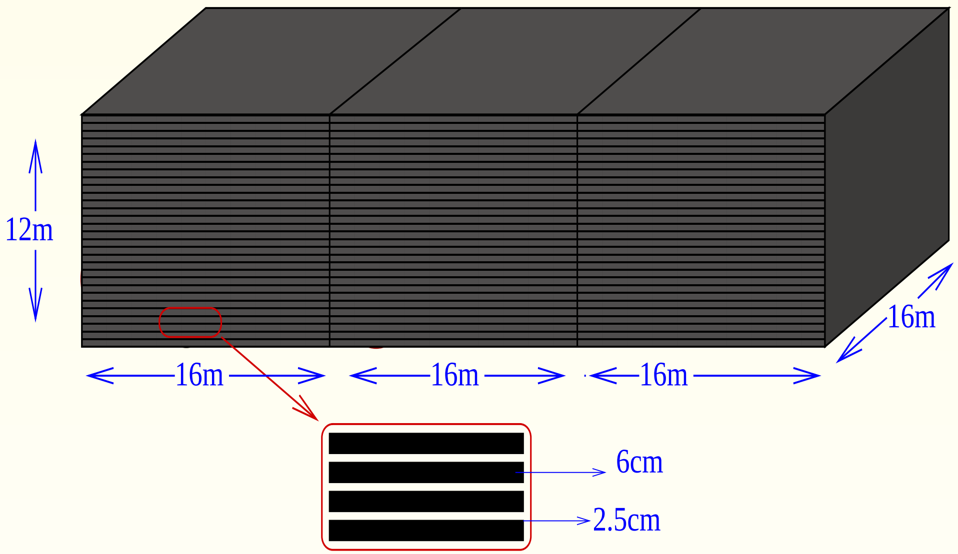
INO – The Site

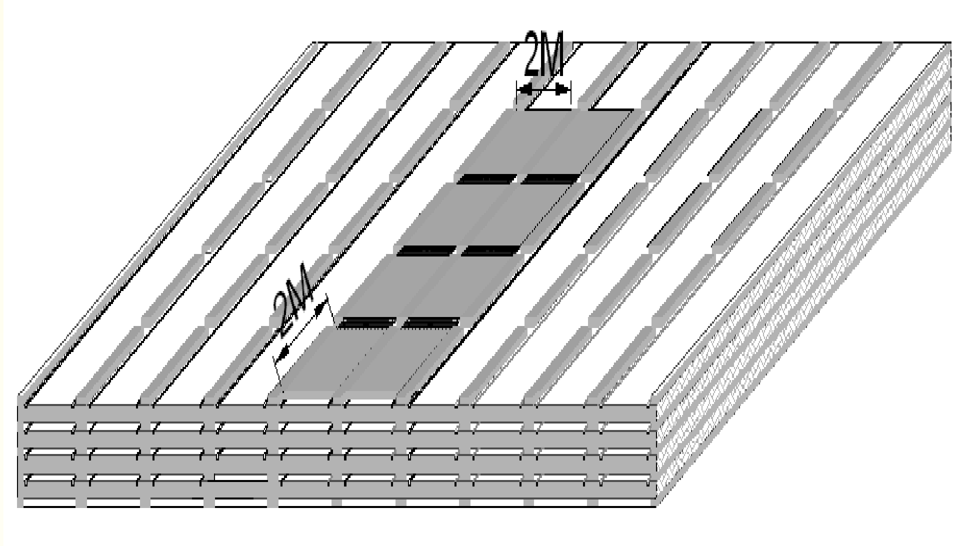
- BACKGROUNDS

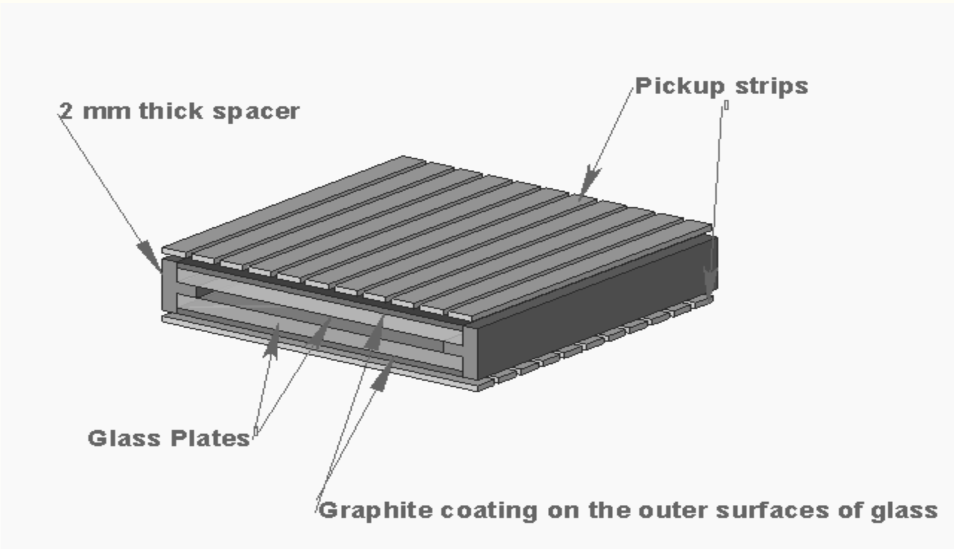


- Quite deep compared to other laboratories

INO – The Detector







INO – The Detector

No of modules	3
Module dimension	16 m X 16 m X 12 m
Detector dimension	48 m X 16 m X 12 m
No of layers	140
Iron plate thickness	6 cm
Gap for RPC trays	2.5 cm
Magnetic field	1.5 Tesla
RPC unit dimension	2 m X 2 m
Readout strip width	2 cm
No of RPC units/layer	192
Total number of RPC units	27000
Total number of electronic channels	3.6 X 10^6

INO – The Detector

- R&D on glass RPCs running in the avalanche mode at TIFR
- R&D on bakelite RPCs running in the streamer mode at SINP/VECC
- Stack of 12 (1 m X 1 m) glass RPCs running at TIFR and observing cosmic ray muons
- Live online display of these tracks recorded at TIFR
- Long term stability of the glass RPCs tested – some of them running for 2 years
- One (1 m X 1 m) bakelite RPCs working at SINP/VECC – more under construction
- The bakelite RPCs being coated with silicone from inside
- Long term stability checks on bakelite RPCs being done at SINP/VECC

INO – The Detector Prototype

- At VECC, Kolkata
- Mass = 40 tons
- No of RPC layers = 12
- RPC size = 1 m X 1 m
- Readout channels $\sim$ 1000 – being developed
- Magnetic field $\sim$ 1.5 Tesla
- Both glass and bakelite RPCs will be tested in the INO prototype

INO – Simulations

- Nuance is being used as the generator for atmospheric neutrino events.
- A number of collaborating institutions across India involved in the ICAL@INO simulations.
- Completely ported ICAL/INO code from Geant3 to Geant4. Checks are being done across the two versions.
- New improved code for track reconstruction using cellular automata/Kalman filter. It appears to be working ok for fully contained tracks. Still being optimised.
- Roughly three main sub-groups have been identified: (1) code developer (2) physics studies (3) application of code to physics signals. Since the codes are still in the verifying stages, the physics studies are expected to begin as soon as the code is ready, which should be soon.

INO – Graduate Program

- A training programme with strong emphasis in experimental high energy physics and astroparticle physics has been started in August 2008
- Students will be attached to training guides at various collaborating institutions for a PhD degree
- First batch of students (5 students) have started their training courses at TIFR, Mumbai
- Students will also be visiting other collaborating institutions for further training

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- Reconfirm neutrino *oscillations* by observing them

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Physics Goals for ICAL@INO

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- Probe CPT violation

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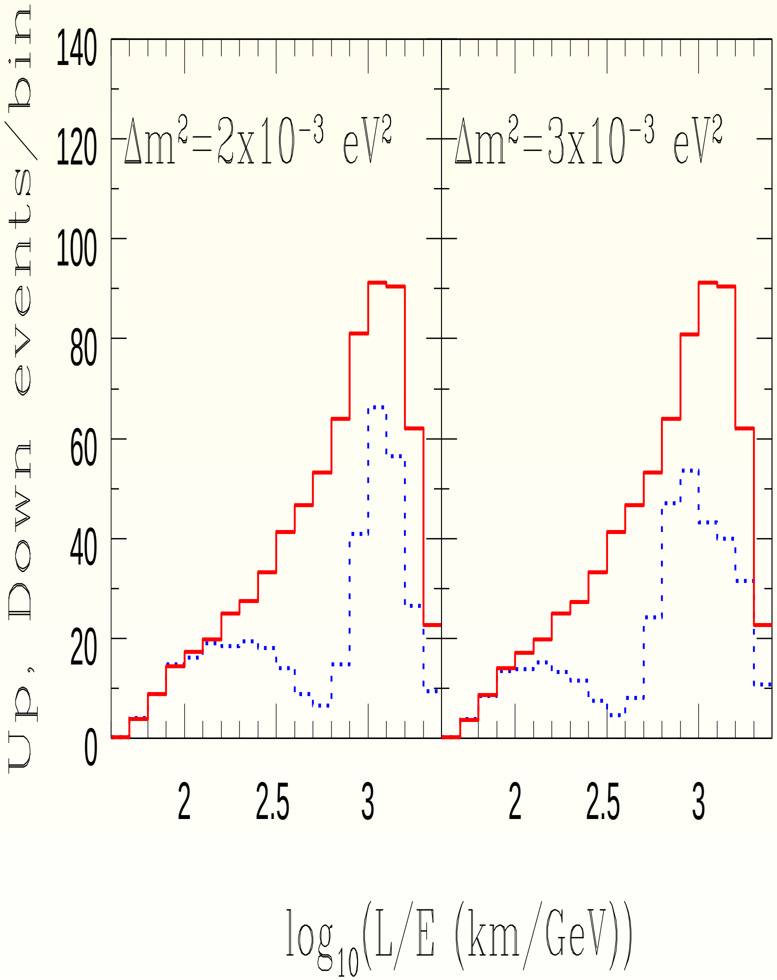
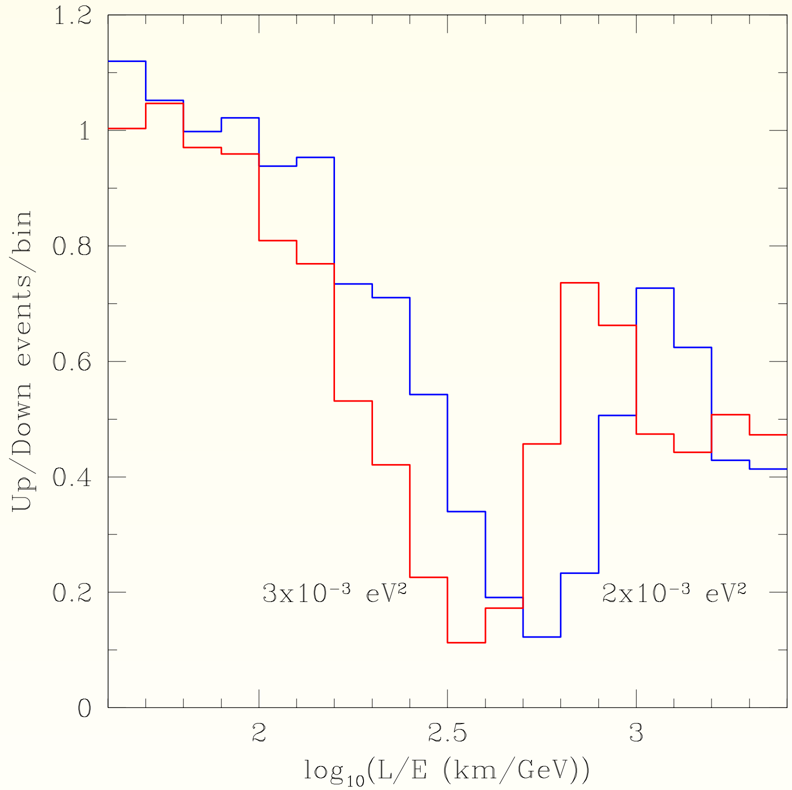
- Probe CP violation in lepton sector
- Probe octant, CPTV, sterile neutrinos and NSI
- UHE neutrinos and VHE muons, neutrinos from Dark Matter

Physics with INO

Phase-I: Physics with Atmospheric Neutrinos

Confirmation of Oscillations





- The first oscillation dip should be clearly observable
- Better measurement of Δm^2_{31}

INO collaboration

Precision Measurement of Δm^2_{31} and $\sin^2\theta_{23}$

- 3σ spread ($|\Delta m^2{}_{31}|$ = 2.39×10^{-3} eV^2, $\sin^2\theta_{23} = 0.5$).

	$\lvert\Delta m^2{}_{31}\rvert$	$\sin^2\theta_{23}$
current	15%	32%
T2K	6%	23%
NOvA	13%	43%
INO, 50 kton, 5 years	10%	30%

Fogli et al., arXiv:0806.2649, Maltoni,Schwetz, arXiv:0812.3161

Huber,Lindner,Rolinec,Schwetz,Winter, hep-ph/0403068

INO Interim Report

(See also, Samanta, arXiv:0812.4639)

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

The Unanswered Questions

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- What is the magnitude of θ_{13}?
  - Main channels to determine θ_{13}
    - $\nu_e \to \nu_e$ or $\bar{\nu}_e \to \bar{\nu}_e$: P_{ee} or $P_{\bar{e}\bar{e}}$; Disappearance Expts
    - $\nu_\mu \to \nu_e$ or $\nu_e \to \nu_\mu$: $P_{\mu e}$ or $P_{e\mu}$; Appearance Expts
- Is there CP violation in the lepton sector?
  - Main channel to see δ_{CP}
    - $\nu_\mu \to \nu_e$ or $\nu_e \to \nu_\mu$: $P_{\mu e}$ or $P_{e\mu}$; Appearance Expts
    - Also in principle possible using $\nu_\mu \to \nu_\mu$
- What is the sign of Δm^2_{31}?
  - Main channels to determine $sign(\Delta m^2_{31})$
    - $\nu_\mu \to \nu_e$ or $\nu_e \to \nu_\mu$: $P_{\mu e}$ or $P_{e\mu}$; Appearance Expts
    - "binned" $\nu_\mu \to \nu_\mu$ $P_{\mu\mu}$; Disappearance Expts
    - $\nu_e \to \nu_e$ P_{ee}; Disappearance Expts

Neutrino Oscillations in Two Generations

- Flavor Eigenstates $\neq$ Mass Eigenstates

$$\nu_\mu = \cos\theta\,\nu_2 + \sin\theta\,\nu_3$$

$$\nu_\mu(t) = \cos\theta\, e^{-iE_2}\,\nu_2 + \sin\theta\, e^{-iE_3}\,\nu_3$$

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2\, L}{4E}\right)$$

- No dependence on the octant of θ
- No dependence on the sign of Δm^2

Three Flavor Oscillations in Vacuum

- Flavor Eigenstates $\neq$ Mass Eigenstates
- $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$P_{\beta\gamma}(L) = \delta_{\beta\gamma} \quad -4\sum_{j>1} Re\left(U_{\beta i}U^{\star}_{\gamma i}U^{\star}_{\beta j}U_{\gamma j}\right)\frac{\sin^2 \Delta m^2_{ij} L}{4E}$$

$$\pm 2\sum_{j>1} Im\left(U_{\beta i}U^{\star}_{\gamma i}U^{\star}_{\beta j}U_{\gamma j}\right)\frac{\sin \Delta m^2_{ij} L}{2E}.$$

Three Flavor Oscillations in Matter

- Flavor Eigenstates $\neq$ Mass Eigenstates
- $|\nu_\alpha\rangle = \sum_i U^m_{\alpha i}|\nu^m_i\rangle$

$$U^m = \begin{pmatrix} c^m_{12}c^m_{13} & s^m_{12}c^m_{13} & s^m_{13}e^{-i\delta^m} \\ -s^m_{12}c^m_{23} - c^m_{12}s^m_{23}s^m_{13}e^{i\delta^m} & c^m_{12}c^m_{23} - s^m_{12}s^m_{23}s^m_{13}e^{i\delta^m} & s^m_{23}c^m_{13} \\ s^m_{12}s^m_{23} - c^m_{12}c^m_{23}s^m_{13}e^{i\delta^m} & -c^m_{12}s^m_{23} - s^m_{12}c^m_{23}s^m_{13}e^{i\delta^m} & c^m_{23}c^m_{13} \end{pmatrix}$$

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$$M_F = U M_D U^\dagger \quad (Vacuum)$$

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$$M^m_F = U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- $A = \pm 2\sqrt{2} G_F n_e E$ ($+ \Rightarrow$ neutrinos) ($- \Rightarrow$ antineutrinos)

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$$M_F^m = U^m M_D^m U^{m\dagger} \quad (Matter)$$

$$M_F^m = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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- $A = \pm 2\sqrt{2} G_F n_e E$ ($+ \Rightarrow$ neutrinos) ($- \Rightarrow$ antineutrinos)
- $A = \pm 7.56 \times 10^{-5} \rho(\mathrm{gm/cc}) E(\mathrm{GeV})$ eV^2

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- $A = \pm 7.56 \times 10^{-5} \rho(\mathrm{gm/cc}) E(\mathrm{GeV})$ eV^2
- $|A| \sim 2 \times 10^{-3} \frac{4.5}{\rho(\mathrm{gm/cc})} \frac{5.0}{E(\mathrm{GeV})}$ eV^2 $\sim |\Delta m^2_{31}|$

Three Flavor Oscillations in Matter

- Mass squared difference in matter changes to:

$$(\Delta m^2_{31})^m = \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

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$$A = \Delta m^2_{31}\cos 2\theta_{13}$$

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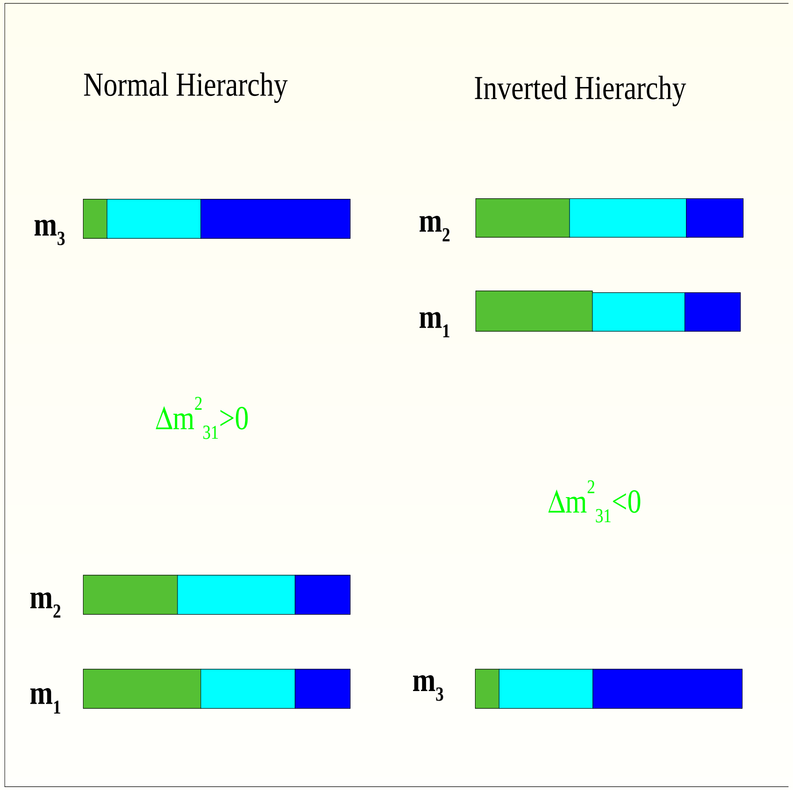
Matter Enhanced (MSW) Resonance

Wolfenstein 1978, Mikheyev and Smirnov 1985-6

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 $\Delta m^2_{31} > 0$ matter resonance in neutrinos
- For $\Delta m^2_{31} < 0$ matter resonance in anti neutrinos
- Experiments sensitive to matter effects can probe the mass hierarchy
- Matter effects for Δm^2_{31} channel depend crucially on θ_{13}
- Thus both parameters get related

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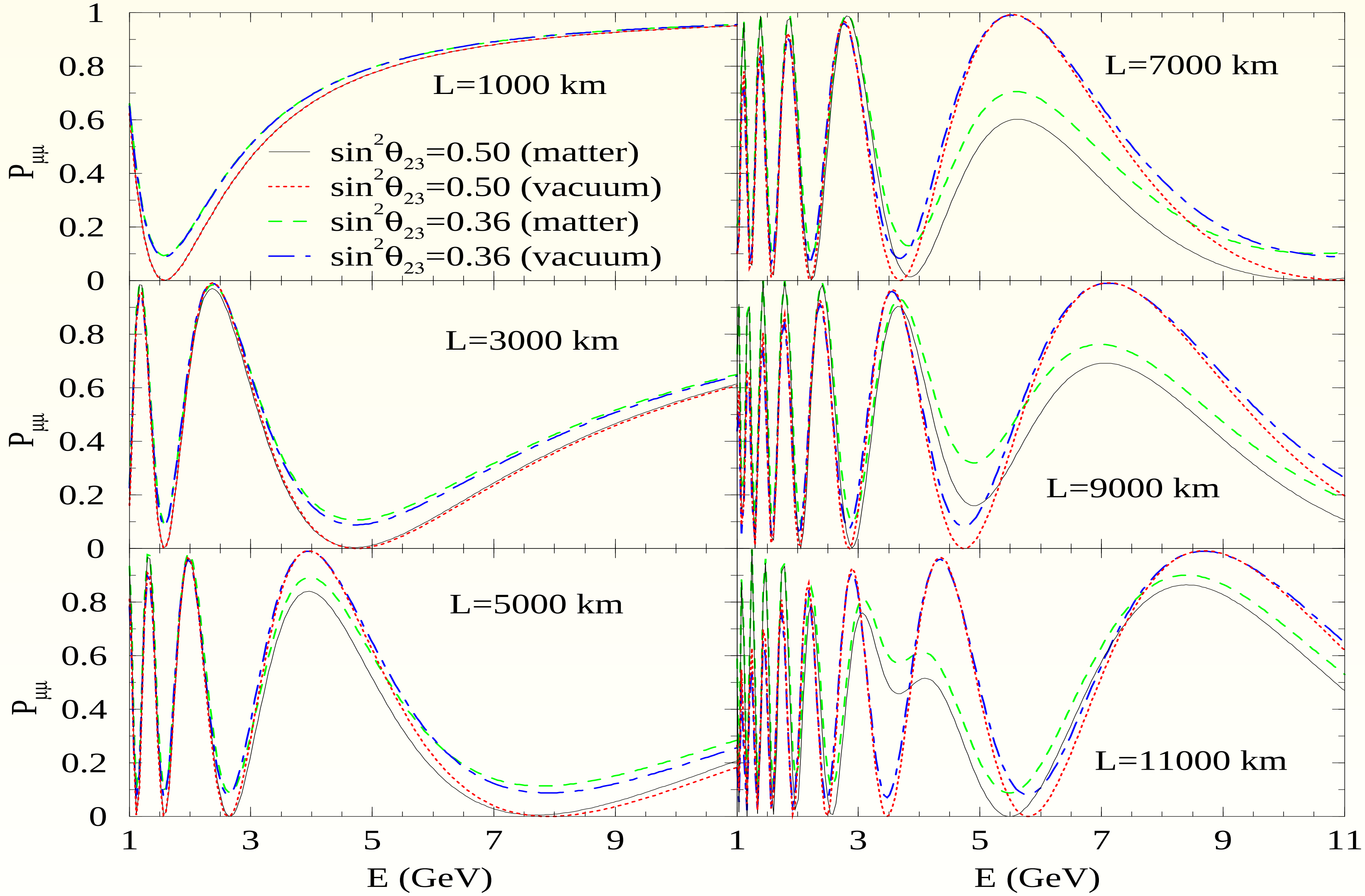
$$P^3_{\mu\mu}(L,E) = \sin^2 2\theta^M_{13} \sin^4\theta_{23} \sin^2 \frac{(\Delta m^2_{31})^M}{4E} L$$

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

Large Matter Effects in ν_μ Survival Probability



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

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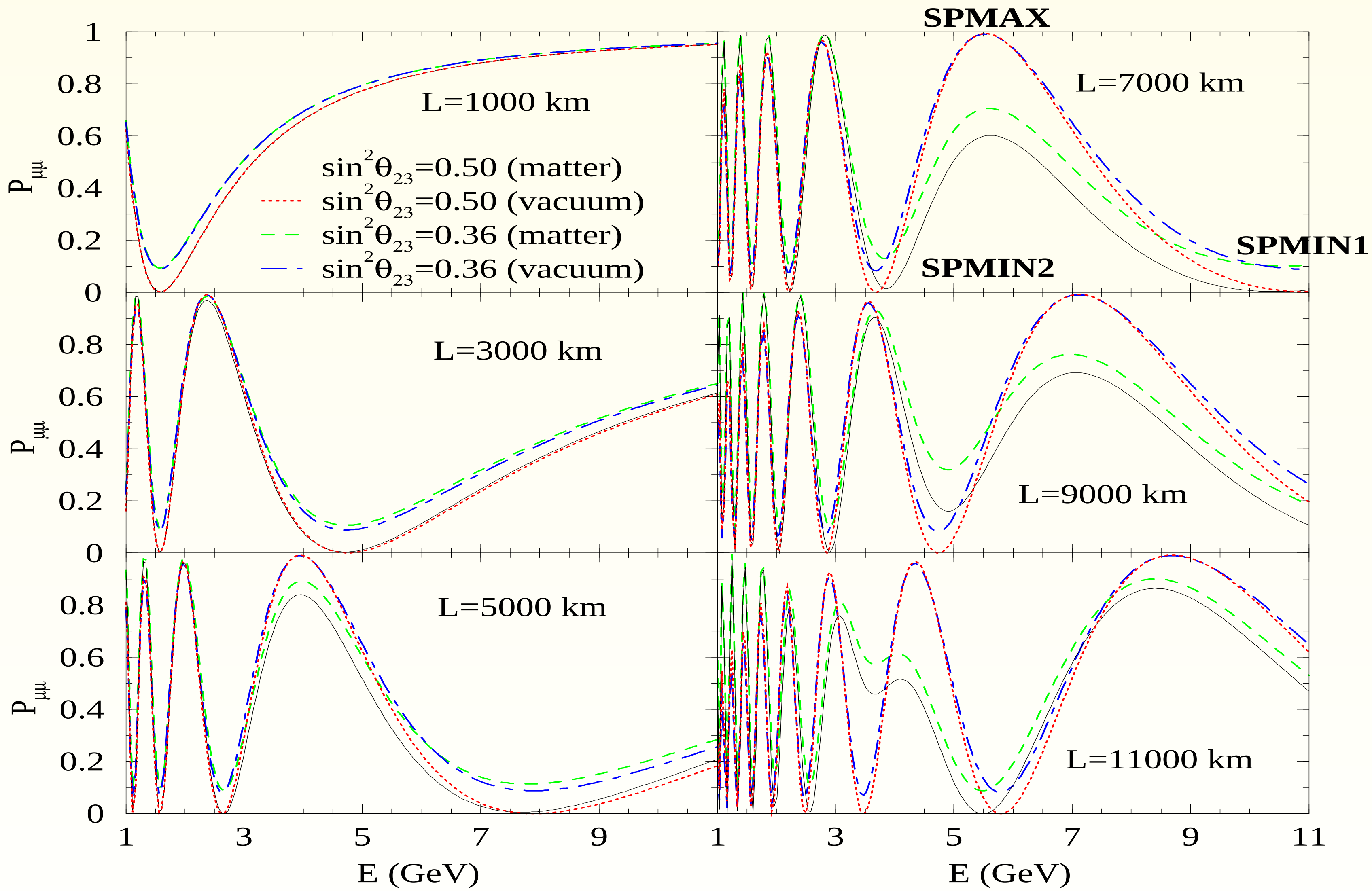

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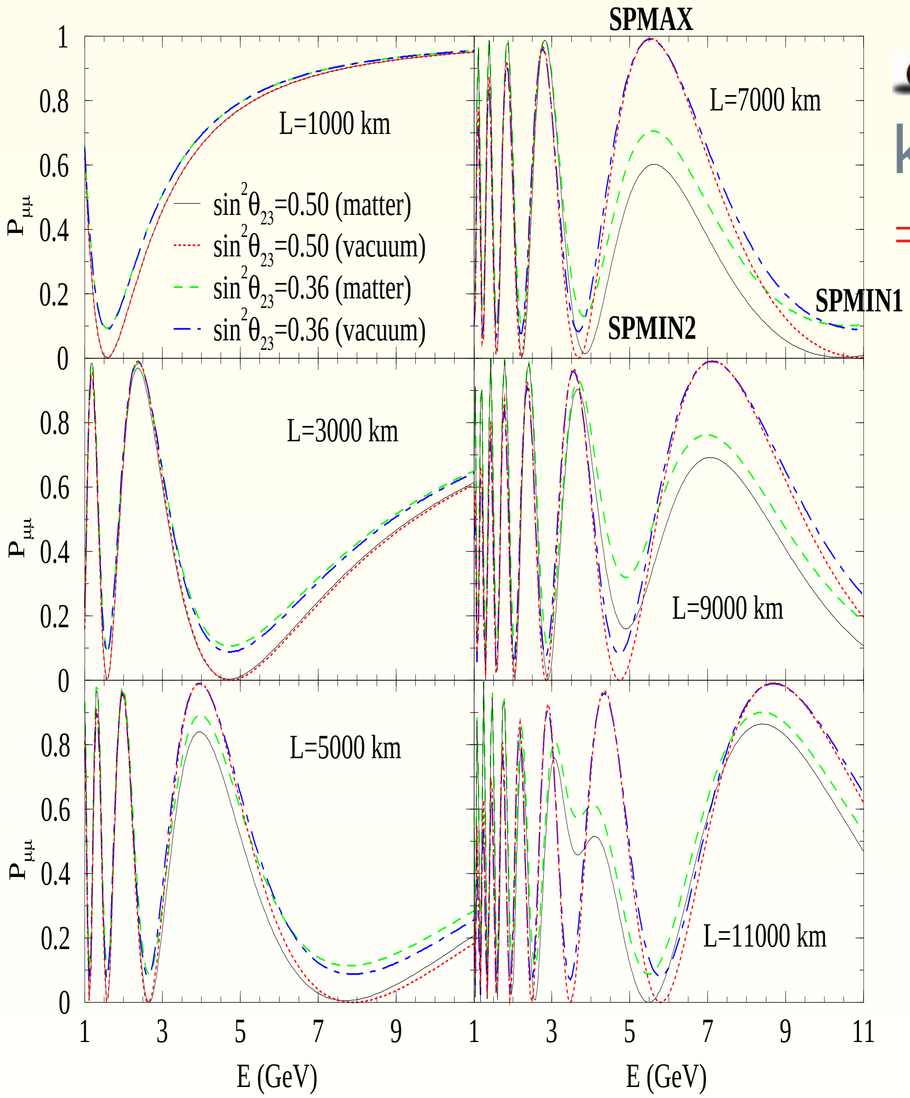

- Max effect for $L \simeq 7000$ km and $E \simeq 6$ GeV $\Rightarrow$ $(E_{\rm SPMAX} \simeq E_{\rm res})$

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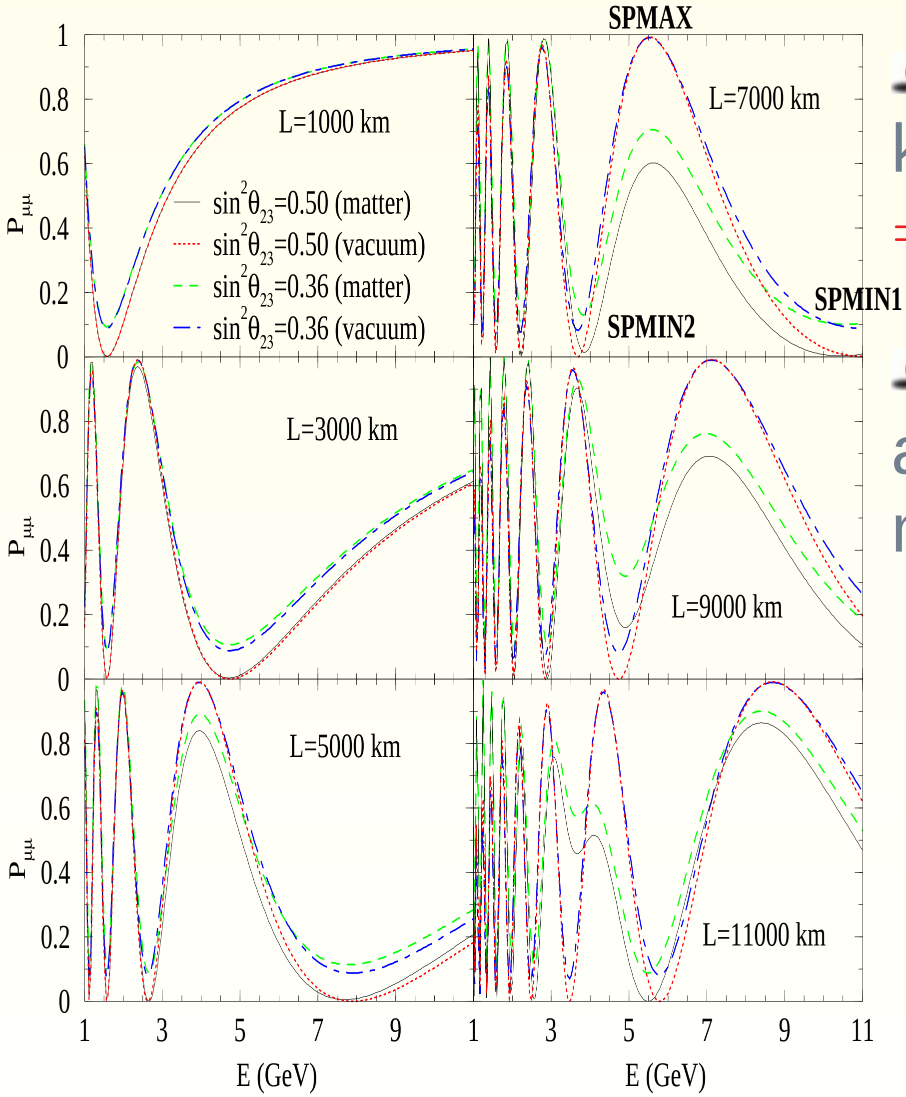
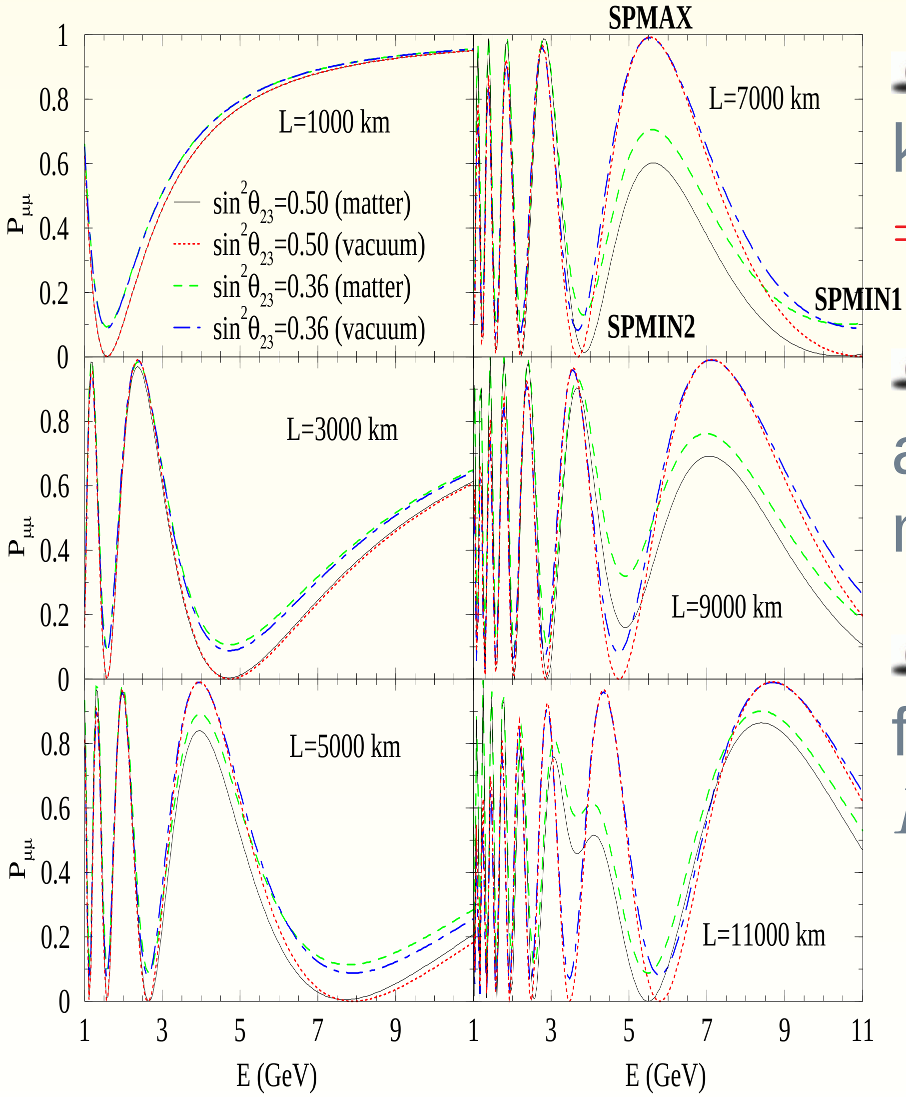


- Max effect for $L \simeq 7000$ km and $E \simeq 6$ GeV $\Rightarrow$ $(E_{\rm SPMAX} \simeq E_{\rm res})$
- $P_{\mu\mu}$ decreases (increases) at SPMAX (SPMIN) due to matter effects

Large Matter Effects in ν_μ Survival Probability



- Max effect for $L \simeq 7000$ km and $E \simeq 6$ GeV $\Rightarrow$ $(E_{\rm SPMAX} \simeq E_{\rm res})$
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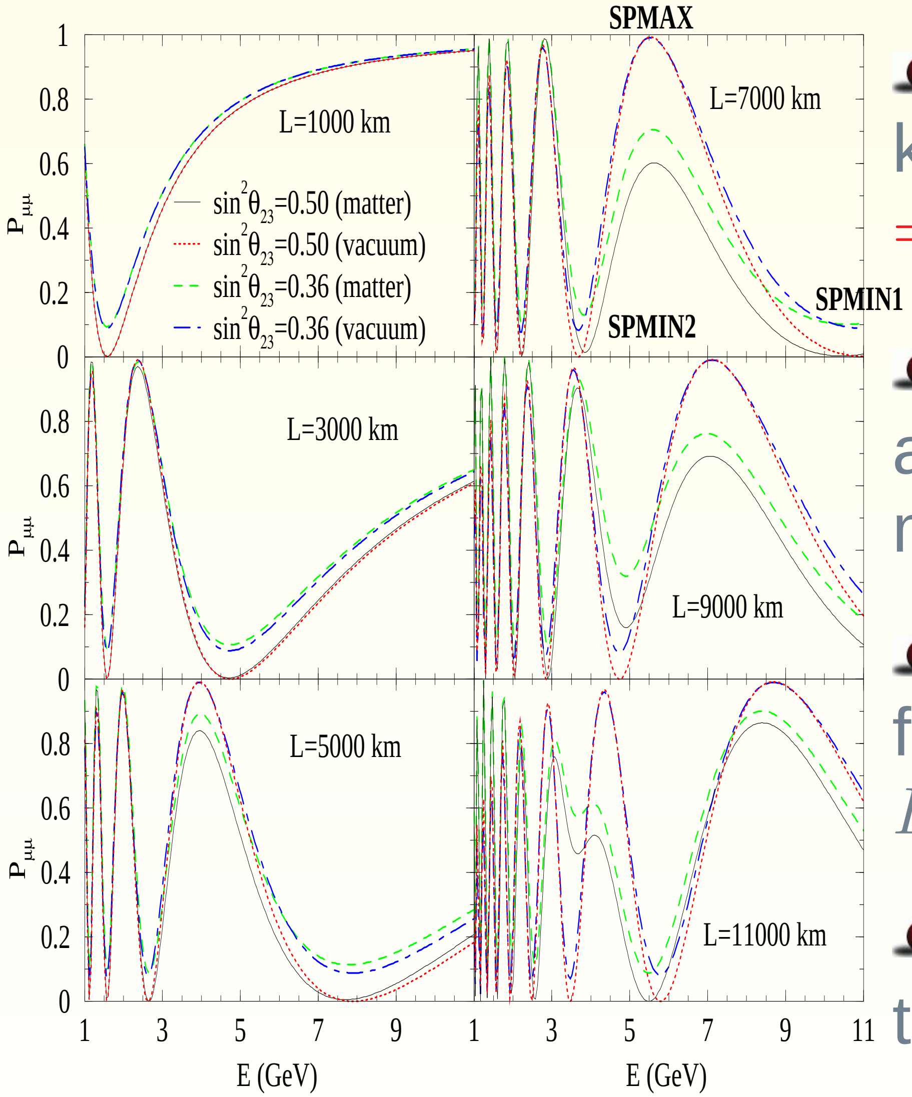

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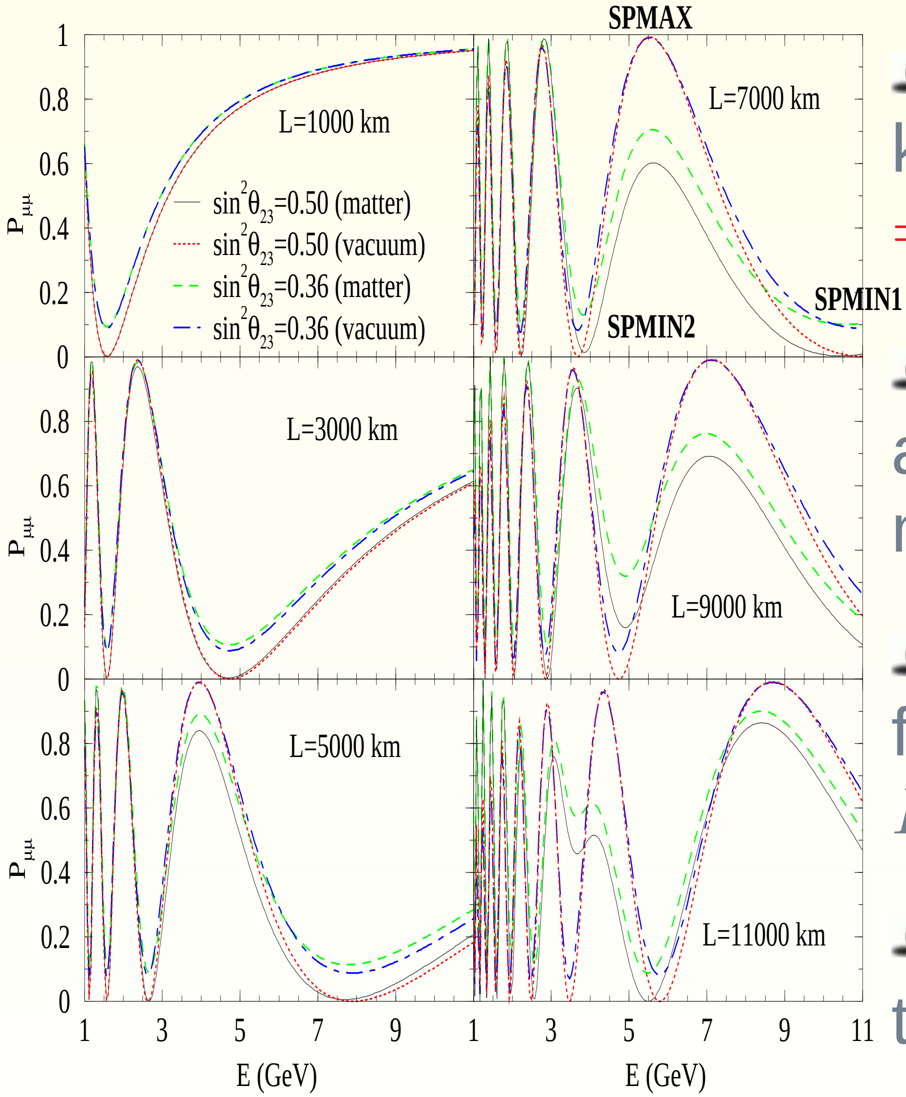

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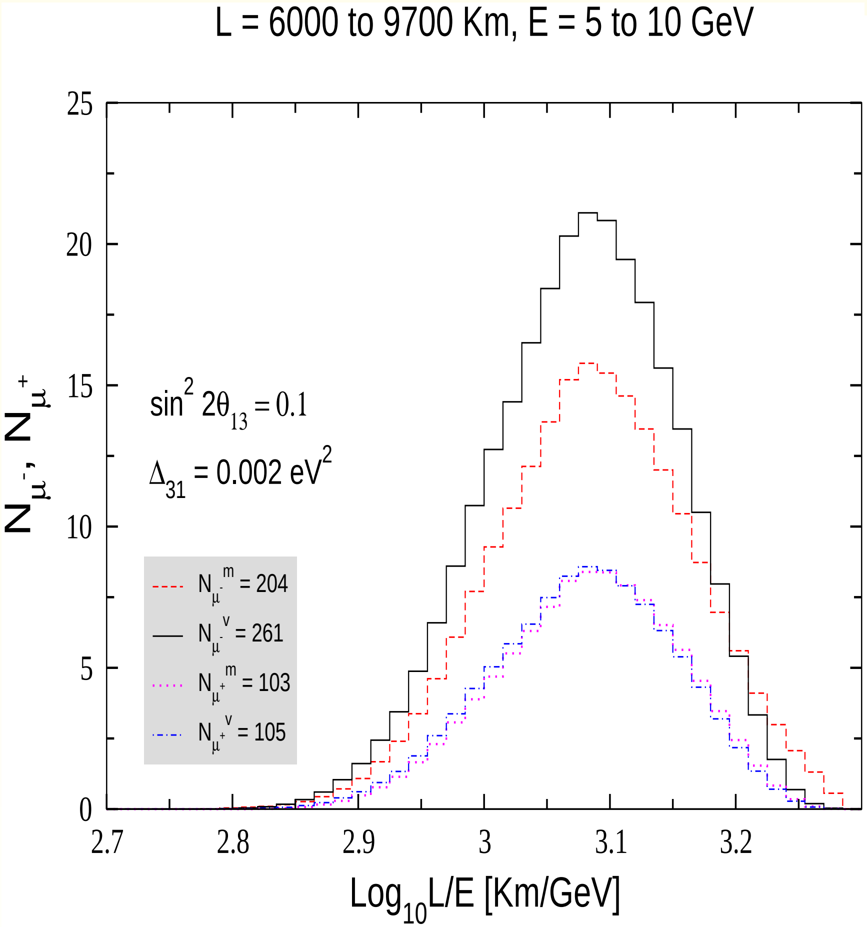
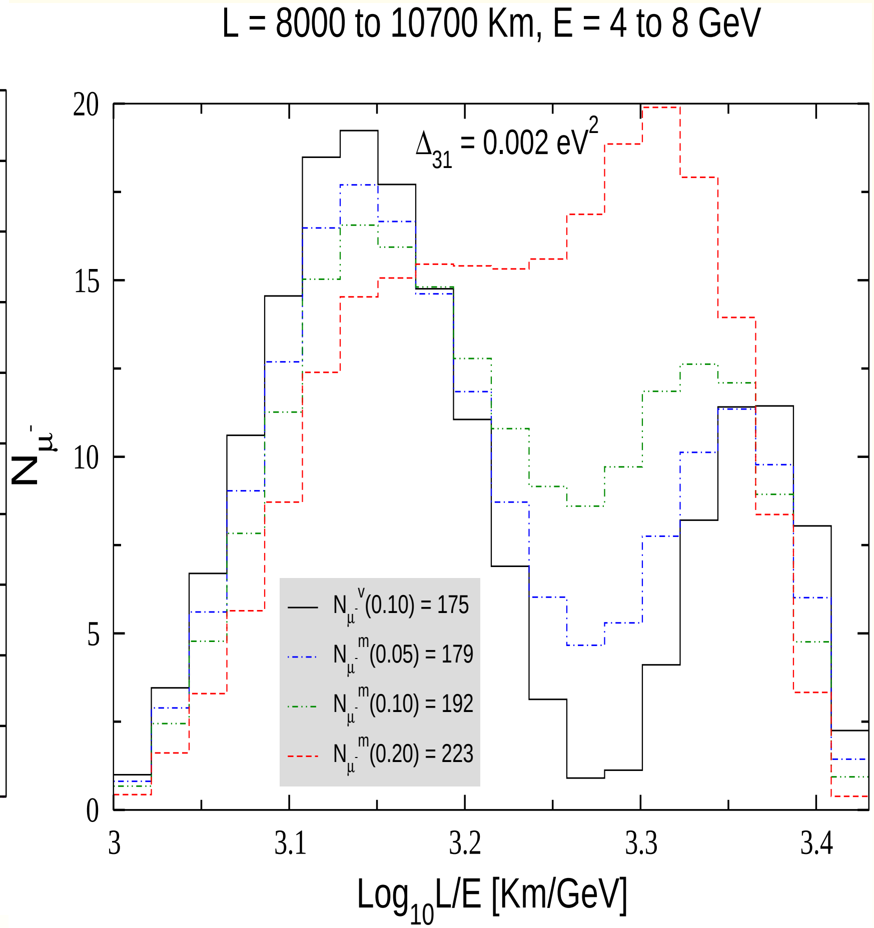
- Sign of the earth matter effects depends on both E and L
- Matter effects depend on the value of $\sin^2\theta_{23}$
- Most imp to choose proper bins in both E and L

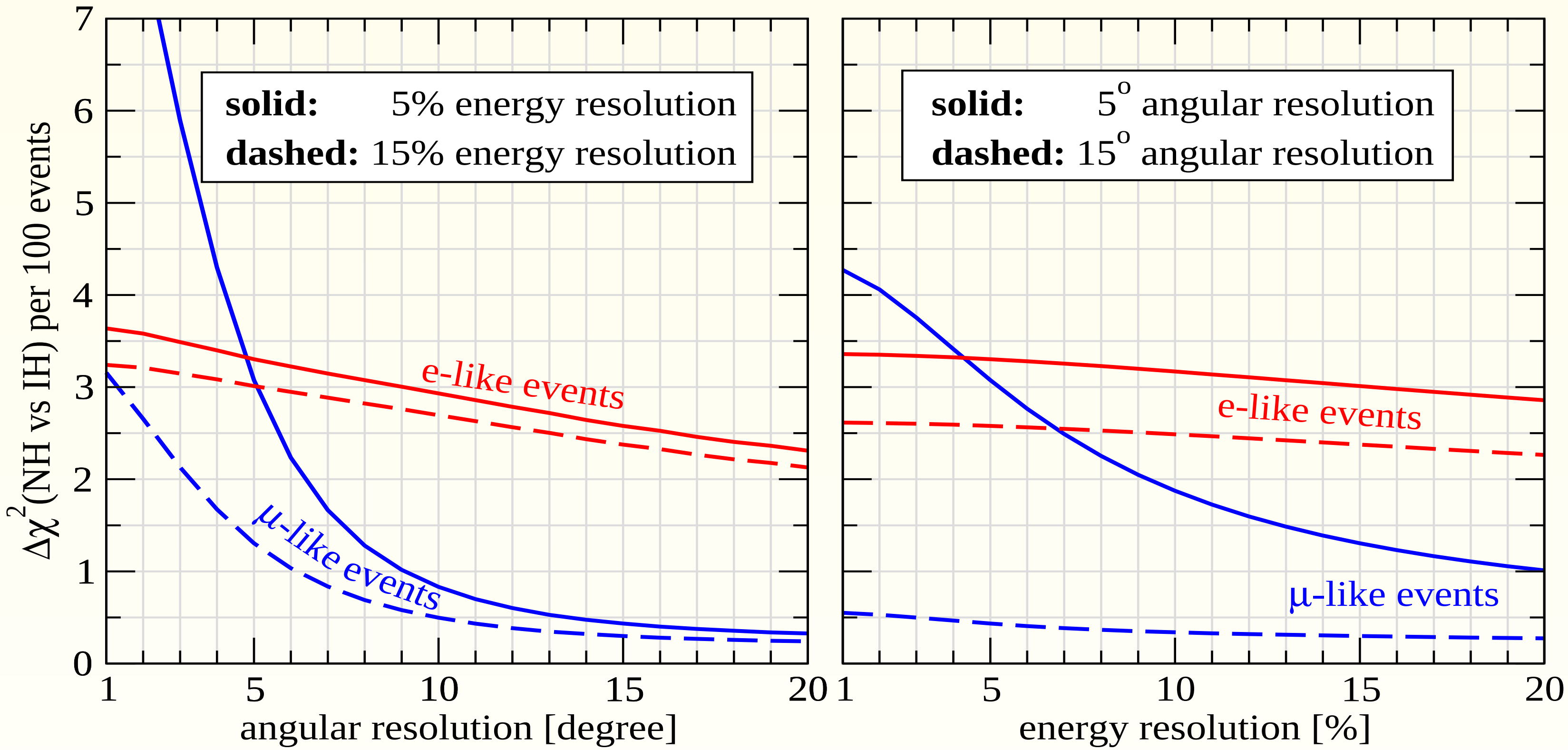
Hierarchy Sensitivity in Atmospheric ν events





- For $\Delta m^2_{31} > 0$ matter effect in ν_μ and $(\mathrm{N}^{\mathrm{mat}}_{\mu^-} \neq \mathrm{N}^{\mathrm{vac}}_{\mu^-})$
- $(\mathrm{N}^{\mathrm{mat}}_{\mu^+} \approx \mathrm{N}^{\mathrm{vac}}_{\mu^+})$ Gandhi,Ghoshal,Goswami,Mehta,Umashankar,hep-ph/0411252

Effect of E and L Resolution



- $\sin^2 2\theta_{13} = 0.1$ and no marginalization
- With increased energy or angular smearing the χ^2 for muon like events decrease.

Schwetz, Petcov, hep-ph/0511277

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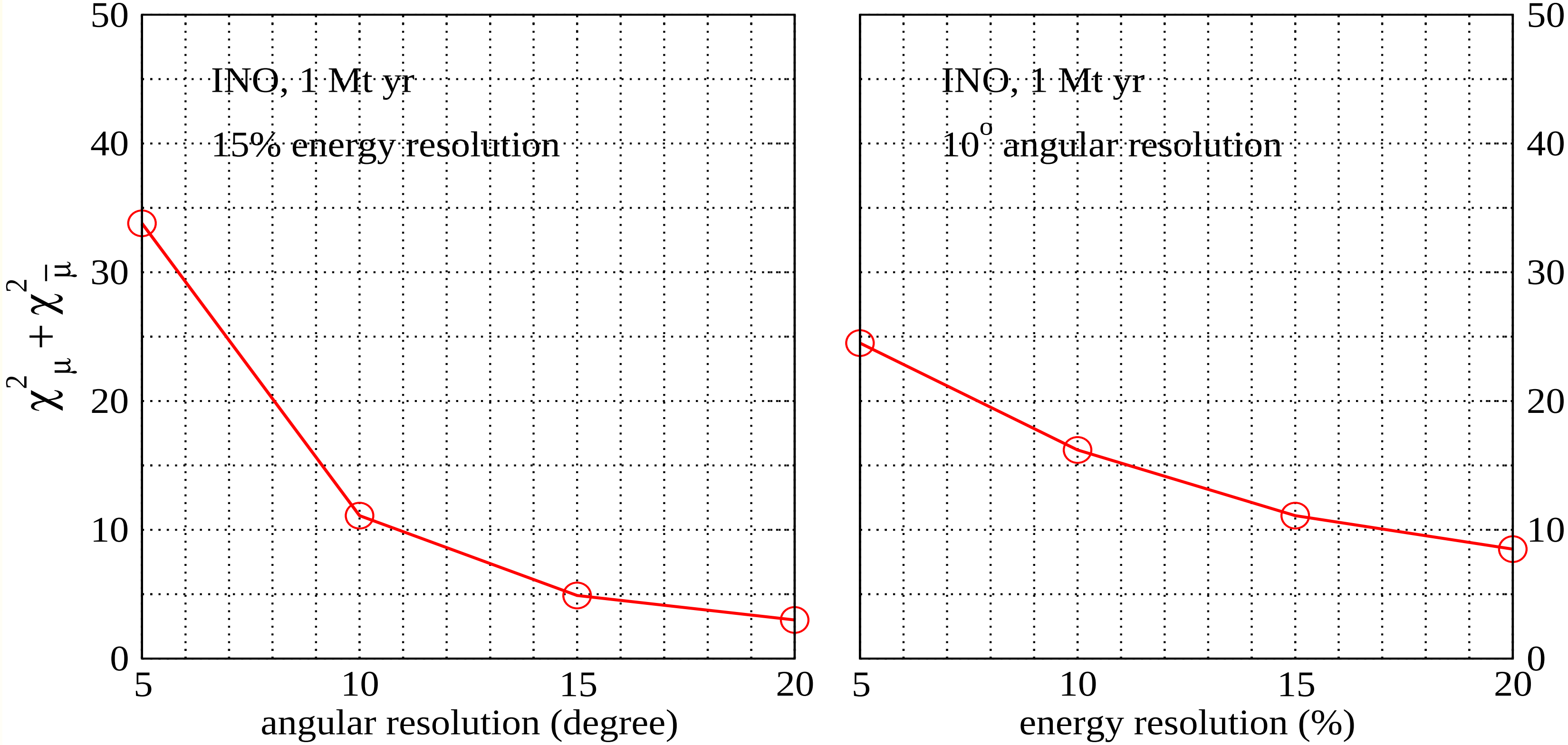

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Gandhi,Ghoshal,Goswami,Mehta,Shalgar,Umashankar, arXiv:0707.1723

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

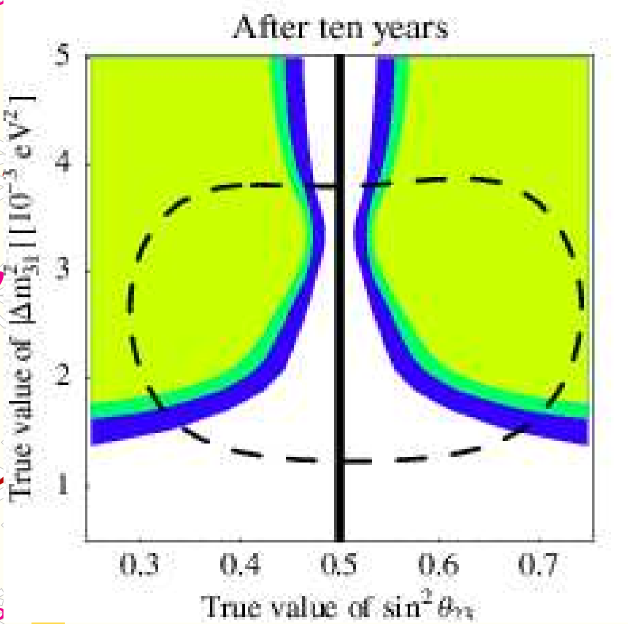
$\sin^2 2\theta_{13}$	$HK\chi^2$	$INO\chi^2$	LiqAr χ^2
0.04	3.6	4.5	13.8
0.1	5.9	9.6	27.5
0.15	7.1	16.9	

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)

Testing maximality of θ_{23}

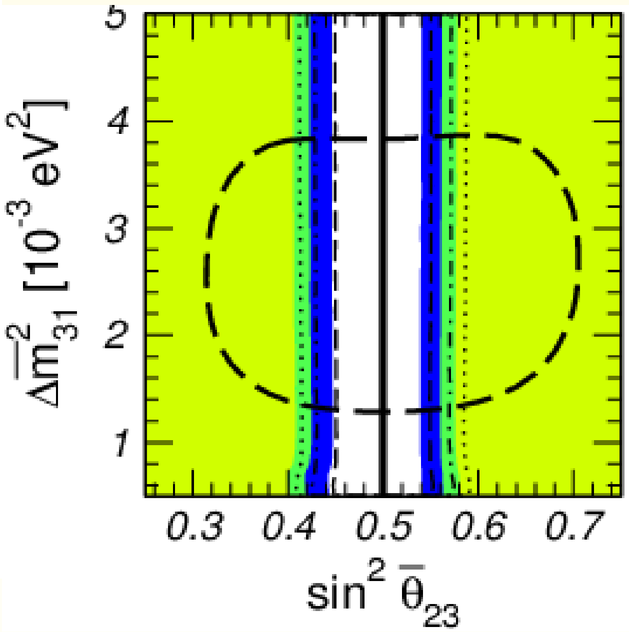


$|D|$ within 14%

LBL combined

Antusch, et al,

hep-ph/0404268

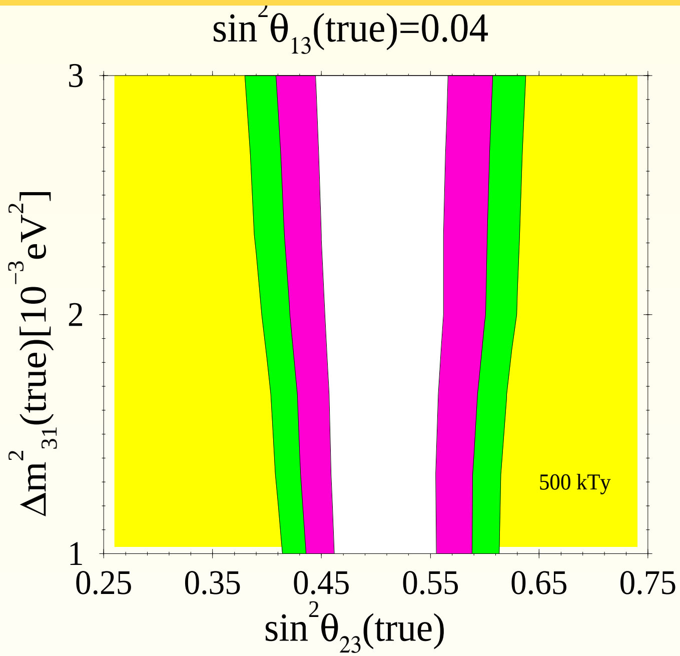


$|D|$ within 19%

SK50

Gonzalez-Garcia, et al,

hep-ph/0408170



$|D|$ within 23%

INO-ICAL 500 kTy

S.C. and P. Roy,

hep-ph/0509197

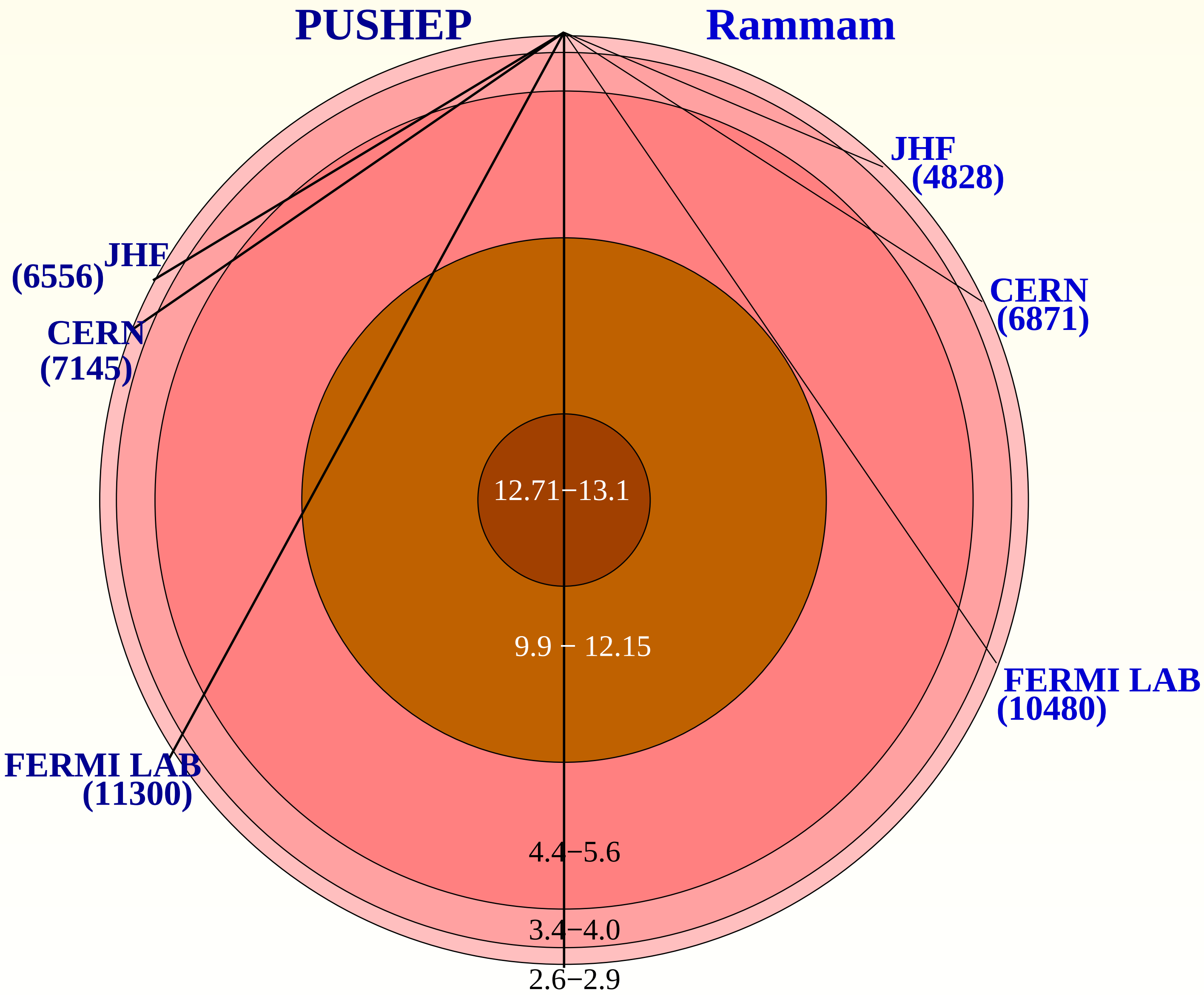
- Sensitivity to $|D|$ in INO improves marginally with θ_{13}
- Sensitivity to $|D|$ in SK50 improves remarkably with θ_{13}

Octant of $\sin^2\theta_{23}$

- **Octant:**
- For every non-maximal $\sin^2\theta_{23}$(true) there exists a $\sin^2\theta_{23}$(false) ($\sin^2\theta_{23}$(false) = 1 - $\sin^2\theta_{23}$(true))
- Given by the sign of D
- Possible to get some handle on the octant sensitivity thru matter effects in the atmosheric muon neutrino signal in INO, if θ_{13} is large

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

Phase-II: Physics with Neutrino Beams



The "Golden Channel" ($\nu_e \to \nu_\mu$)

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

- $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\hat{A} = A/\Delta m^2_{31}$
- $\Delta = \Delta m^2_{31}L/4E$, $A = \pm 2\sqrt{2}G_F n_e E$
- A is positive for neutrinos
- A is negative for antineutrinos

Cervera *et al.*, hep-ph/0002108

Freund, Huber, Lindner, hep-ph/0105071

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

- Depends on θ_{13}, δ_{CP} and $sgn(\Delta m^2_{31})$ and hence can measure them all simultaneously: GOLDEN
- This dependence however brings in the problem of PARAMETER DEGENERACIES

Degeneracies in the Golden Channel

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

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

- Octant of θ_{23} Degeneracy — Fogli, Lisi, hep-ph/9604415
- $Sgn(\Delta m^2_{31}) - \delta_{CP}$ Degeneracy — Minakata, Nunokawa, hep-ph/0108085
- Intrinsic $(\delta_{CP}, \theta_{13})$ Degeneracy — Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258
- **Degeneracies create Clone Solutions**

Killing the Clones at The Magic Baseline

The Magic Baseline

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

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\end{aligned}
$$

- If $\sin(\hat{A}\Delta) \simeq 0$

The Magic Baseline

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- $(\delta_{CP}, \theta_{13})$ and $(\delta_{CP}, sgn(\Delta m^2_{31}))$ degeneracies vanish
- “Clean” measurement of θ_{13} and $sgn(\Delta m^2_{31})$

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$$\sin(\hat{A}\Delta) \simeq 0$$

$$\Rightarrow$$

$$L_{magic} \simeq 7690 \text{ km}$$

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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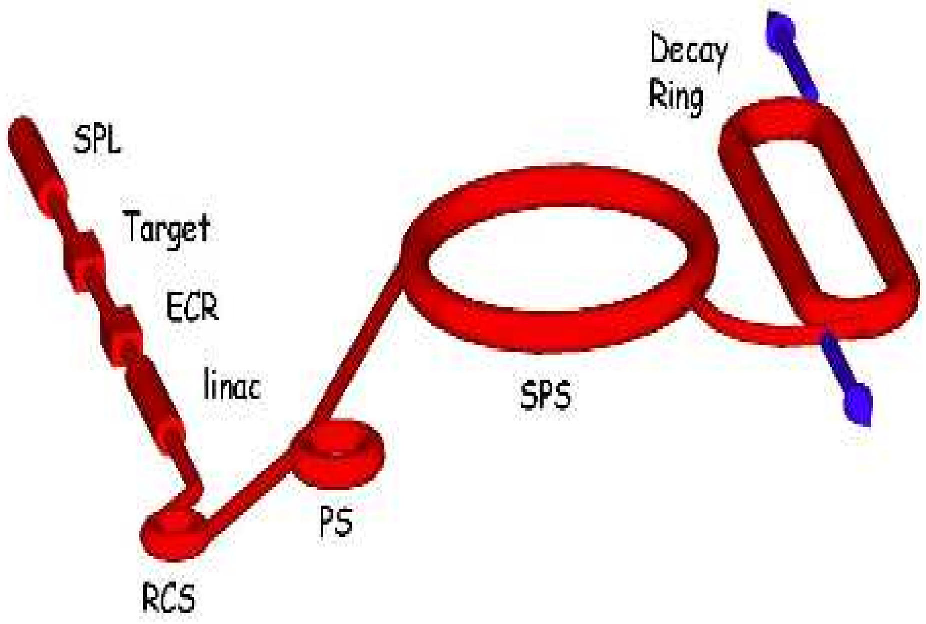
Location of INO is ideal!!

Beta-beams

Beta-beams

- Beta-Beams are produced from beta decay of accelerated radioactive ions, circulating in a storage ring

$$(A, Z) \rightarrow (A, Z+1) + e^{+} + \nu_e \quad \text{or} \quad (A, Z) \rightarrow (A, Z-1) + e^{-} + \bar{\nu}_e$$



- Pure Flavor –
- Intense Source –
- Known beam –
- Spectrum $\Rightarrow \gamma$ & E_0 –
- Flux norm $\Rightarrow \gamma$ & N_β –
- Beam divergence $\Rightarrow \gamma$ –

- Very low systematic uncertainties
- Very small backgrounds

Zucchelli, PLB 532, 166, (2002)

CERN-INO Magical Beta-Beam Experiment

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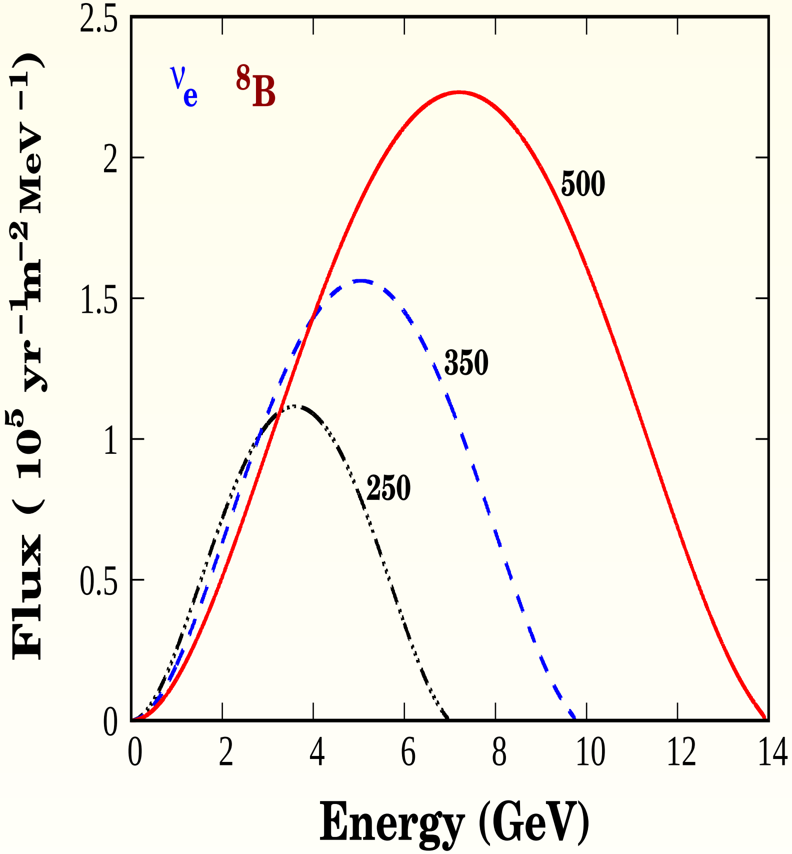
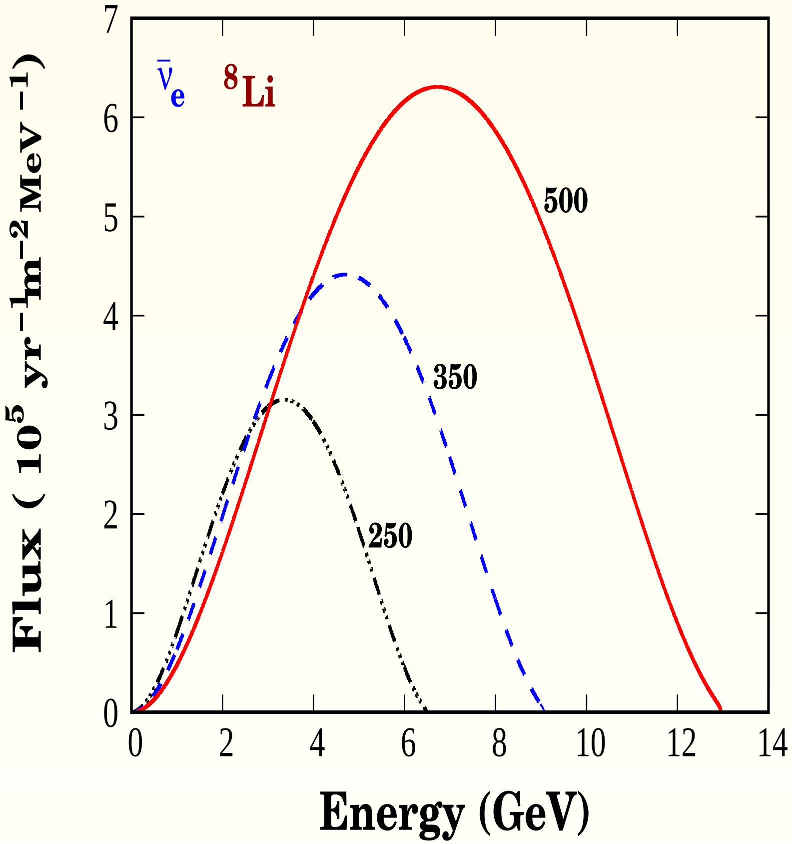
- Beta beam spectrum depends on the end point energy of the beta unstable ion and Lorentz boost γ
- The standard Beta-Beam ions ^{18}Ne and ^{6}He would require very large gamma
- Alternative ions ^{8}B and ^{8}Li have large end-point energy and hence "harder" spectra. Works!!

The CERN-INO Beta-Beam Experiment





Agarwalla, SC, Raychaudhuri, hep-ph/0610333

- Flux peaks at $E \simeq 6$ GeV for $\gamma = 350 - 500$

Near-Resonant Matter Effects

- Large Distance ⇒ Large Matter effects

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

$$E_{res} = \frac{|\Delta m^2_{31}| \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

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- Maximal oscillations when $\sin^2 2\theta^m_{13} \simeq 1$ and $\sin^2(\frac{(\Delta m^2_{31})^m L}{4E}) \simeq 1$ simultaneously

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

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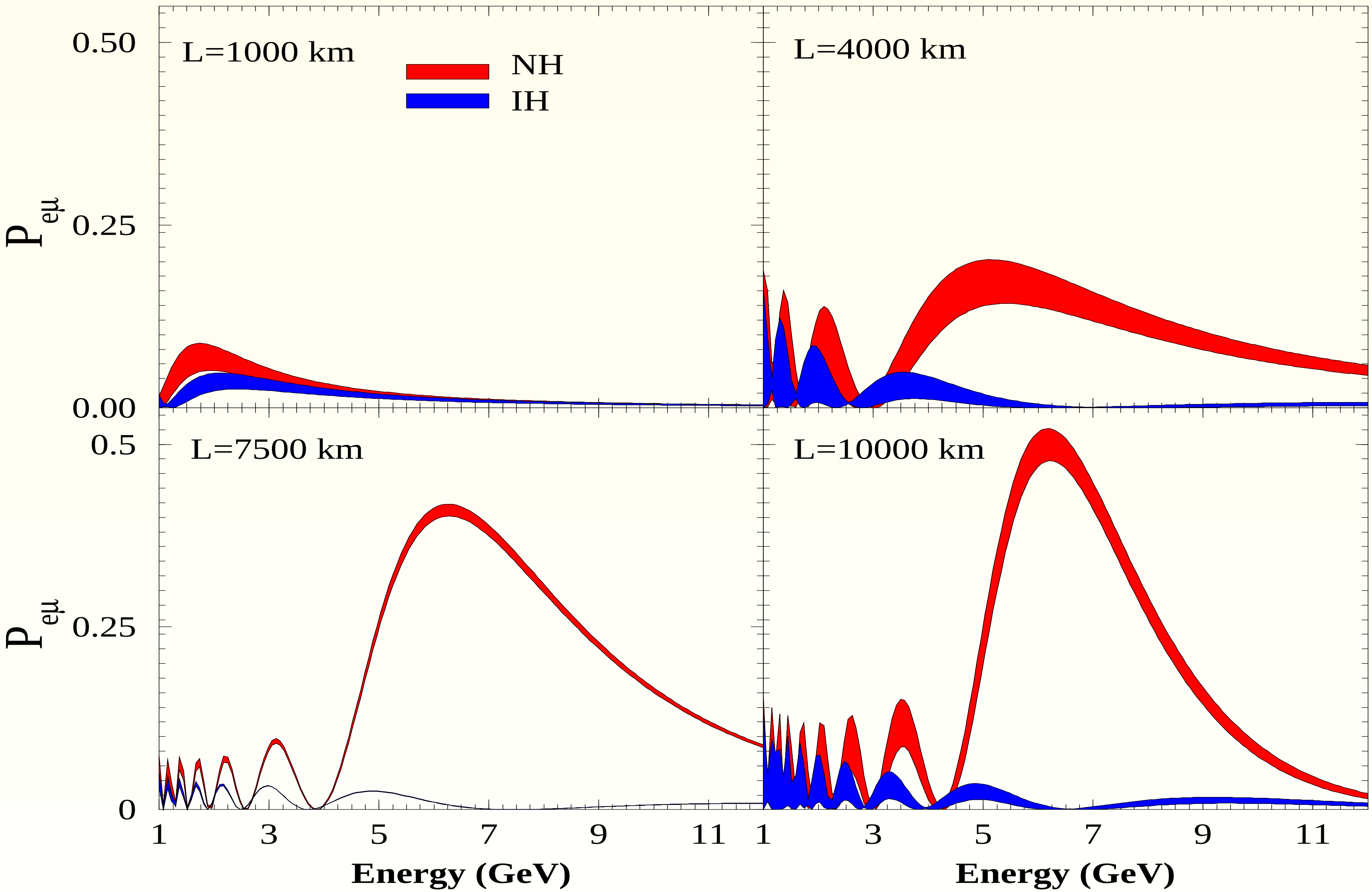
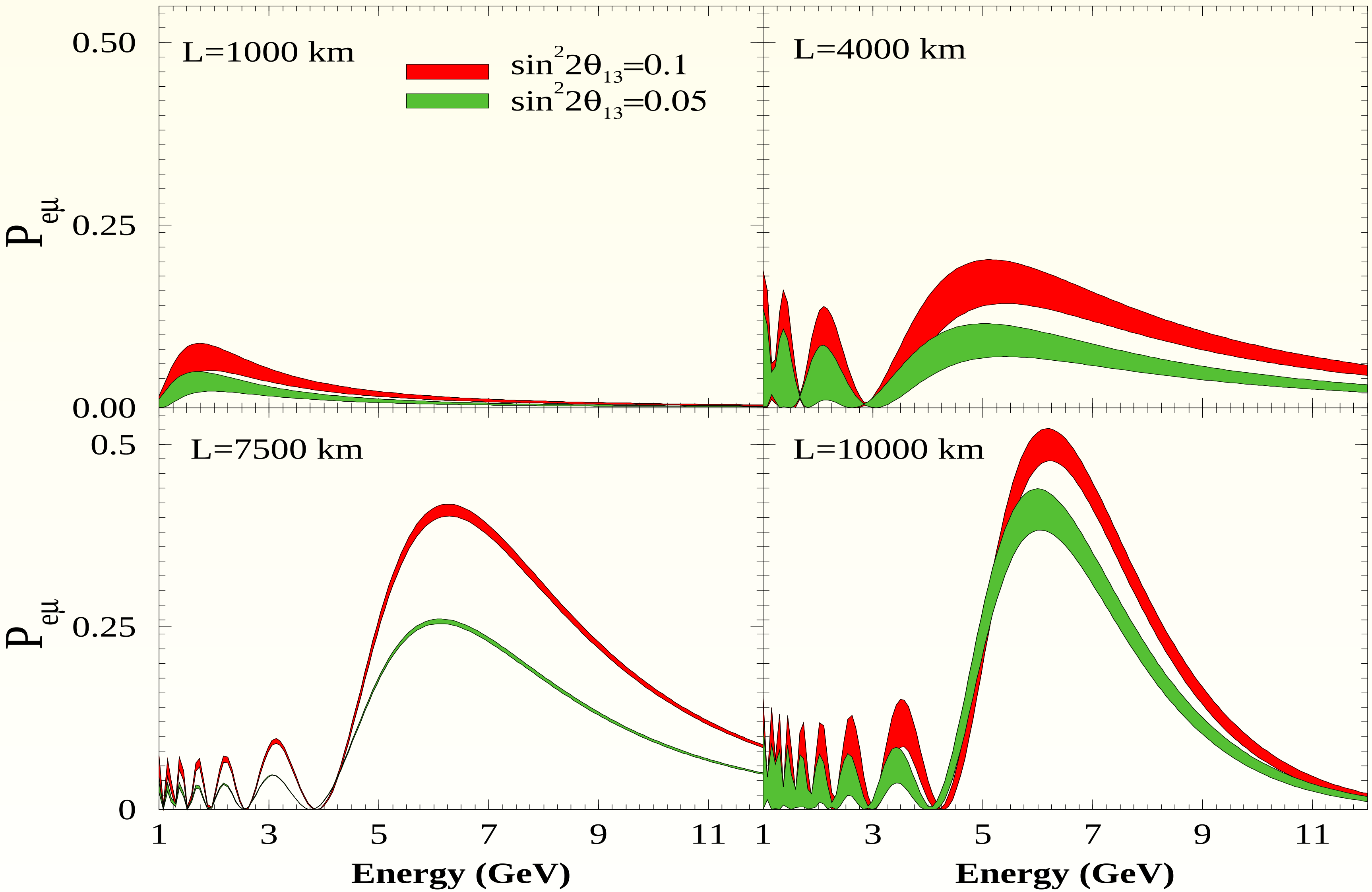
  Gandhi, Ghoshal, Goswami, Mehta, Umashankar, hep-ph/0408361
- At the magic baseline, largest oscillations come when $E \simeq 6$ GeV

The Probability



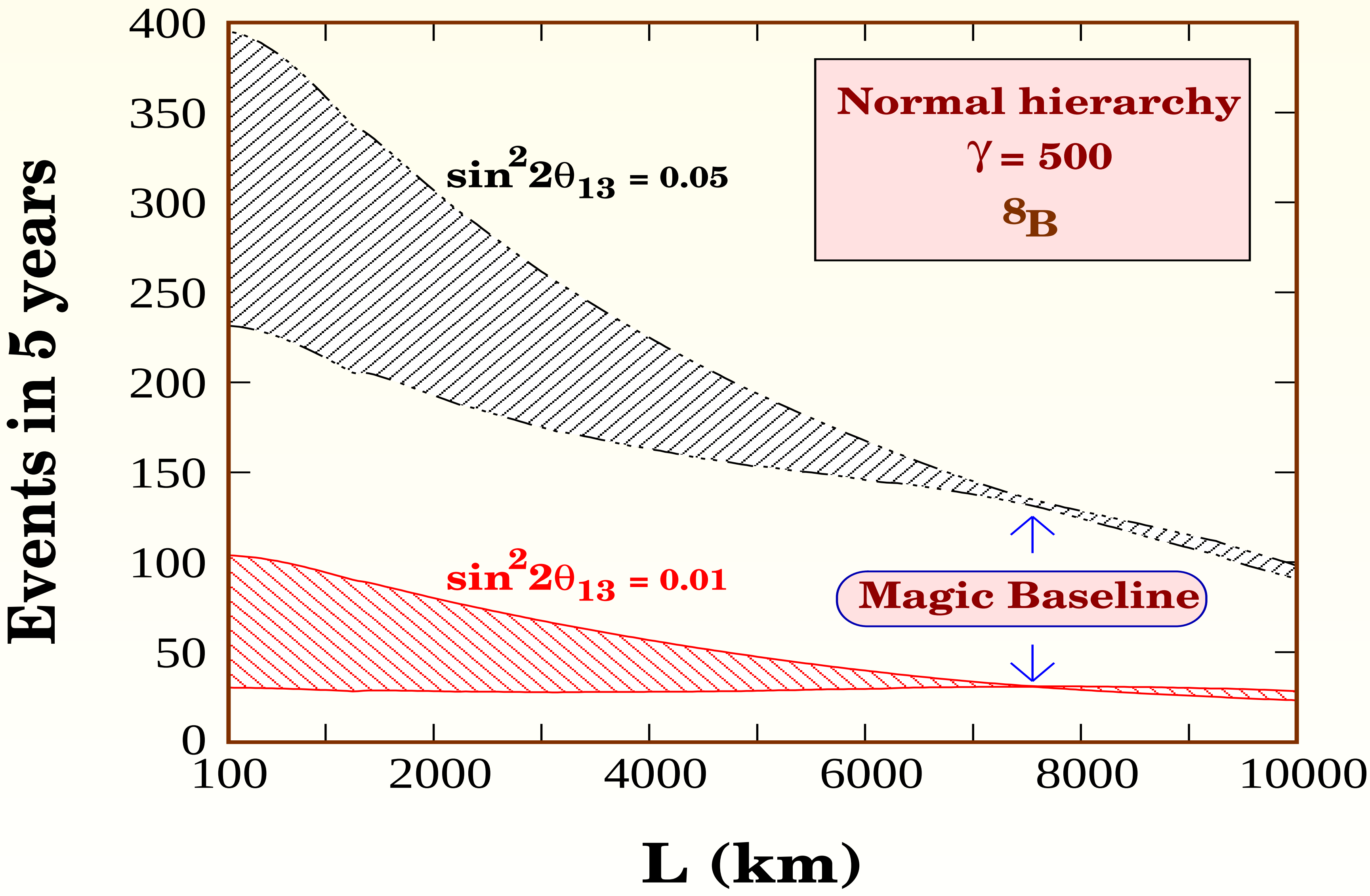
Agarwalla, S.C., Raychaudhuri, hep-ph/0610333

The Probability



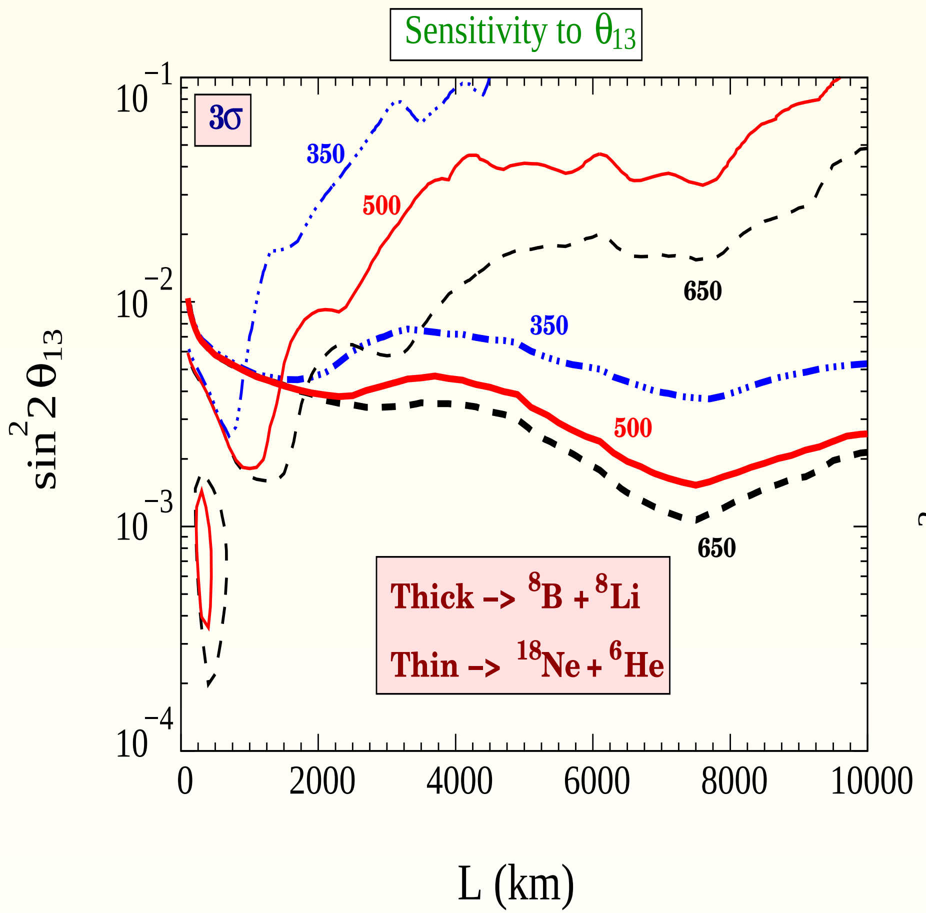
Agarwalla, S.C., Raychaudhuri, hep-ph/0610333

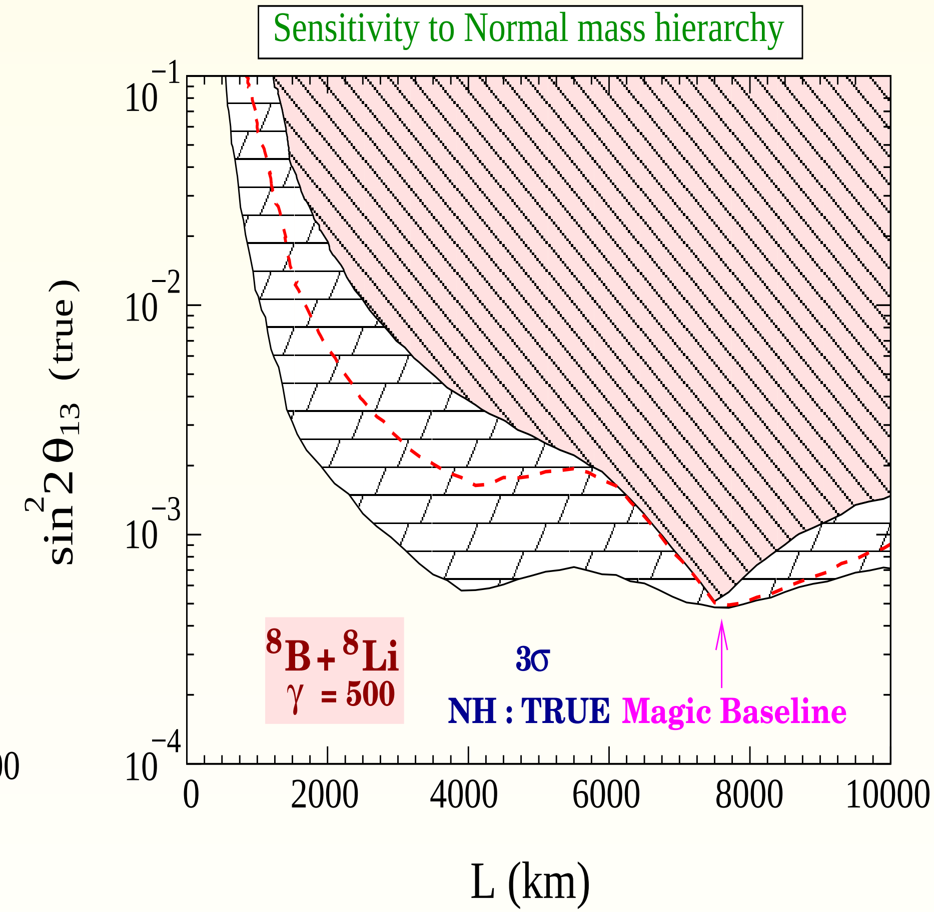
The Magic



Agarwalla, S.C., Raychaudhuri, arXiv:0711.1459

Optimizing the Beta-Beam Experiment





- Best sensitivity comes at the Magic Baseline

Agarwalla, S.C., Raychaudhuri, Winter, arXiv:0802.3621

Location of INO is indeed ideal!!

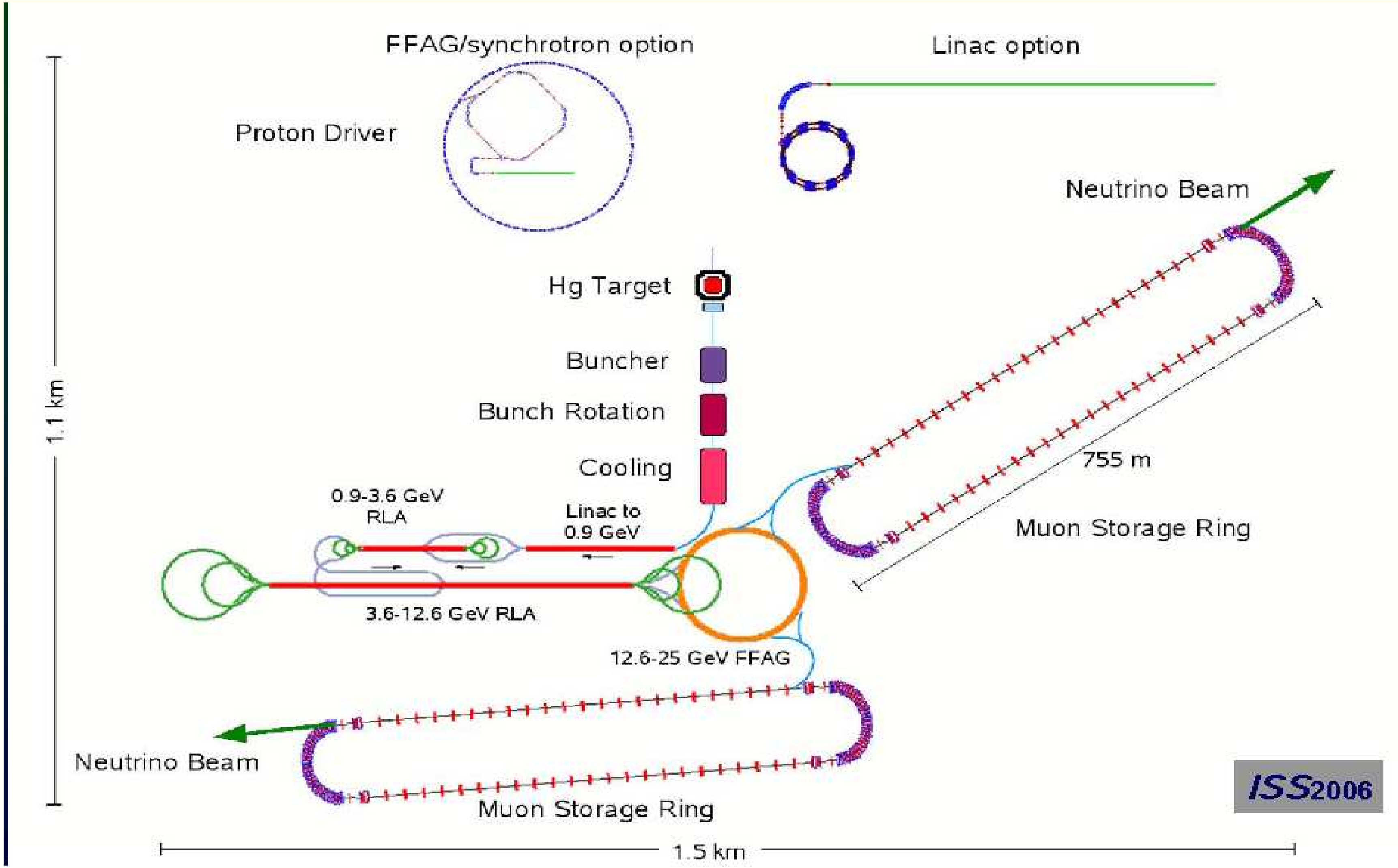
CP Violation with ICAL@INO PLUS

- No CP sensitivity at the magic baseline
- Add another detector at a different baseline
- The combined two baseline set-up could be used to study CP violation to exceptional levels

Agarwalla, S.C., Raychaudhuri, arXiv:0804.3007

Coloma, Donini, Fernandez-Martinez, Lopez-Pavon, arXiv:0712.0796

Neutrino Factory



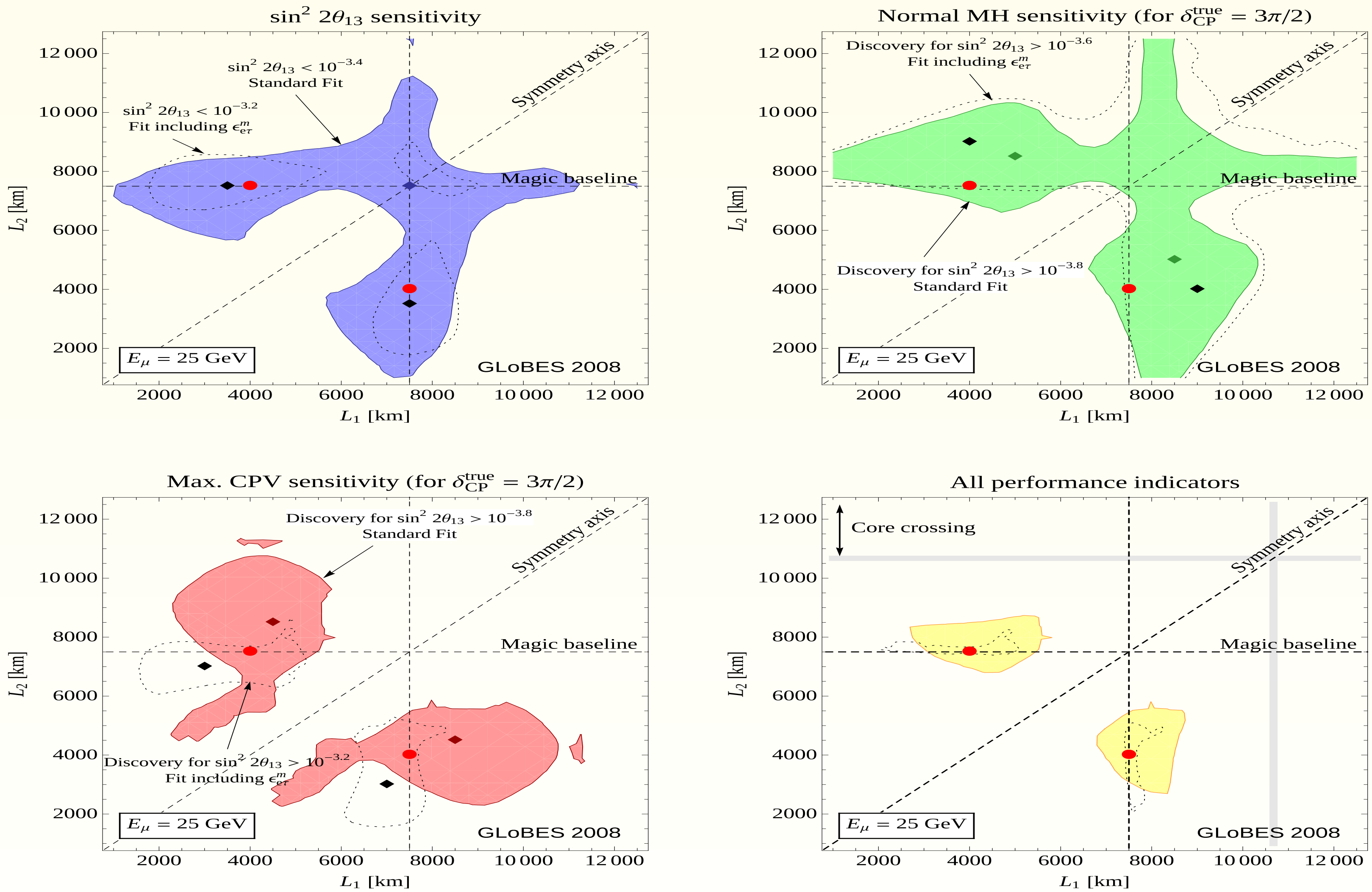
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Neutrino Factory

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

- Charge identification is a MUST for nufacts
- ICAL@INO is a NuFact detector!
- Physics performance using NuFact beam has been carried out
- Sensitivity to neutrino parameters is tremendous
- Optimization of both the Beta-beam and NuFact technology is underway under a number of R&D initiatives world-wide
- Efforts are on for doing dedicated INO simulations for Beta-beam and NuFact beams

Optimizing the NuFact Experiment



Ota,Winter, arXiv:0804.2261

Huber,Lindner,Rolinec,Winter, hep-ph/0606119

Other Physics with ICAL@INO

Other Physics with ICAL@INO

- Constraining CPT violation:

  Datta, Gandhi, Mehta, Uma Sankar, hep-ph/0312027

  Dighe, Ray, arXiv:0802.0121

- Probing sterile neutrinos:

  Dighe, Ray, arXiv:0709.0383

- Constraining NSI:

  Adhikari, Agarwalla, Raychaudhuri, hep-ph/0608034

- Probing WIMP dark matter models:

  Mena, Palomares-Ruiz, Pascoli, arXiv:0706.3909

- Very High Energy Muons:

  Gandhi and Panda, hep-ph/0512179

Conclusions

Conclusions

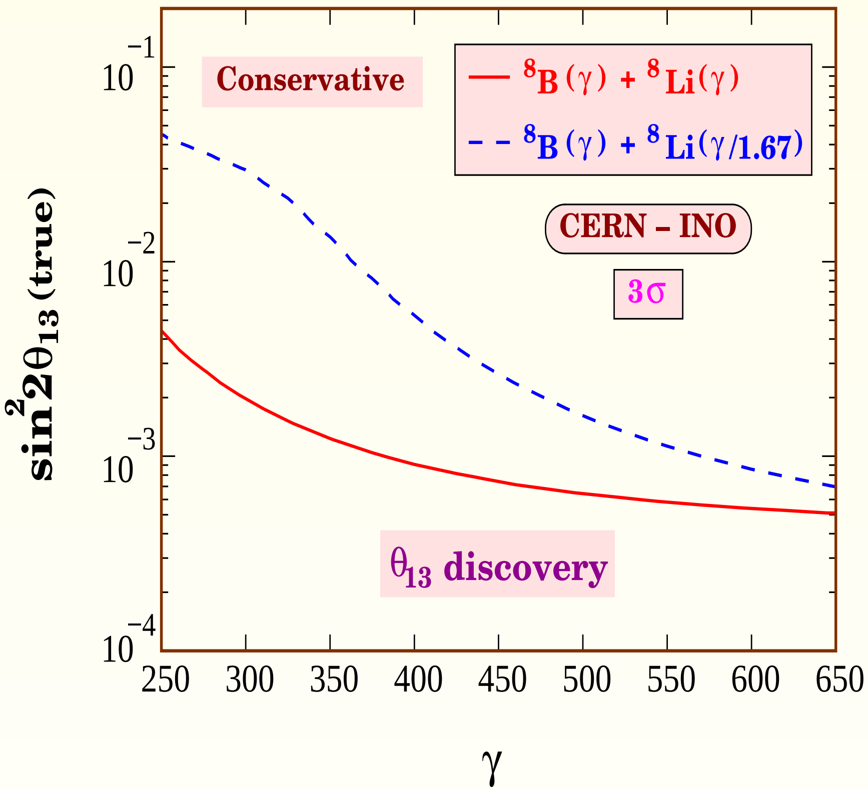
- A large magnetized iron calorimeter detector has substantial physics potential using atmospheric neutrinos.
  - Reconfirmation of L/E dip and precision of $|\Delta m^2_{31}|$
  - Matter effect and Sign of Δm^2_{31}
  - Determination of octant of θ_{23}
  - CPT violation, Long Range Forces .....
- It 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

Conclusions

THANK YOU

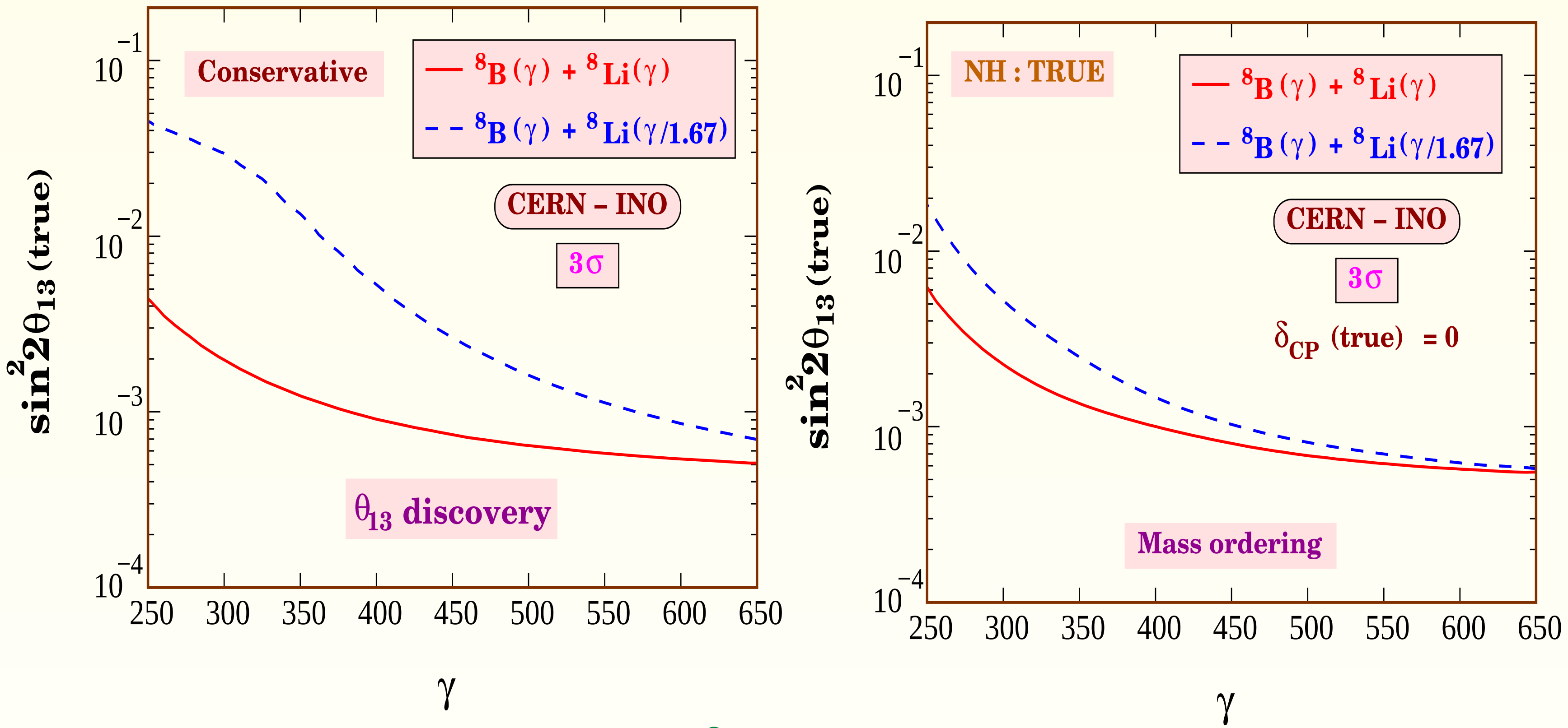
Reach of The Resonant-Magical Experiment



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

Agarwalla, S.C., Raychaudhuri, arXiv:0711.1459

Reach of The Resonant-Magical Experiment



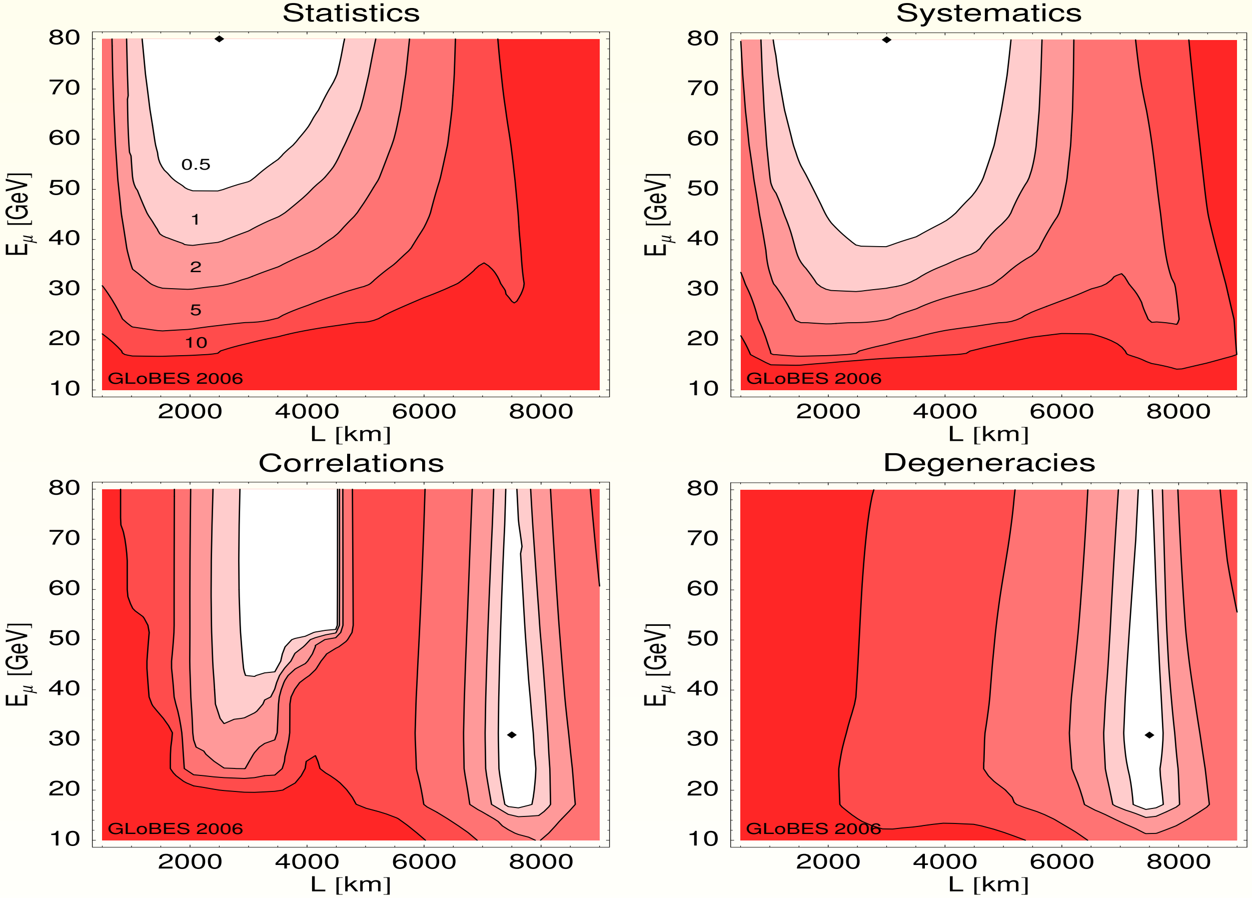
- Signal for θ_{13} at 3σ if $\sin^2 2\theta_{13}$(true) $\geq 5.1 \times 10^{-4}$
- Mass Hierarchy at 3σ if $\sin^2 2\theta_{13}$(true) $\geq 5.6 \times 10^{-4}$

Agarwalla, S.C., Raychaudhuri, arXiv:0711.1459

This is a no-risk experiment

Physics Reach of Neutrino Factory

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

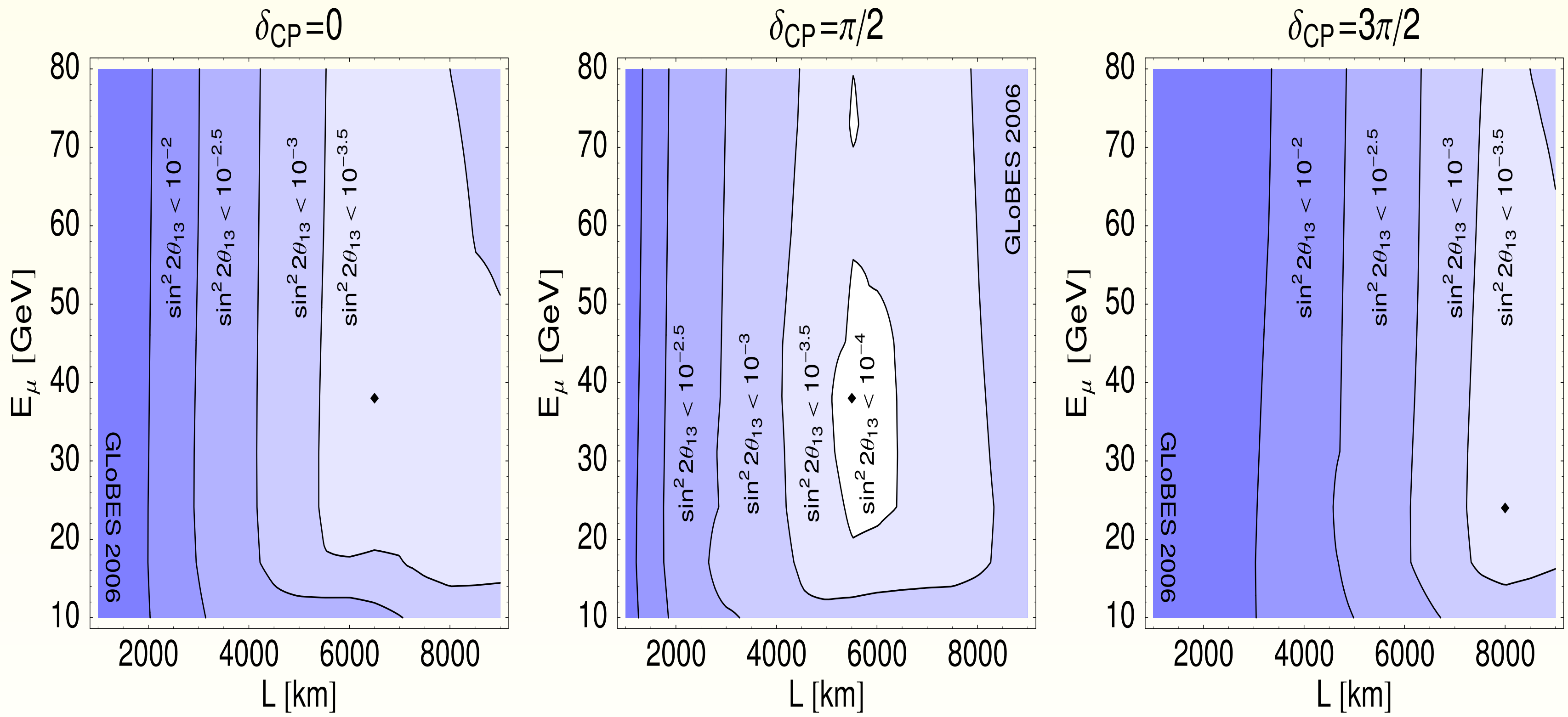


Huber *et al.*, hep-ph/0606199

- Best sensitivity comes at the Magic Baseline

Physics Reach of Neutrino Factory

- Sensitivity to $sgn(\Delta m^2_{31}) \gtrsim 1.8 \times 10^{-4}$ (3σ)



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

- Best sensitivity comes near the Magic Baseline

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 uncerts are taken care of by Marginalization