Neutrino Oscillation Parameters: Results and Prospects – II

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- 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 possible using $\nu_\mu \to \nu_\mu$ $P_{\mu\mu}$; Disapp Expts

Measuring θ_{13}, δ_{CP} and $sgn(\Delta m^2_{31})$

Measuring θ_{13} with Reactors

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$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right) + O(\alpha^2)$$

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- Sensitivity (90% C.L.):

$$\sin^2 2\theta_{13} < 0.032 \quad \text{Double Chooz}$$

$$\sin^2 2\theta_{13} < 0.009 \quad \text{Reactor II}$$

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

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\begin{aligned}
P_{app}^{vac} &\simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta \\
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where $\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$, $\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$ and we have expanded the probability in α and θ_{13} keeping only lower order terms

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- $$\left(\frac{P_\nu + P_{\bar\nu} - 2C}{2A}\right)^2 + \left(\frac{P_\nu - P_{\bar\nu}}{2B}\right)^2 = 1$$

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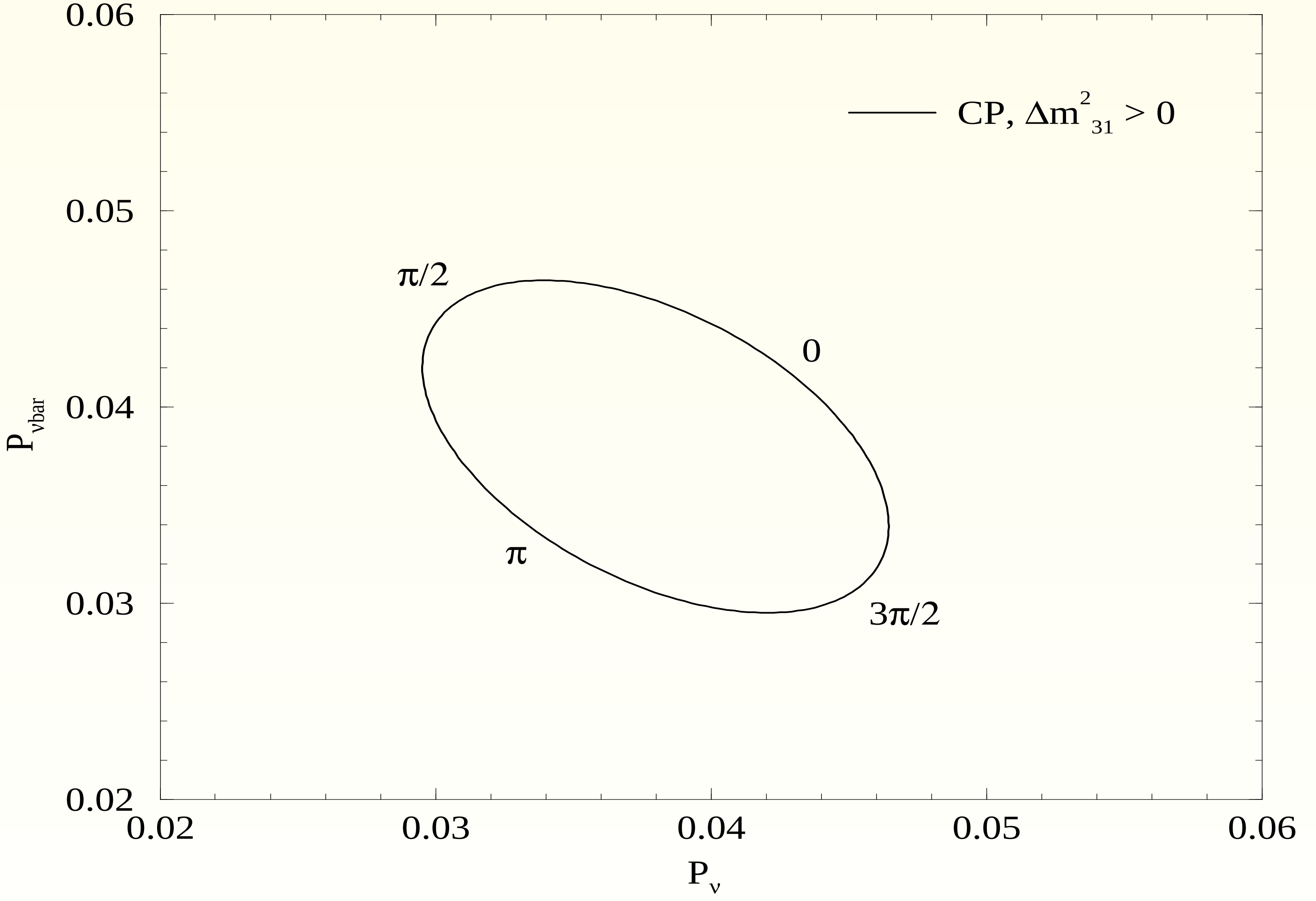
- This is the eqn of an ellipse in the $P_\nu - P_{\bar\nu}$ plane. These are called "bi-probability plots". Major (minor) axes measure the amplitude of $\sin\delta_{CP}(\cos\delta_{CP})$term

Bi-Probability Plots



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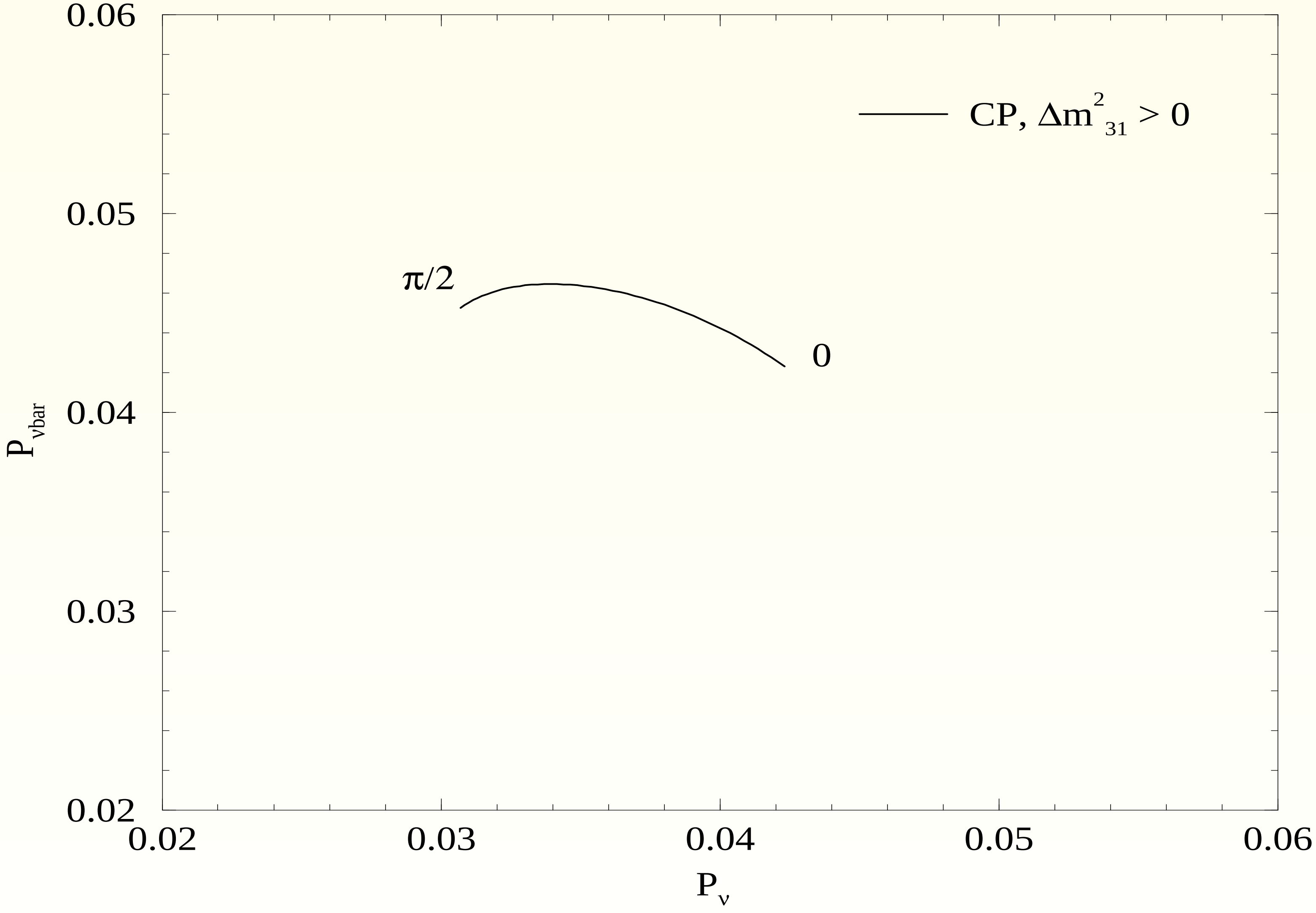

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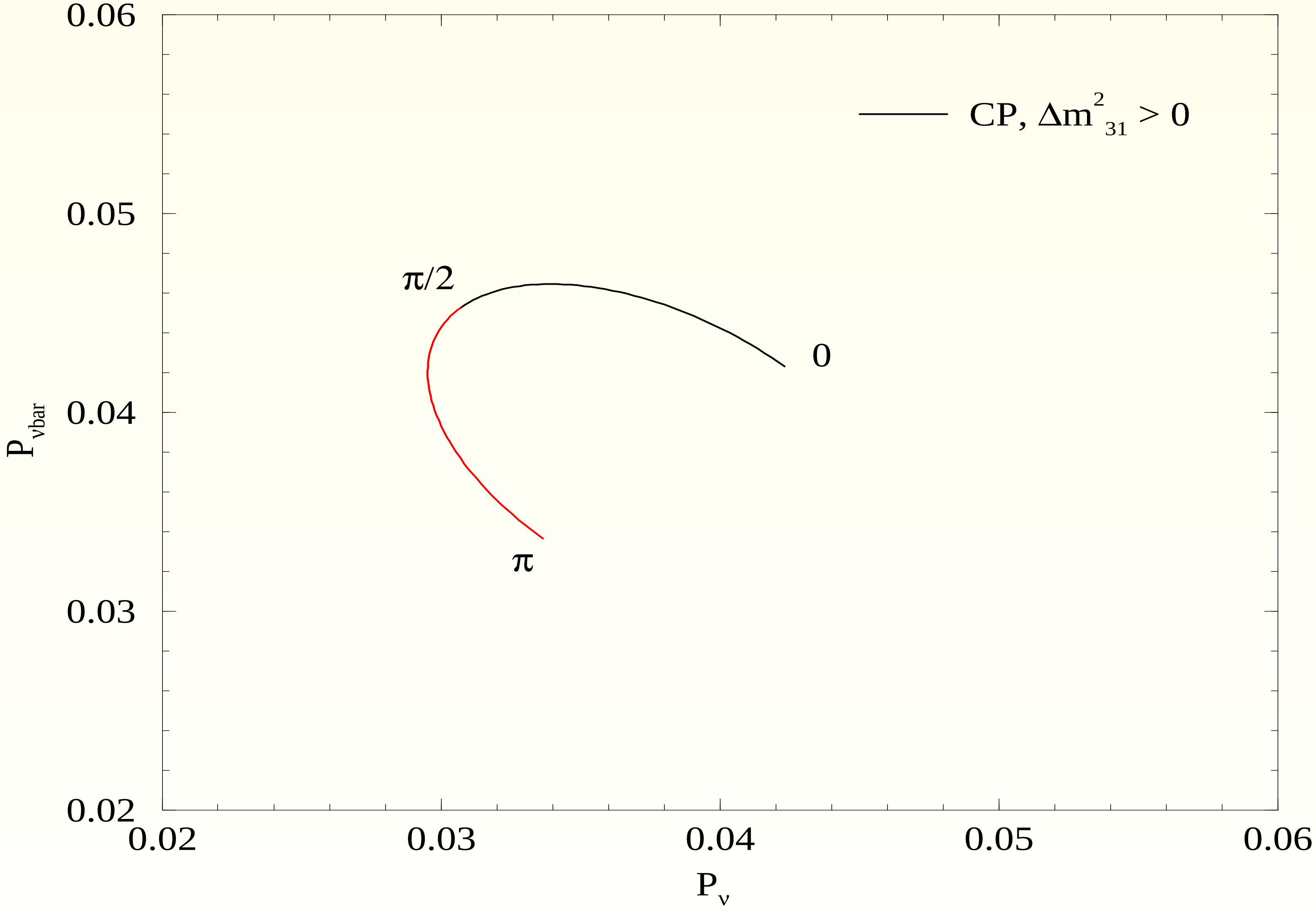

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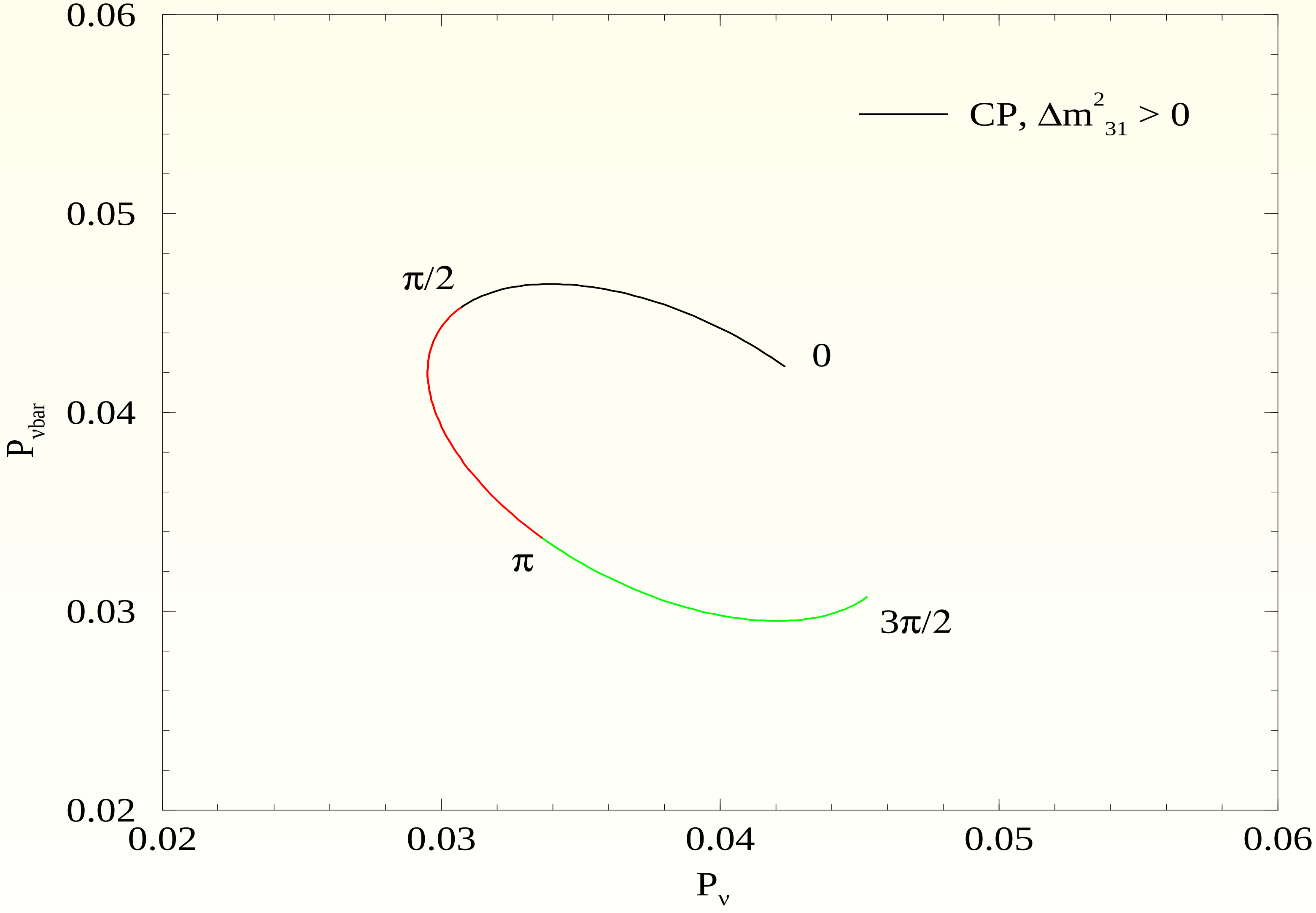

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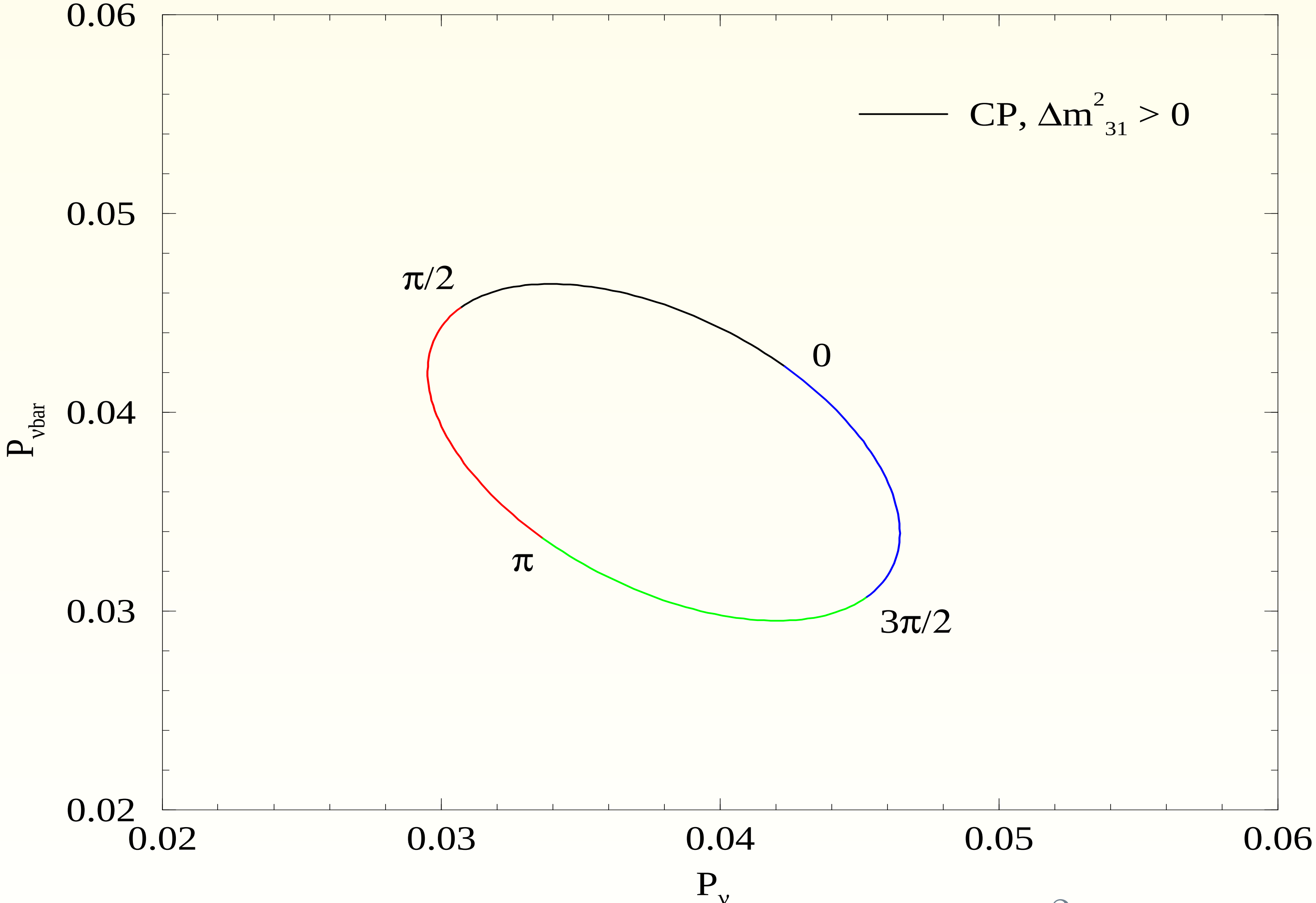

- The ellipse moves anticlockwise for $\Delta m^2_{31} > 0$.
- You can check that it goes clockwise for $\Delta m^2_{31} < 0$.

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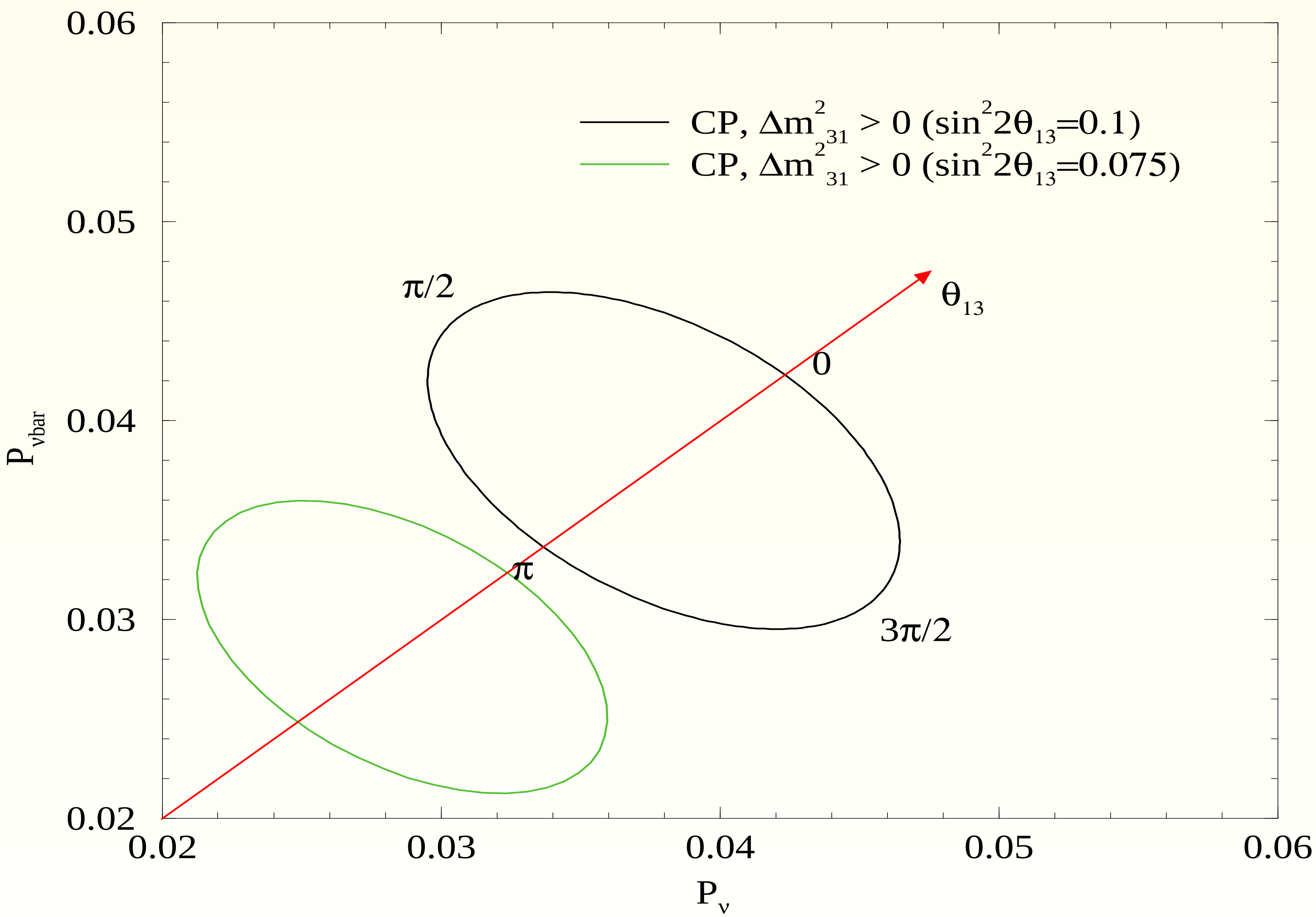

- Smaller $\theta_{13} \Rightarrow \delta_{CP}$ measurement more difficult .

Degeneracies

$Sgn(\Delta m^2_{31})$ Degeneracy

-

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- Do the simultaneous transformation

$$\delta_{CP} \to \pi - \delta_{CP}$$
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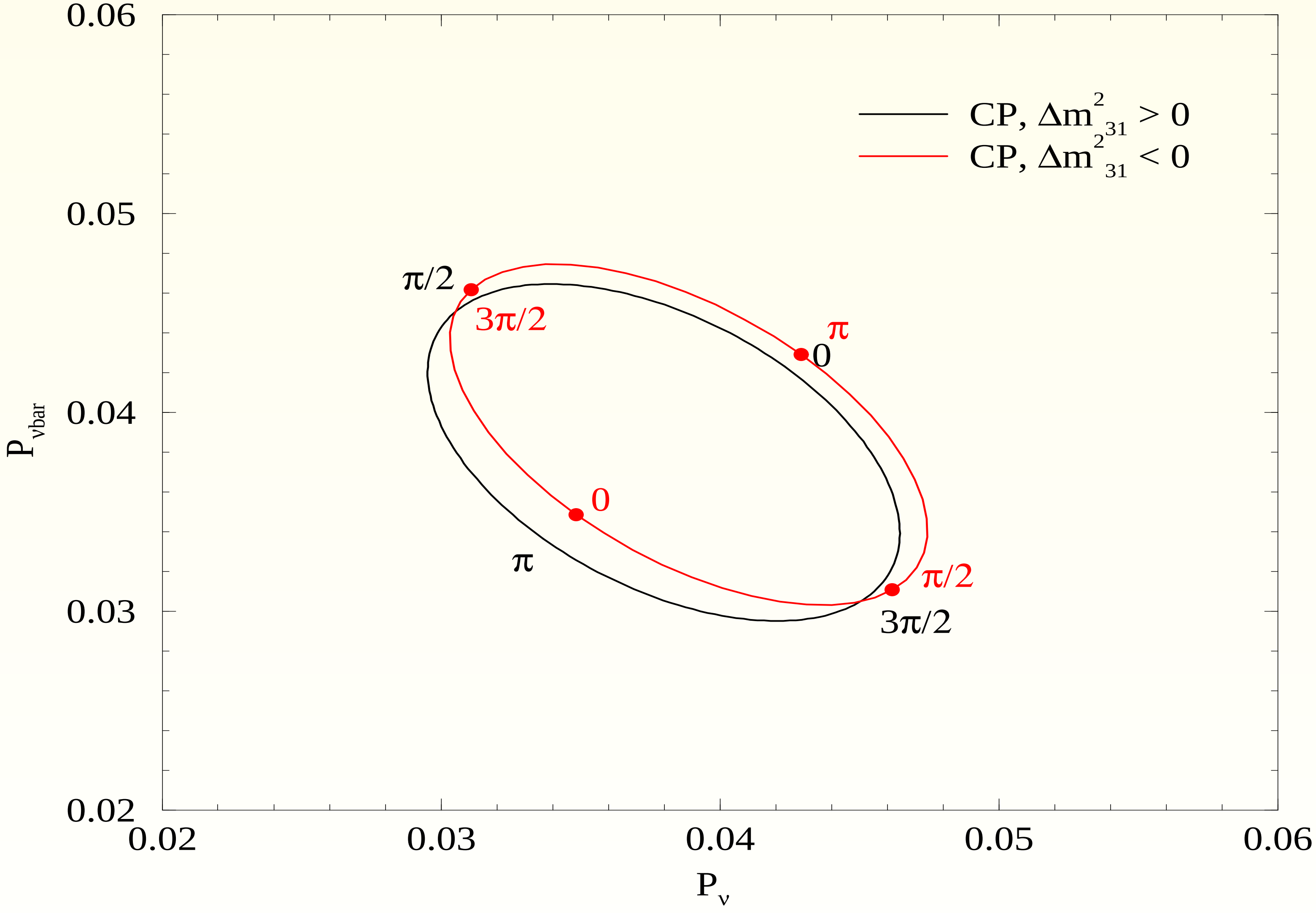
- The expression for $P_{appearance}$ remains invariant
- Since $Sgn(\Delta m^2_{31})$ is unknown, there will always be an ambiguity in the measured value of δ_{CP}

$Sgn(\Delta m^2_{31})$ Degeneracy



Octant of θ_{23} Degeneracy

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- For every non-maximal $\sin^2 2\theta_{23}$, there are 2 possible $\sin^2\theta_{23}$

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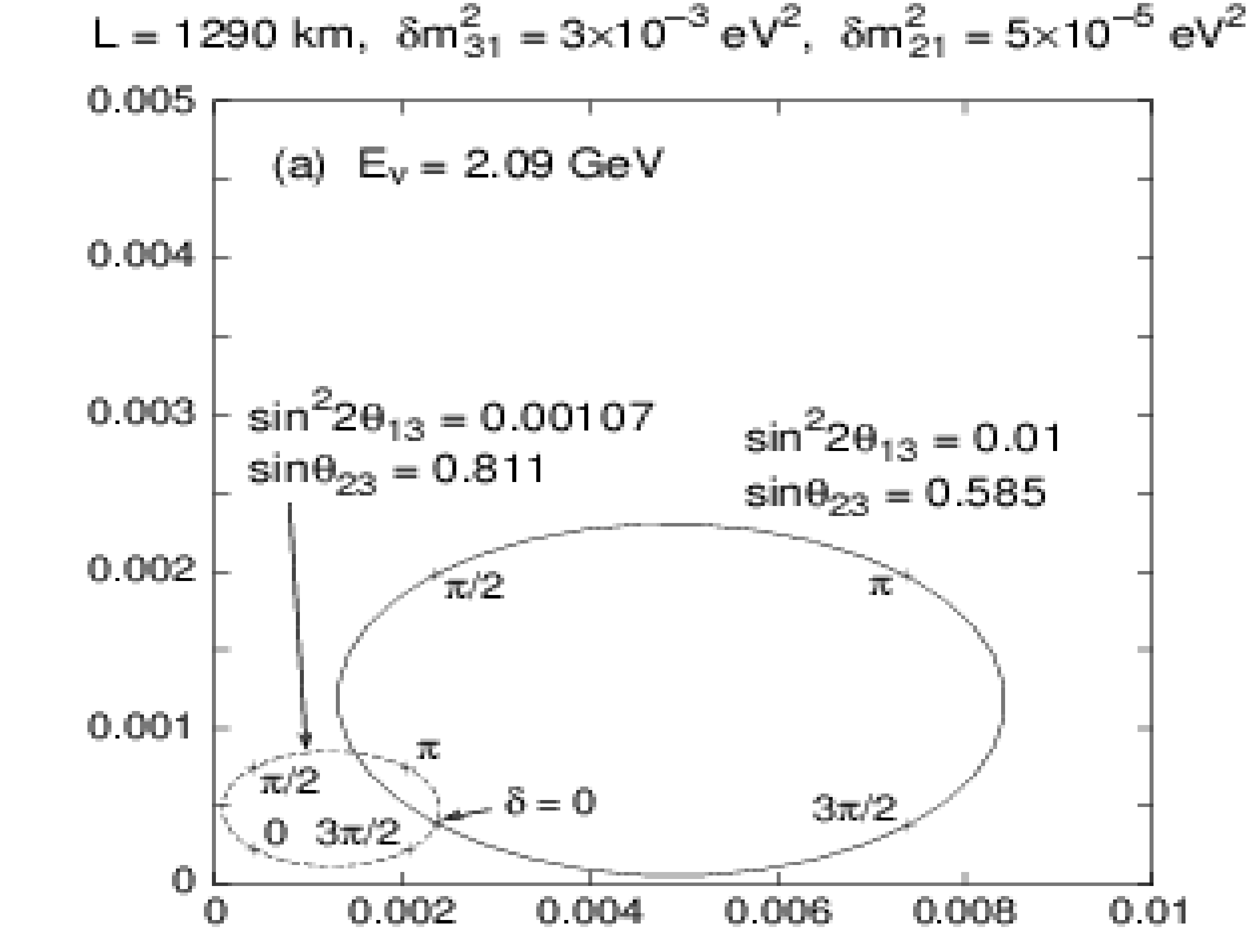
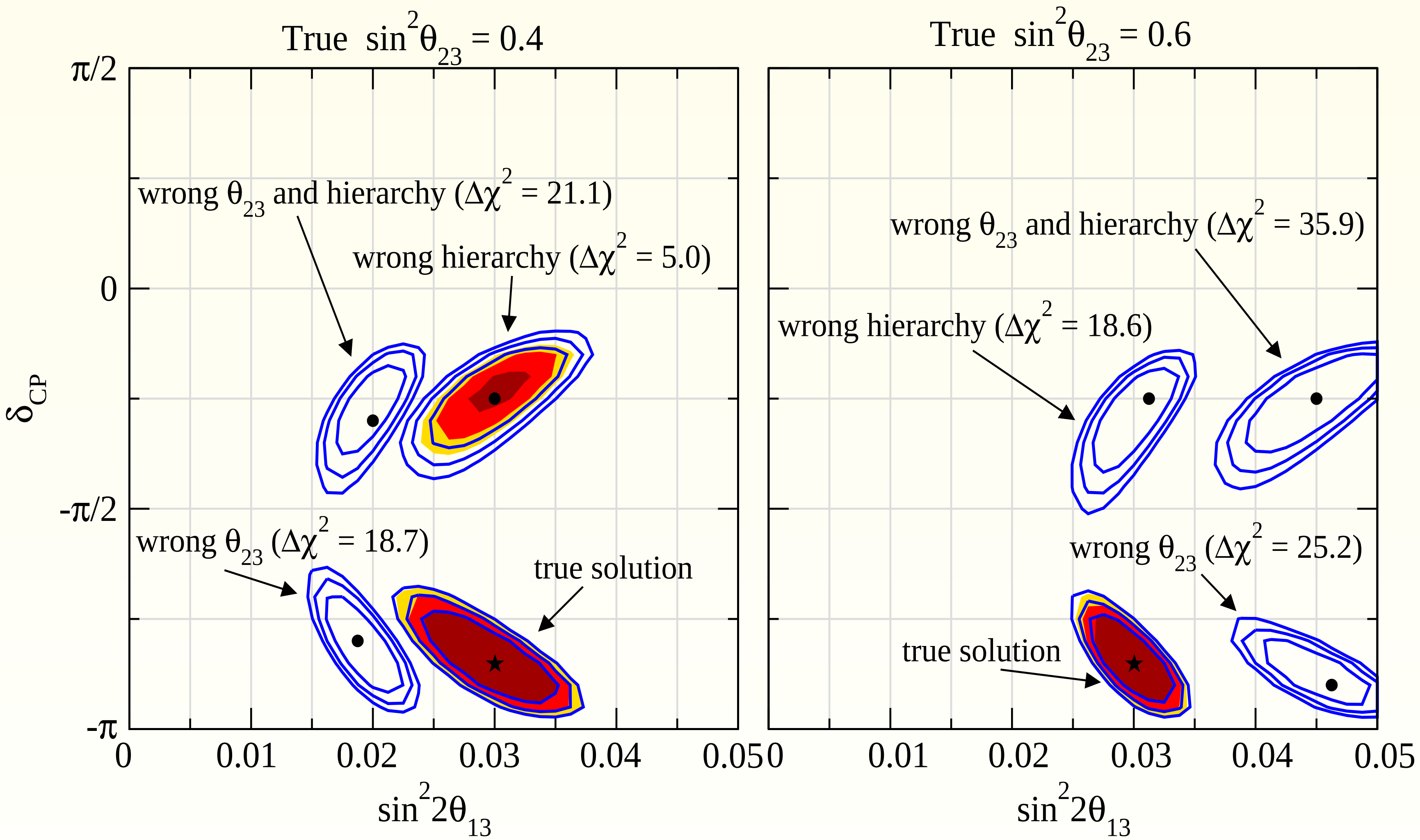
- We only have measurement on $\sin^2 2\theta_{23}$.
- For every non-maximal $\sin^2 2\theta_{23}$, there are 2 possible $\sin^2\theta_{23}$
- This will give 2 disjoint fitted value for θ_{13}.

Octant of θ_{23} Degeneracy



Barger et al, hep-ph/0112119

- If $\sin^2 2\theta_{23} = 0.9$ then both $\sin^2 2\theta_{13} = 0.01$ and 0.0011 would fit the data from a given LBL expt.



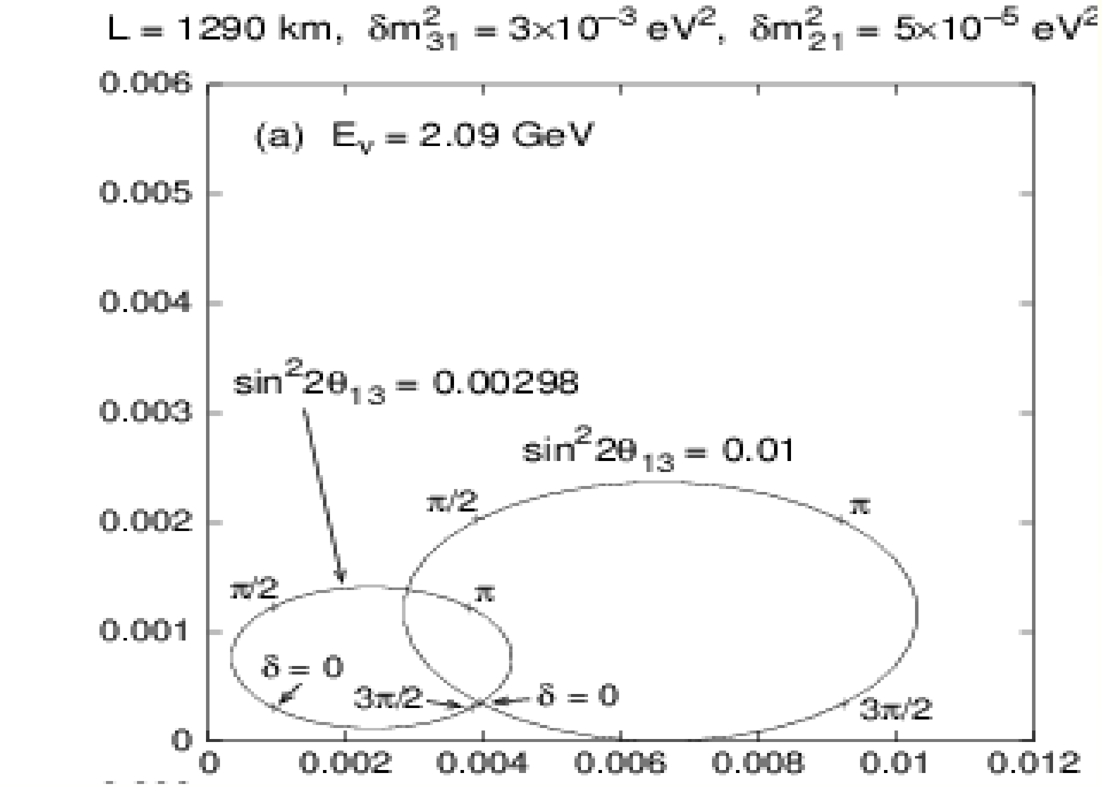
Huber et al, hep-ph/0501037

Intrinsic $(\delta_{CP}, \theta_{13})$ Degeneracy

- For a fixed value of E, it might happen that

$$P_{app}(\theta_{13}, \delta_{CP}) = P_{app}(\theta'_{13}, \delta'_{CP})$$
$$\bar{P}_{app}(\theta_{13}, \delta_{CP}) = \bar{P}_{app}(\theta'_{13}, \delta'_{CP})$$

- $(\theta_{13}, \delta_{CP})$ (true solution) & $(\theta'_{13}, \delta'_{CP})$ (fake solution)



Up to Eight-Fold Degeneracy Expected

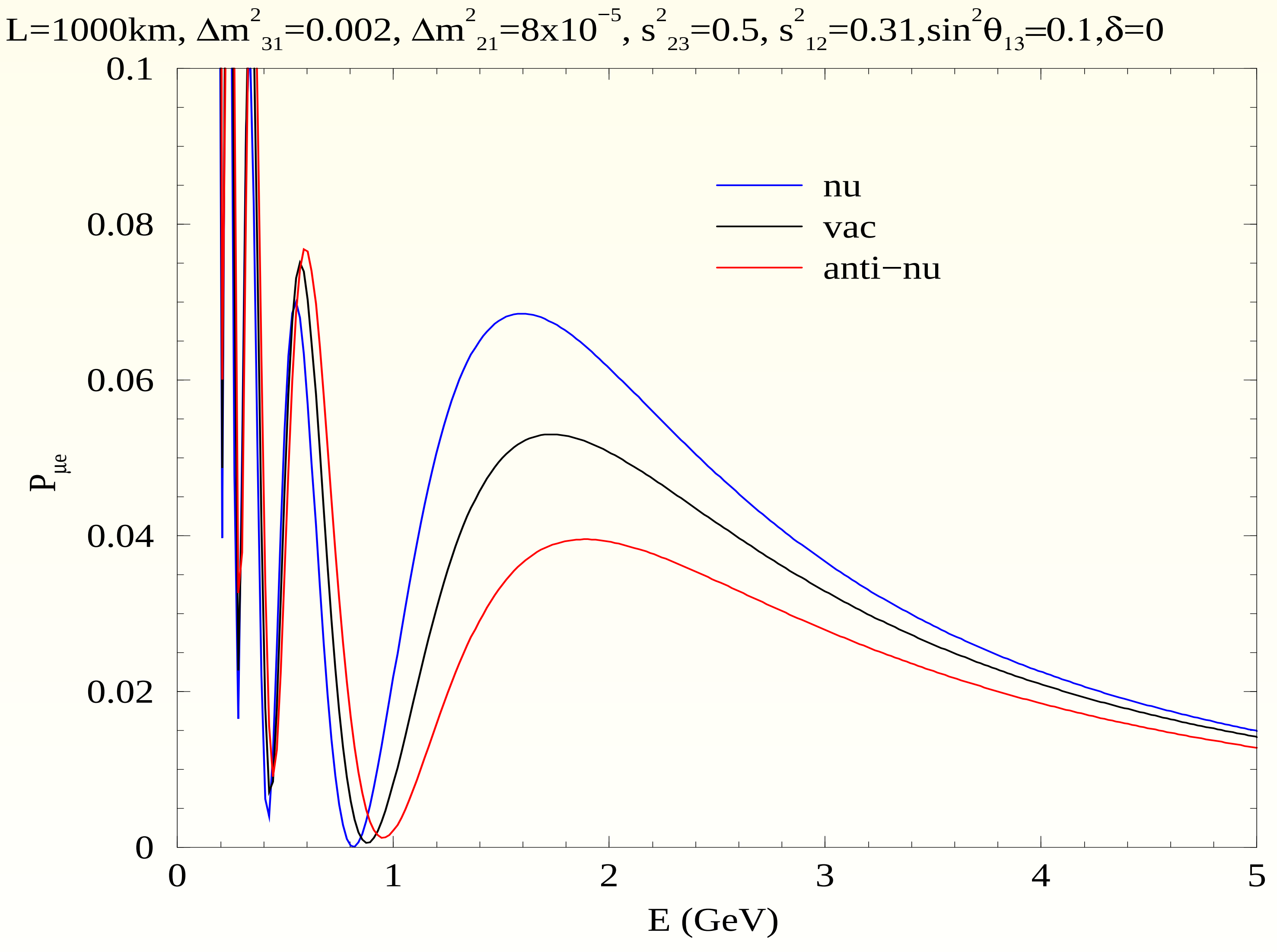
The $\nu_e \rightarrow \nu_\mu$ Channel in Matter

The $\nu_e \to \nu_\mu$ Channel in Matter

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

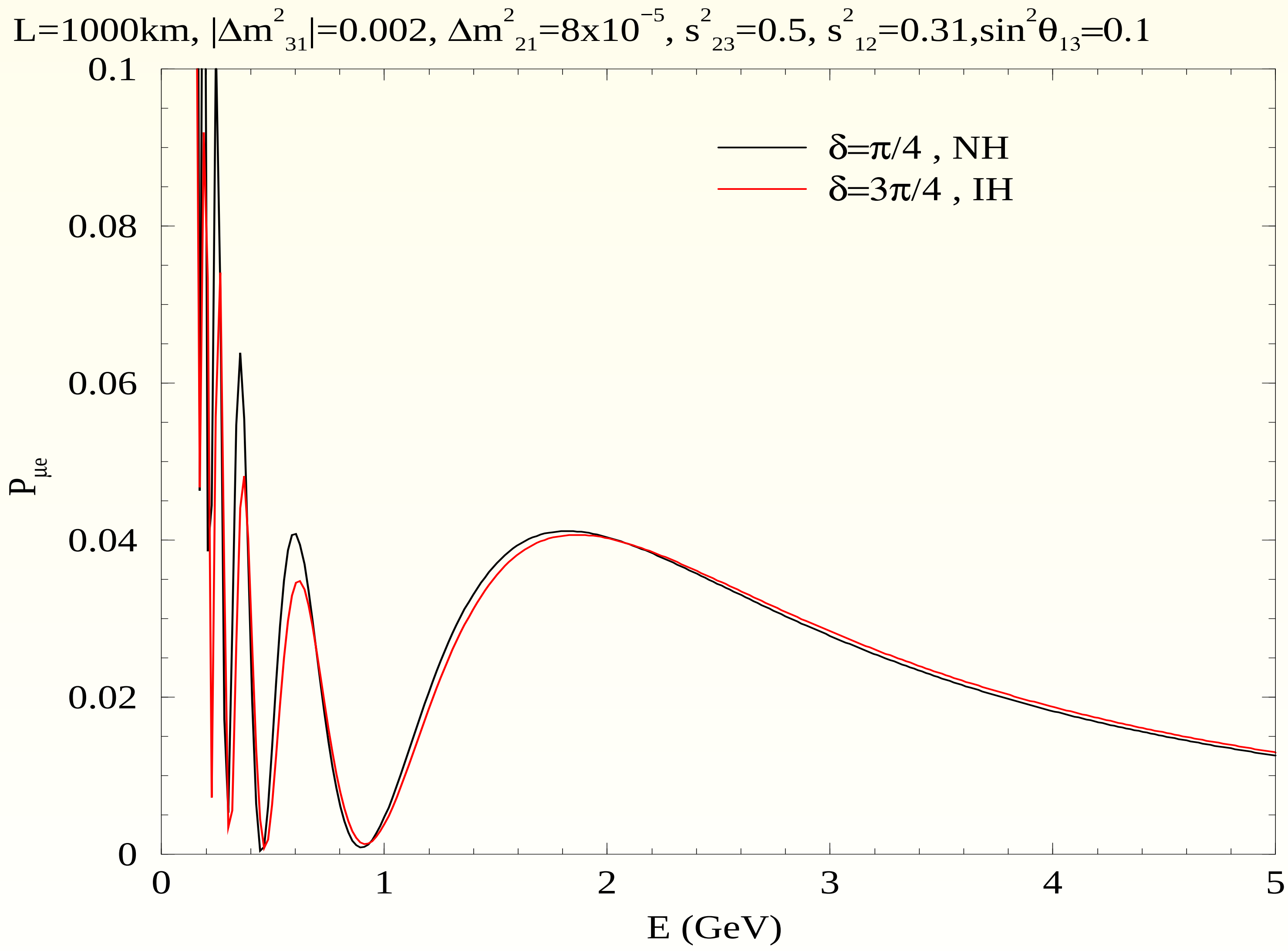
- $\hat{A} = \frac{\pm A}{\Delta m^2_{31}}$
- A is positive for neutrinos
- A is negative for antineutrinos

The $\nu_e \rightarrow \nu_\mu$ Channel in Matter



Resolving the Eight-Fold Degeneracy

Resolving the $Sgn(\Delta m^2_{31})$ Degeneracy



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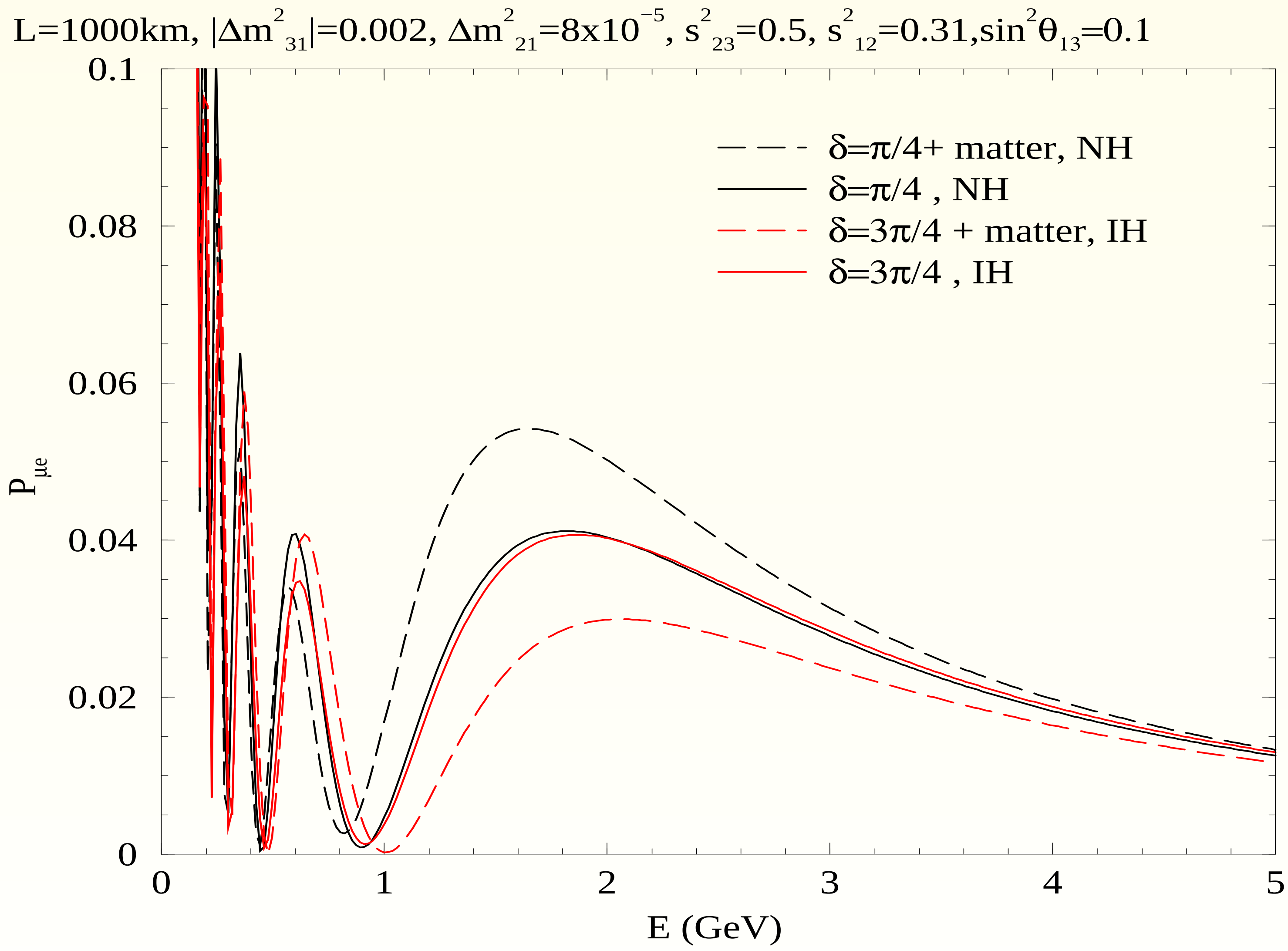

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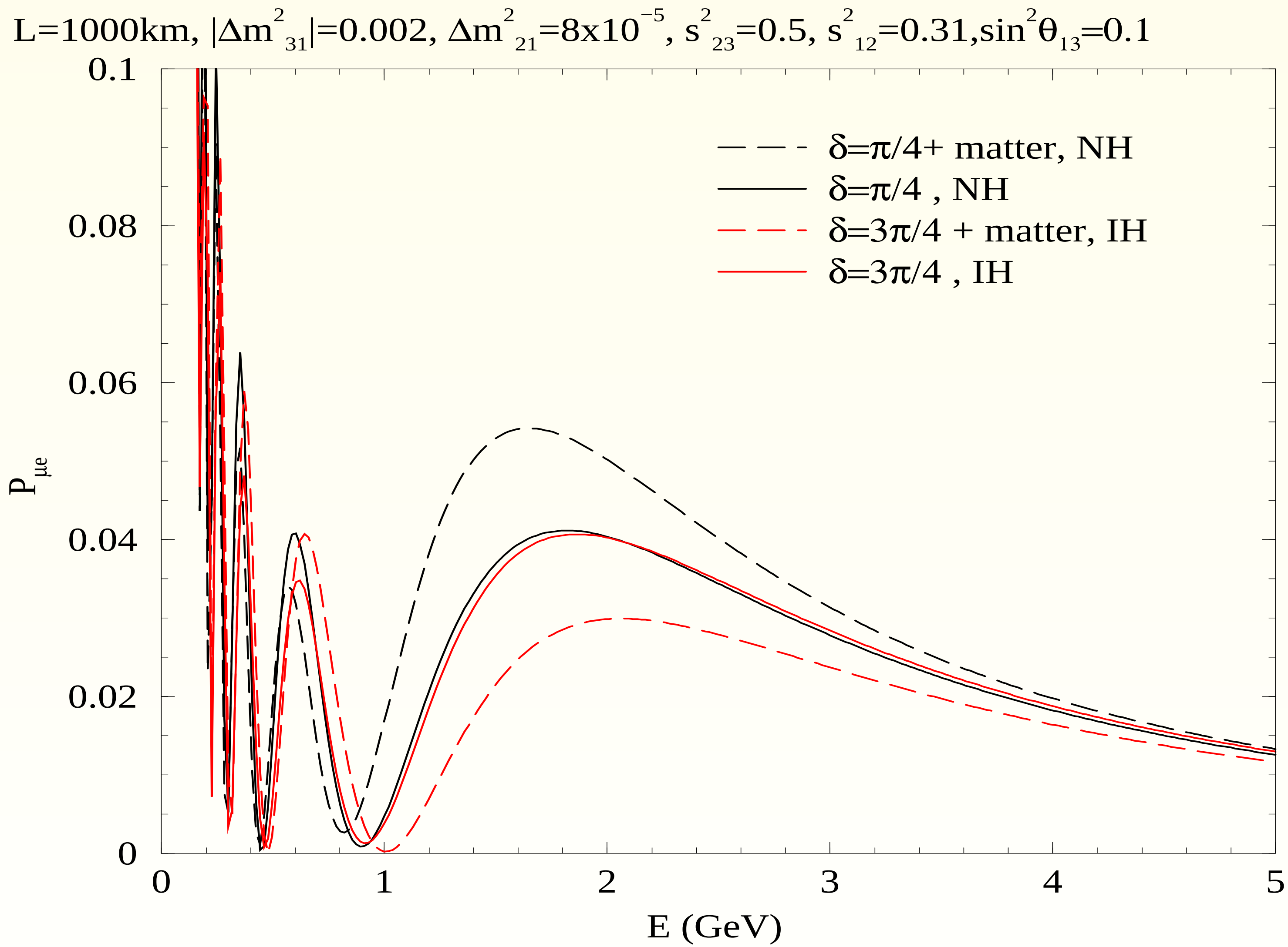

- Matter effects break the $Sgn(\Delta m^2_{31})$ Degeneracy

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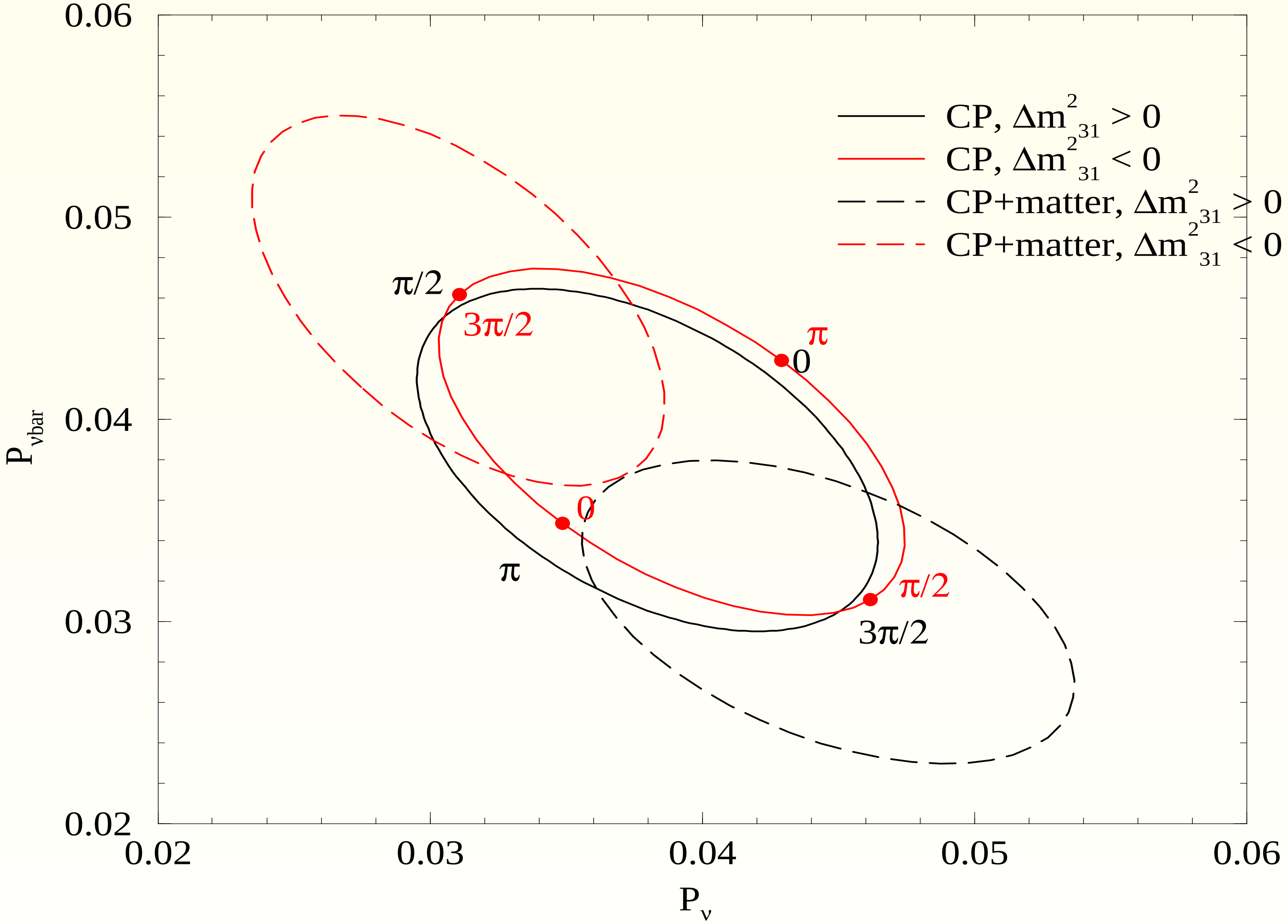
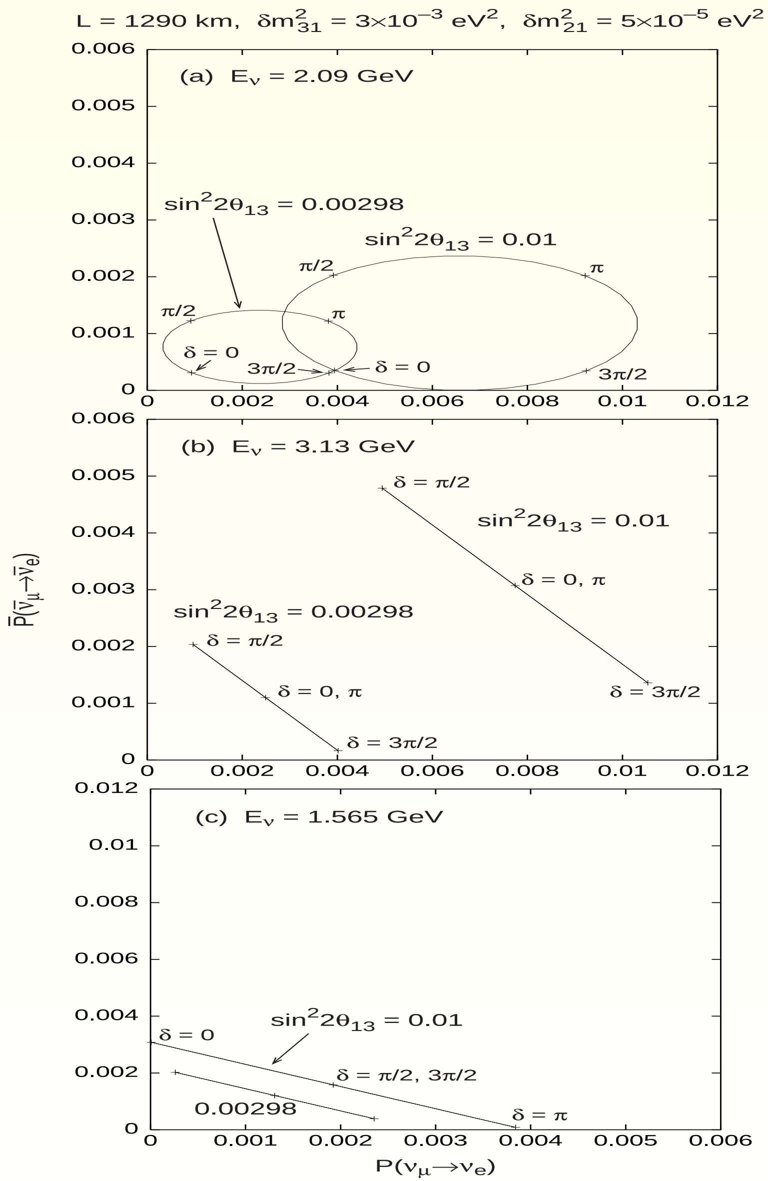


- Matter effects break the $Sgn(\Delta m^2_{31})$ Degeneracy

Resolving the Intrinsic $(\delta_{CP}, \theta_{13})$ Degeneracy



- Choose $\Delta = m\pi/2$.
- The $\cos\delta_{CP}$ term vanishes for $\Delta = (n - \frac{1}{2})\pi$.
- The $\sin\delta_{CP}$ term vanishes for $\Delta = n\pi$.
- Ellipse collapse to a line
- Ambiguity resolved.
- Better to work with $\Delta = (n - \frac{1}{2})\pi$.
- That is where we will directly see CPV.
- Thats where we get the oscillation maxima.

Barger et al, hep-ph/0112119

Resolving the Octant of θ_{23} Degeneracy

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- Using atmospheric neutrino data in
  - √ Megaton water detectors:
    - ⋆ Δm^2_{21} driven osc effects in sub-GeV electrons
    - ⋆ θ_{13} driven matter effects in multi-GeV electrons
  - √ Large magnetized iron detectors:
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- Using data from next generation reactor neutrinos

- Other ways using LBL expts have been suggested.

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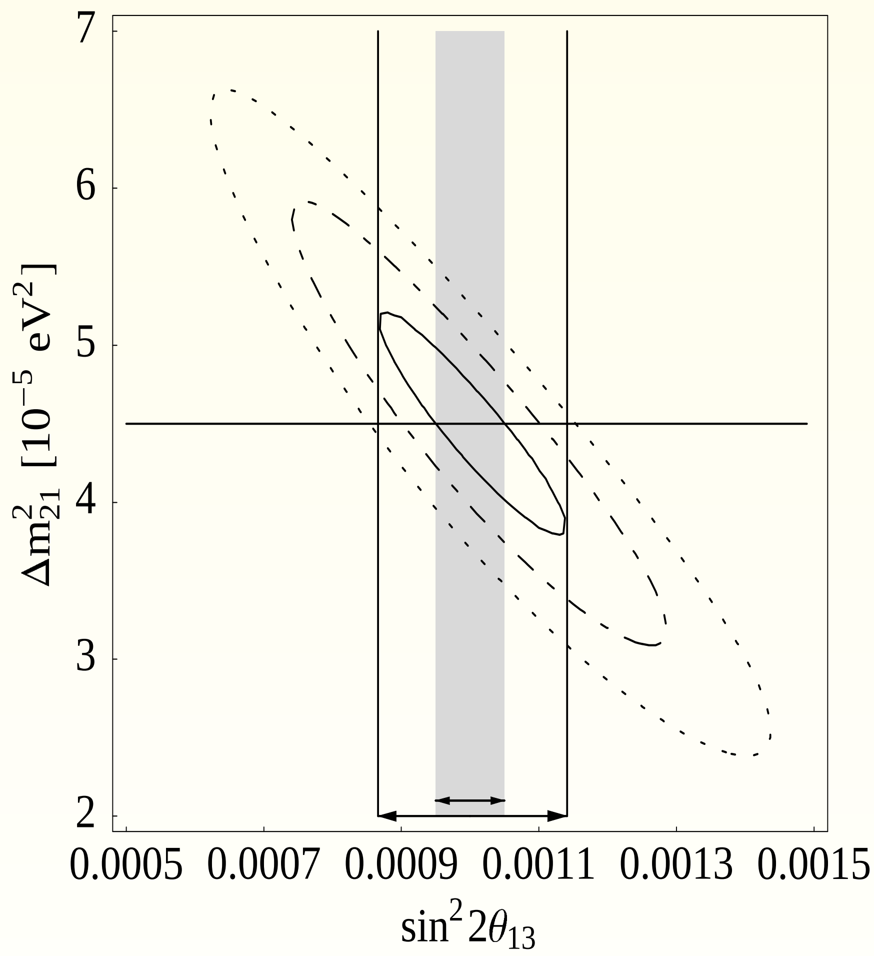
- This correlation between parameters leads to increase in the error in the measured value of the individual parameters.

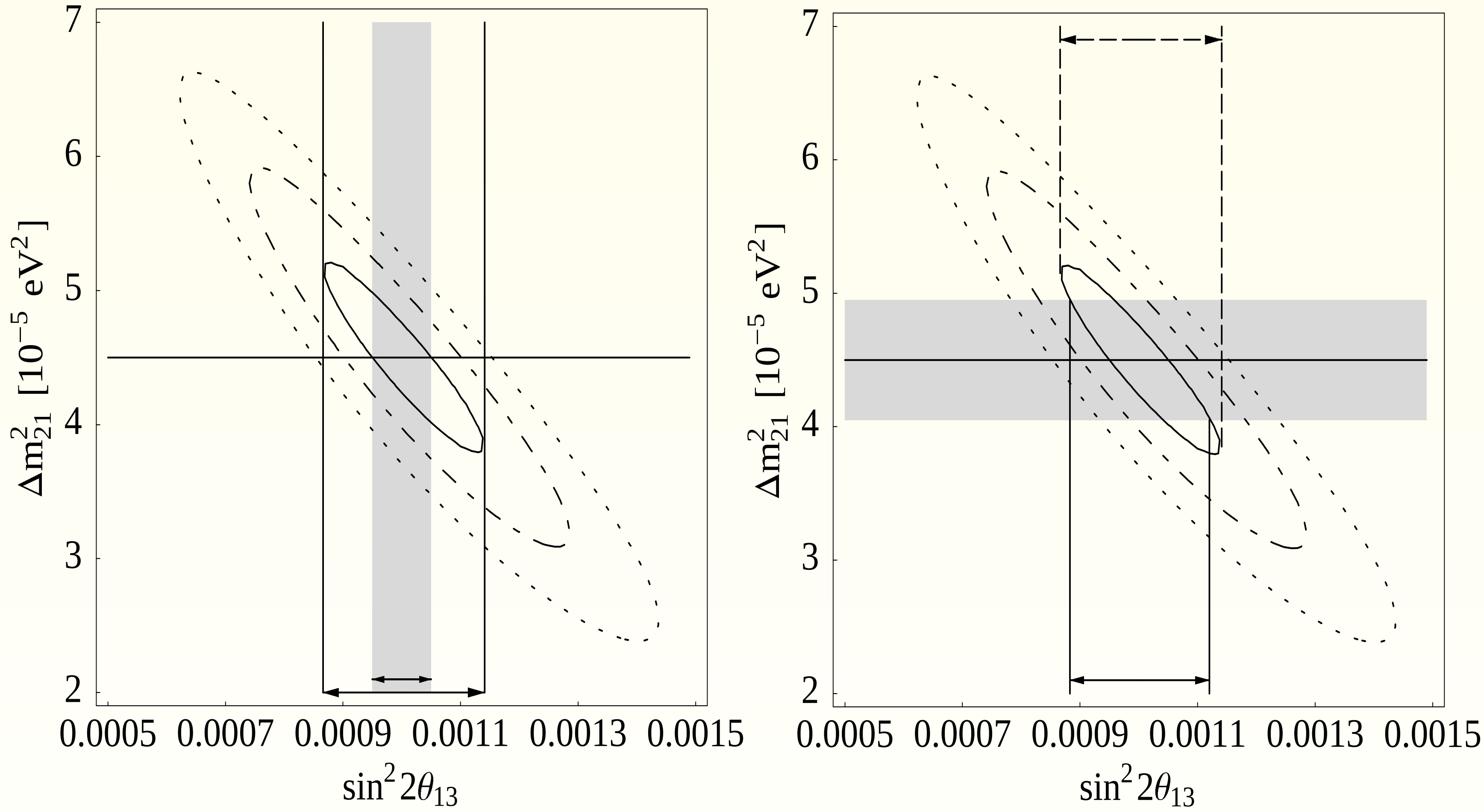
Correlations



Huber et al, hep-ph/0204352

- Note how correlations are increasing the spread.

Correlations



- Input from an external measurement helps.

Huber et al, hep-ph/0204352

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Differentiating Correlations and Degeneracies

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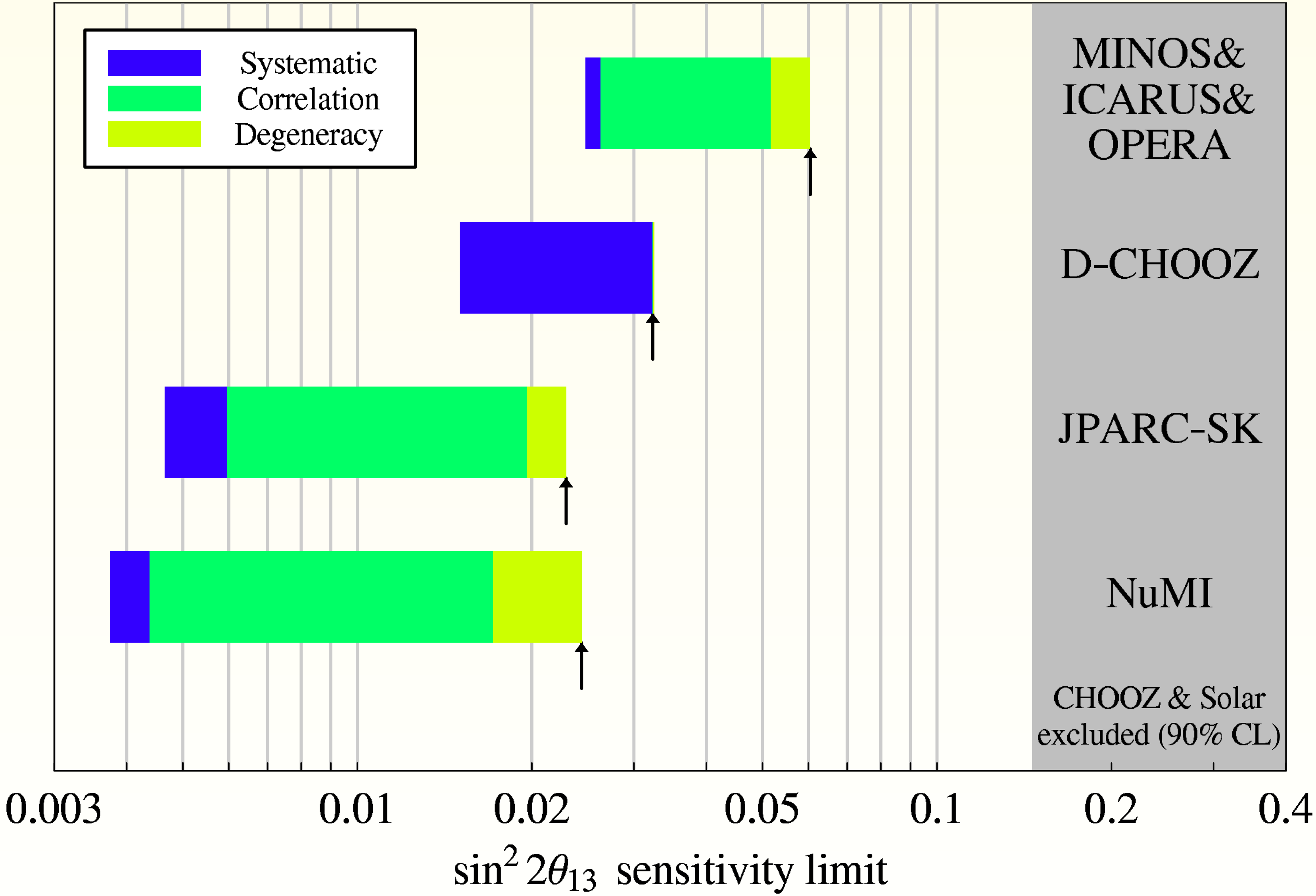
- We discussed some ways to tackle degeneracies.

- The only way to reduce impact of correlations is to combine experiments with different characteristics.

Sensitivity of Near-Future Experiments to θ_{13}



Huber *et al.*, hep-ph/0403068

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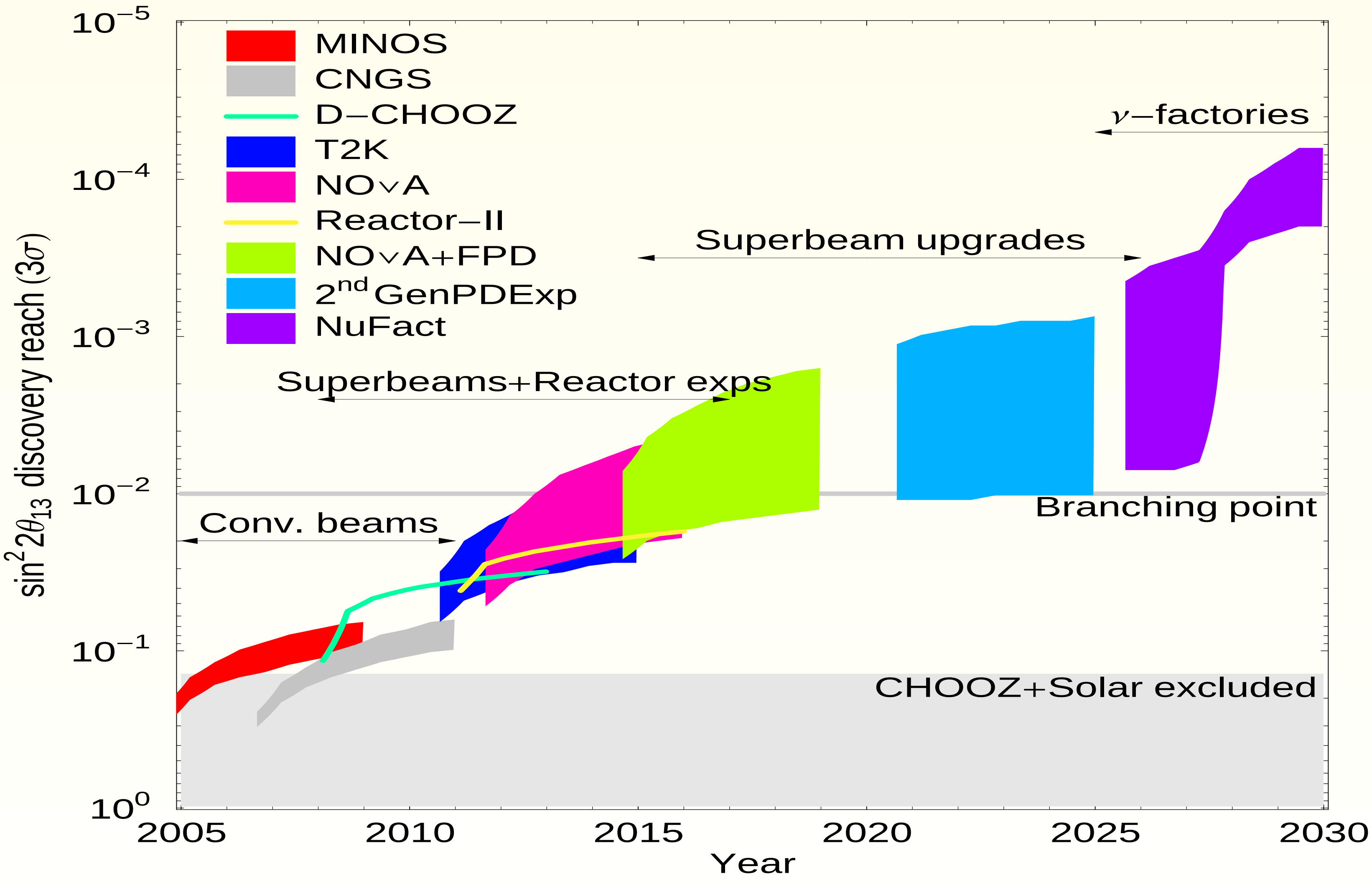

Albrow *et al.*, hep-ex/0509019

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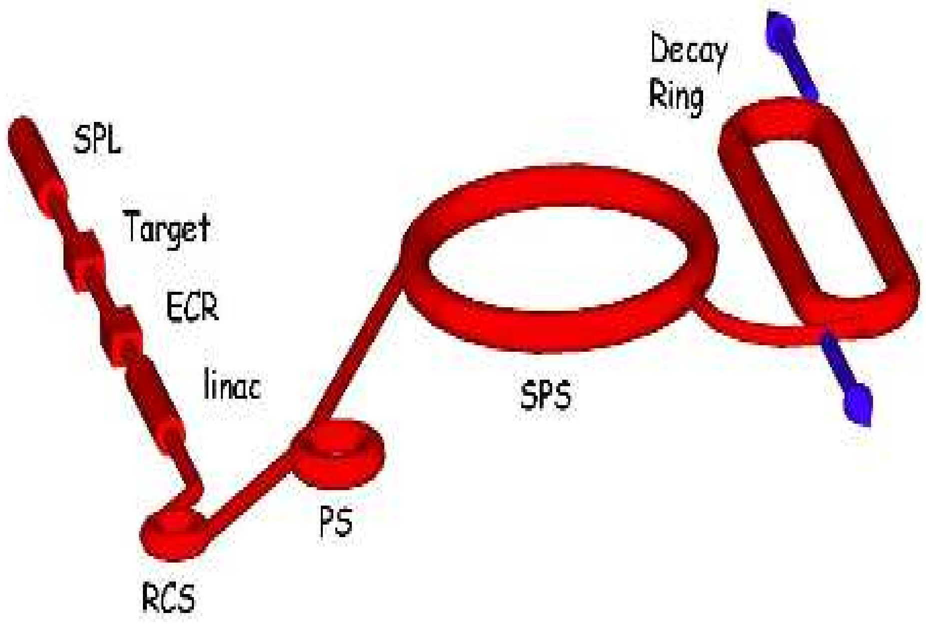
- Neutrino Factory $\Rightarrow P_{e\mu}$

BetaBeams

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

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



- Proton Driver –
  SPL (≈ 4 GeV)
- Target
- Ion Source –
  Pulsed ECR
- Accelerators –
  linac,RCS,PS,SPS
- Storage Ring –
  7000m; 2500m straight

Zucchelli, PLB 532, 166, (2002)

BetaBeams

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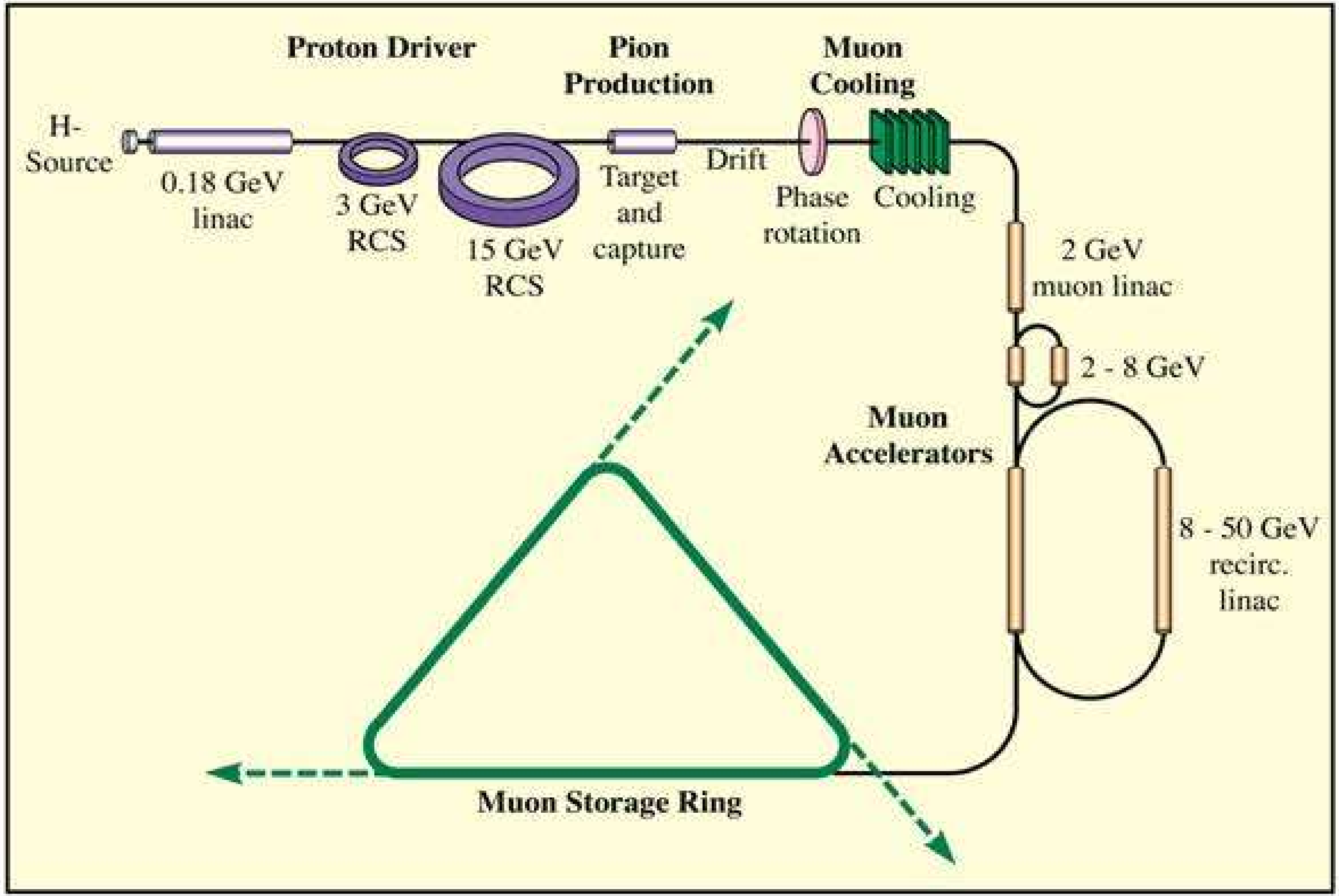
- Beam divergence given by γ: higher boost gives higher collimation
- Can produce either ν_e OR $\bar{\nu}_e$ FLUX

Neutrino Factory



Neutrino Factory at RAL

Neutrino Factory

- Produced be decay of accelerated muons circulating in a storage ring:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \text{ and/or } \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

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- Pure, Intense, Collimated, Known beam
- For a given muon sign in the ring, we will have muons of of both signs in the detector. For a μ^+ source $\bar{\nu}_\mu$ in the original beam will given rise to μ^+ in the detector (right sign muons), while $\nu_e \to \nu_\mu$ oscillations will give μ^- (wrong sign muons).

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- Charge ID is a MUST.
- Need magnetised detectors

Sensitivity of Far-Future LBL Experiments

- SuperBeam $\Rightarrow P_{\mu e}$
- Beta-Beam $\Rightarrow P_{e\mu}$
- Neutrino Factory $\Rightarrow P_{e\mu}$
- One has to find ways to kill the clone solutions
- Various ways have been suggested in the literature for this

Killing the Clones

- Combining data from appearance experiments at different L and/or different E:

Barger, Marfatia, Whisnant, hep-ph/0206038
Barger, Marfatia, Whisnant, hep-ph/0210428
Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258
Huber, Lindner, Winter, hep-ph/0211300
Mena and Parke hep-ph/0408070
Mena, Palomares-Ruiz, Pascoli, hep-ph/0504015
Mena, Palomares-Ruiz, Pascoli, hep-ph/0510182
Mena, Nunokawa, Parke, hep-ph/0609011
Minakata, Nunokawa, hep-ph/9706281
Minakata, Nunokawa, Parke, hep-ph/0301210
Ishitsuka, Kajita, Minakata, Nunokawa, hep-ph/0504026
Hagiwara, Okamura, Senda, hep-ph/0607255

Killing the Clones

- Combining data from different channels:

The Silver Channel $P_{e\tau}$

Autiero *et al.*, hep-ph/0305185

Donini, Meloni, Migliozzi, hep-ph/0206034

Disappearance Channel $P_{\mu\mu}$

Donini, Fernandez-Martinez, Meloni, Rigolin, hep-ph/0512038

Donini, Fernandez-Martinez, Rigolin,hep-ph/0411402

The Platinum Channel $P_{\mu e}$

Killing the Clones

- Combining LBL data with data from other experiments:

Adding reactor antineutrino data

Huber, Lindner, Schwetz, Winter, hep-ph/0303232

Adding atmospheric neutrino data

Huber, Maltoni, Schwetz, hep-ph/0501037

Campagne, Maltoni, Mezzetto, Schwetz, hep-ph/0603172

Killing the Clones at The Magic Baseline

The Magic baseline

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

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

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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

Near-Resonant Matter Effects

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- Large Distance $\Rightarrow$ Large Matter effects

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- For $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} = 0.1$ and the PREM profile $\rho_{av} = 4.13$ gm/cc, $E_{res} \simeq 7.5$ GeV

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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 et al, hep-ph/0408361

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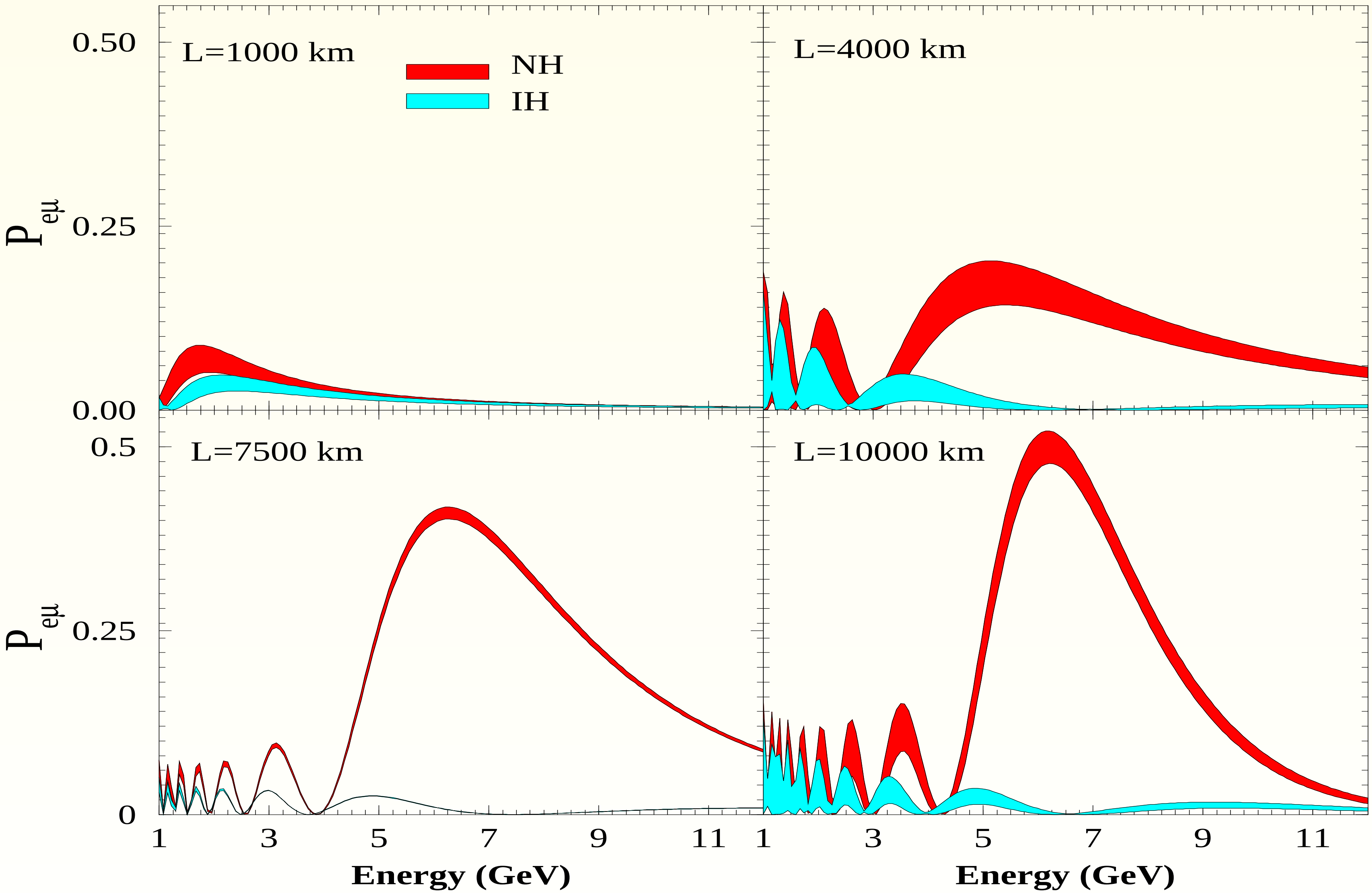
Gandhi et al, hep-ph/0408361

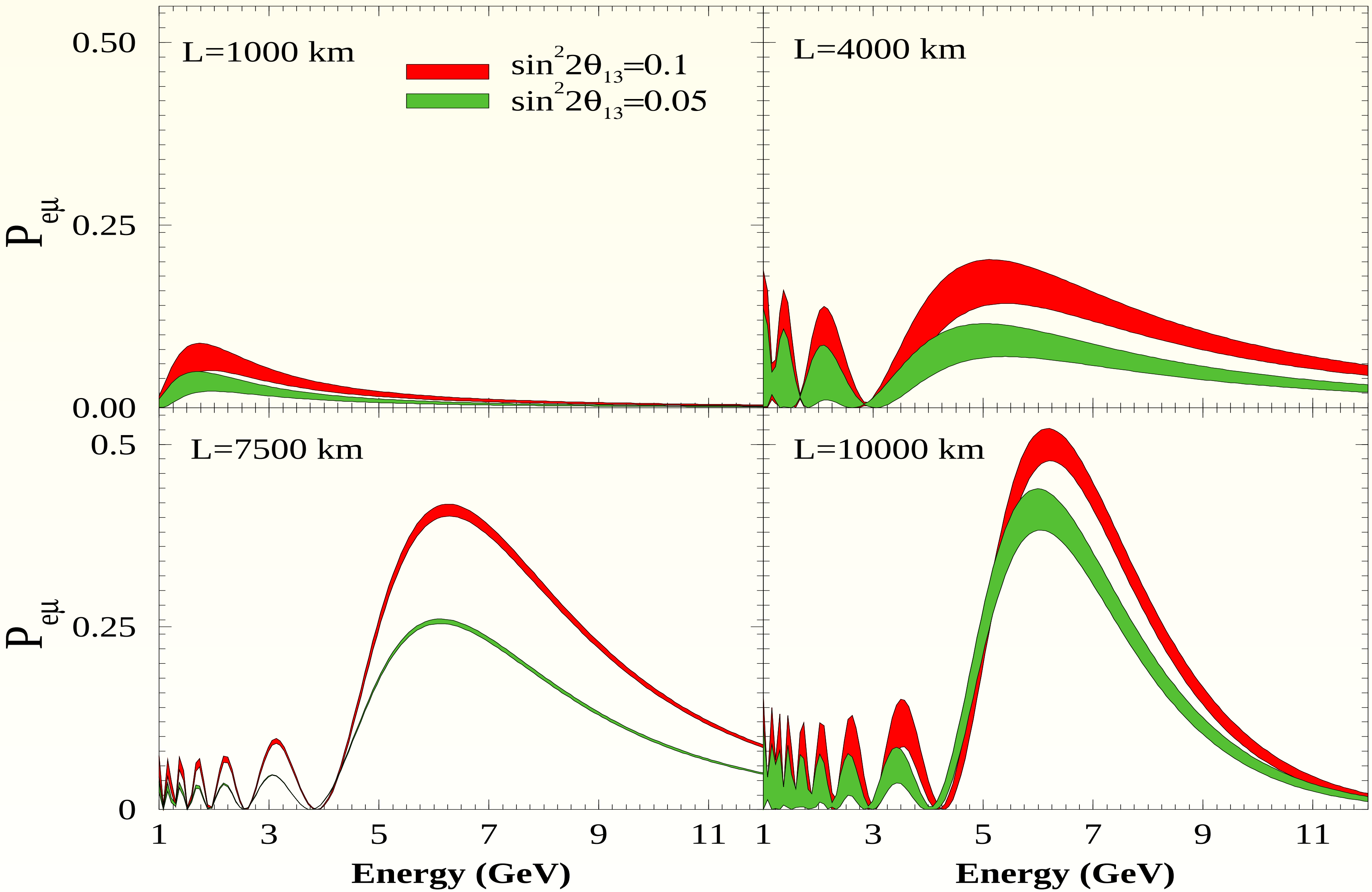
- At the magic baseline, largest oscillations come when $E \simeq 6$ GeV

The Probability



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

The Probability



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

Conclusions (Comparison of different setups)

	γ	L(km)	Detector	$T_\nu/T_{\bar\nu}$	$\sin^2 2\theta_{13}$	$sgn(\Delta m^2_{31})$	Max CPV
NF@3000		3000	50 (MI)	4/4	2.5×10^{-3}	$(0.8-10)\times10^{-3}$	7×10^{-5}
NF@7500		7500	50 (MI)	4/4	2×10^{-4}	2×10^{-4}	No sens
CERN-	350	7152	50 (MI)	10	2.1×10^{-3}	1.1×10^{-2}	No sens
INO	500	7152	50 (MI)	10	8.4×10^{-4}	8.5×10^{-3}	No sens
hep-ph/	100/100	130	440 (WC)	10/10	5×10^{-3} (W)	2.5×10^{-3}	2×10^{-4}
0603172					3×10^{-4} (B)	+SPL+ATM	
hep-ph/	200/200	520	500 (WC)	8/8	1.5×10^{-3}	$(0.7-2)\times10^{-2}$	2×10^{-4}
0506237	500/500	650	50 (TASD)	8/8	1.5×10^{-3}	$(0.6-4.5)\times10^{-2}$	1×10^{-4}
	1000/1000	1300	50 (TASD)	8/8	4×10^{-4}	$(1-7)\times10^{-3}$	7×10^{-5}
hep-ph/	100/60	130	400 (WC)	10(S)	Not	No Sens	1×10^{-3}
0312068	580/350	732	400 (WC)	10(S)	Given	2×10^{-2}	2×10^{-4}
	2500/1500	3000	40 (MI)	10(S)		4×10^{-3}	4×10^{-4}
hep-ph/	120/120	130	440 (WC)	10(S)	5×10^{-3}	Not	1×10^{-3}
0503021	150/150	300	440 (WC)	10(S)	6×10^{-4}	Given	2×10^{-4}
	350/350	730	440 (WC)	10(S)	4×10^{-4}		1×10^{-4}

Backup Slides

The CERN-INO Beta-Beam Experiment

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- Proposal to build a large iron detector (ICAL) at INO

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The CERN-INO Beta-Beam Experiment

- Proposal to build a large iron detector (ICAL) at INO
- A Beta-Beam facility might come up at CERN
- CERN-INO distance is equal to 7152 km
- This is tantalizingly close to the magic baseline

The CERN-INO Beta-Beam Experiment

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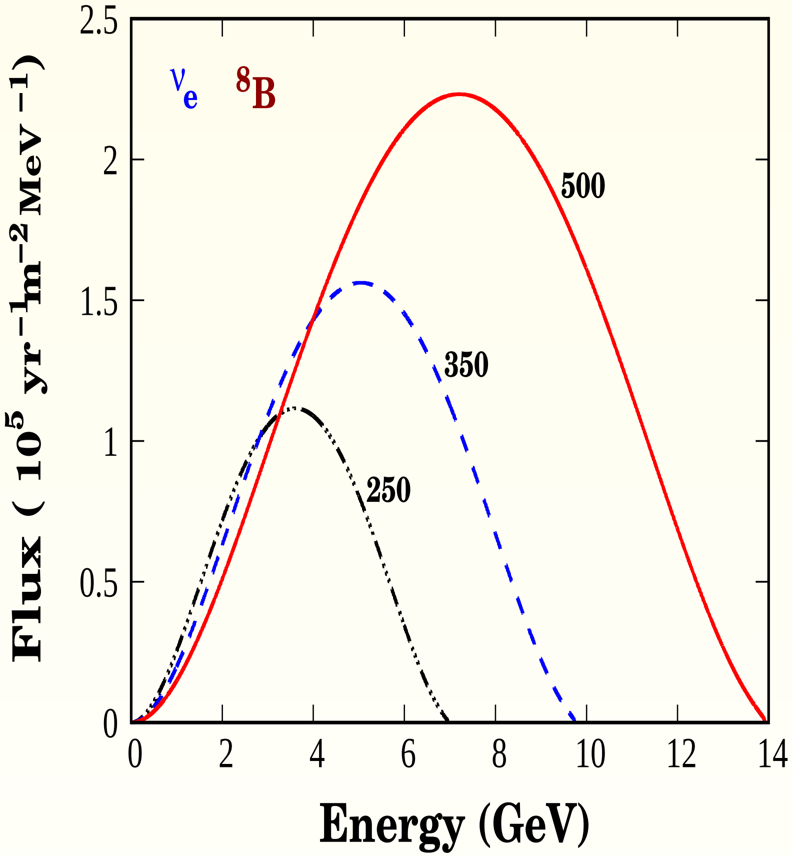
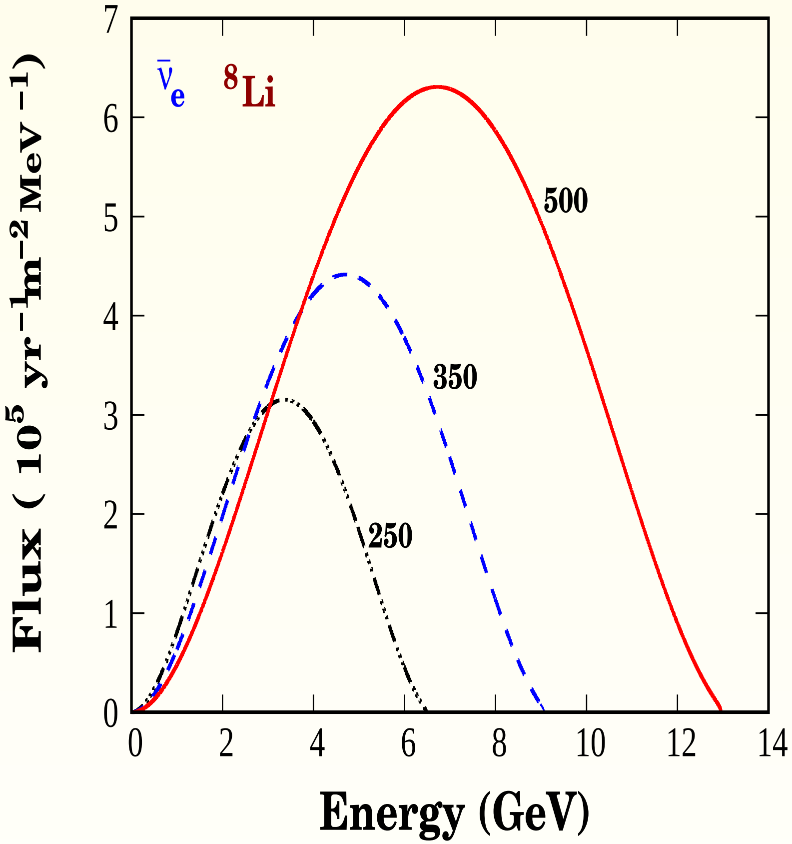
- Alternative ions ^{8}B and ^{8}Li have large end-point energy and hence "harder" spectra. Works!!

The CERN-INO Beta-Beam Experiment

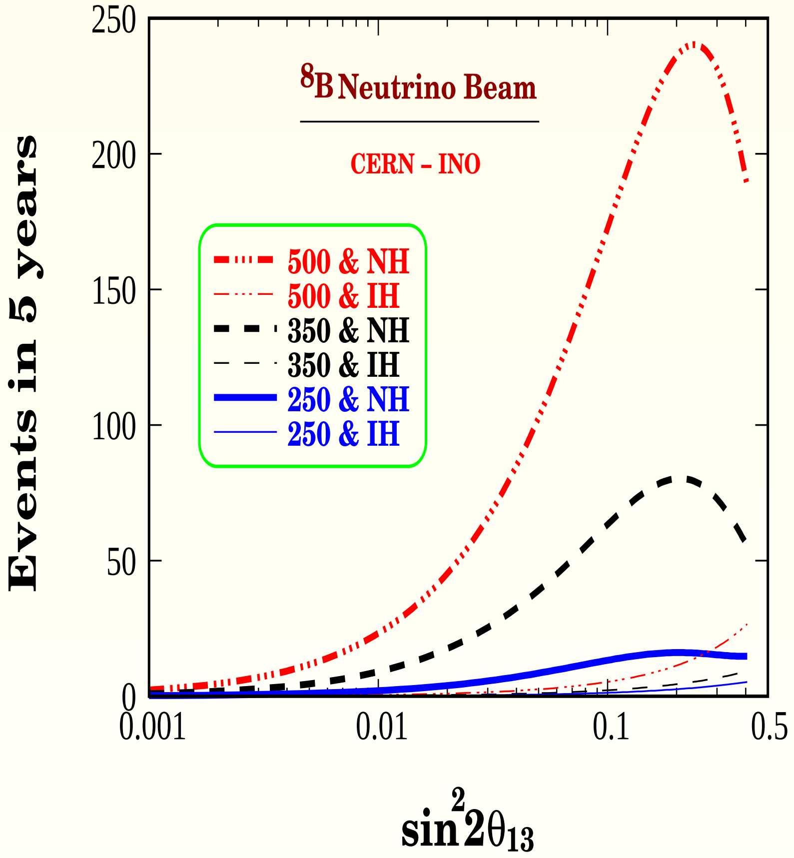


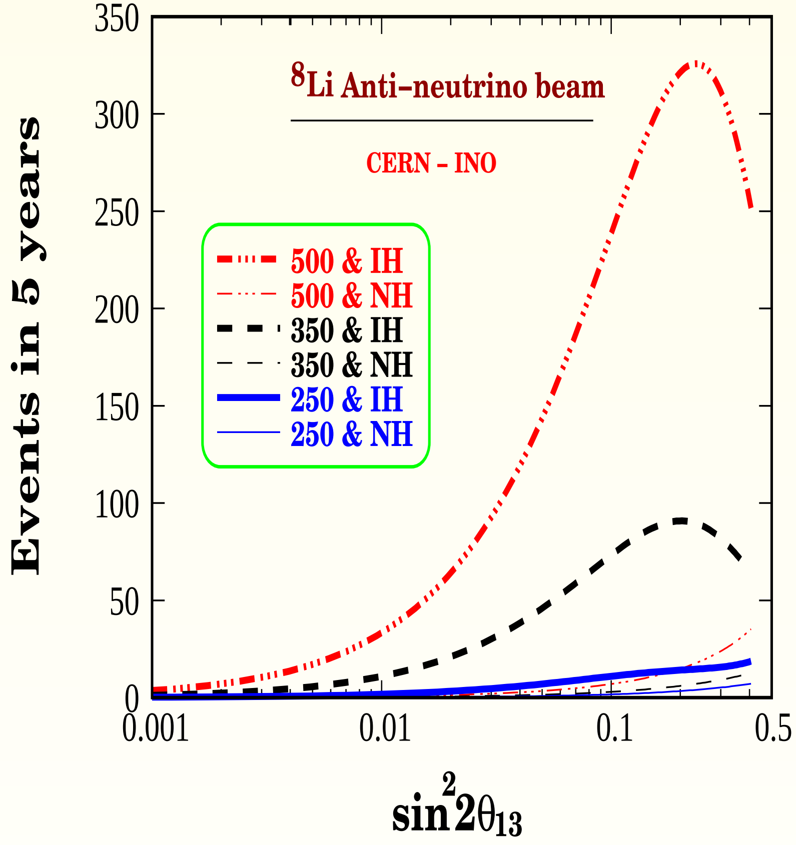


Agarwalla, SC, Raychaudhuri, hep-ph/0610333

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

The CERN-INO Beta-Beam Experiment



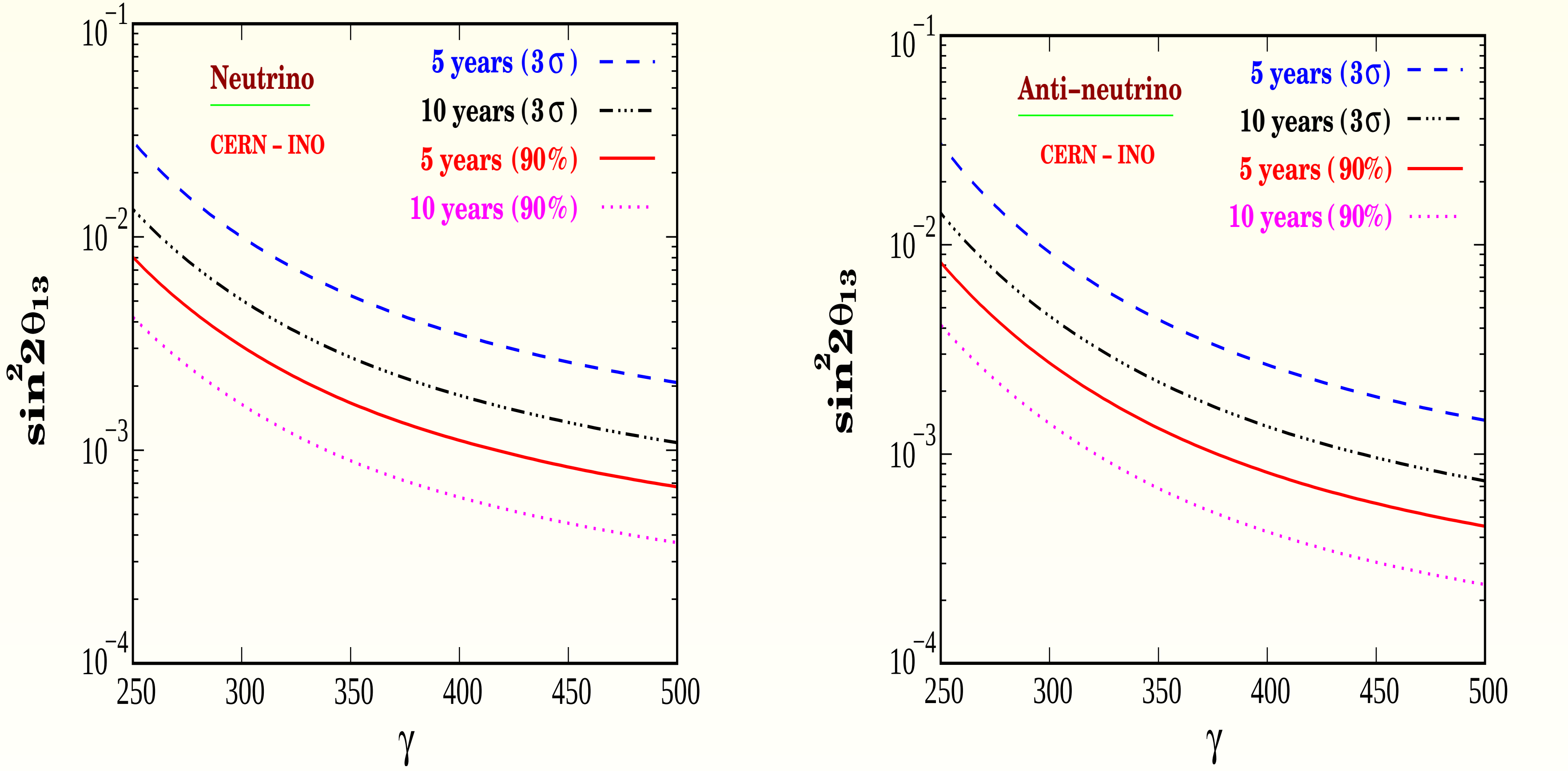


Agarwalla, SC, Raychaudhuri, hep-ph/0610333

- The rate shows a sharp dependence on the hierarchy and θ_{13}

The CERN-INO Beta-Beam Experiment

- Sensitivity to θ_{13}

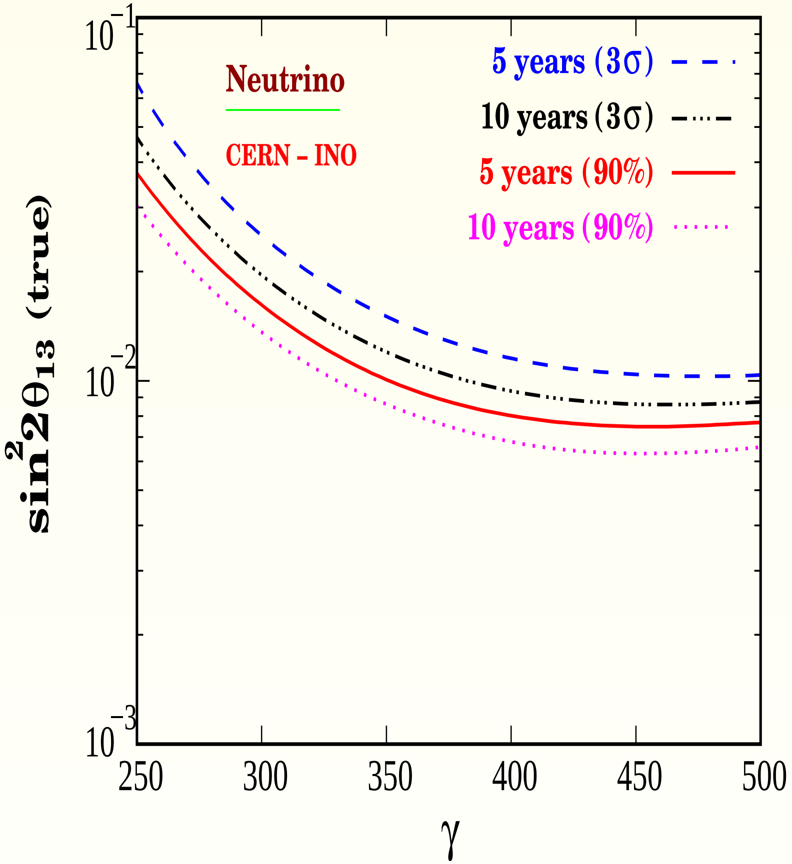


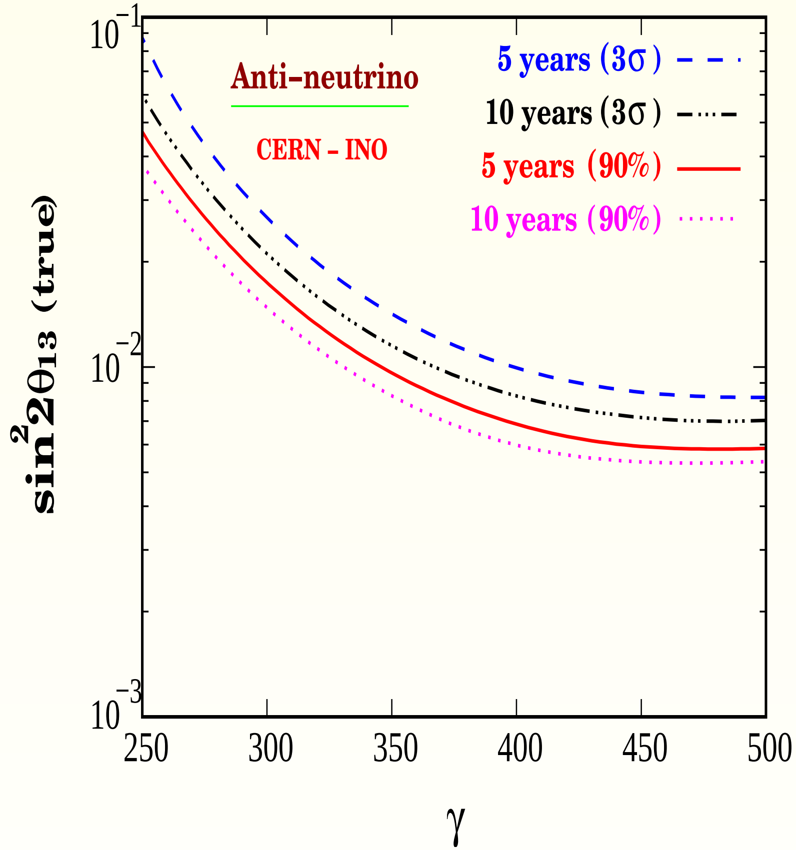
Agarwalla, SC, Raychaudhuri, hep-ph/0610333

- At 3σ, $\sin^2 2\theta_{13} < 8.5 \times 10^{-4}(1.5 \times 10^{-3})$ with 80% efficiency and 10(5) years data

The CERN-INO Beta-Beam Experiment

- Sensitivity to $sgn(\Delta m^2_{31})$





Agarwalla, SC, Raychaudhuri, hep-ph/0610333

- At 3σ, $\sin^2 2\theta_{13} < 8.5 \times 10^{-3} (9.8 \times 10^{-3})$ with 80% efficiency and 10(5) years data

Large Matter Effects in P_{ee}

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$$\lim_{\Delta m^2_{21} \to 0} P_{e\mu} = \sin^2\theta_{23} \sin^2 2\theta^m_{13} \sin^2 \frac{(\Delta m^2_{31})^m L}{4E}$$

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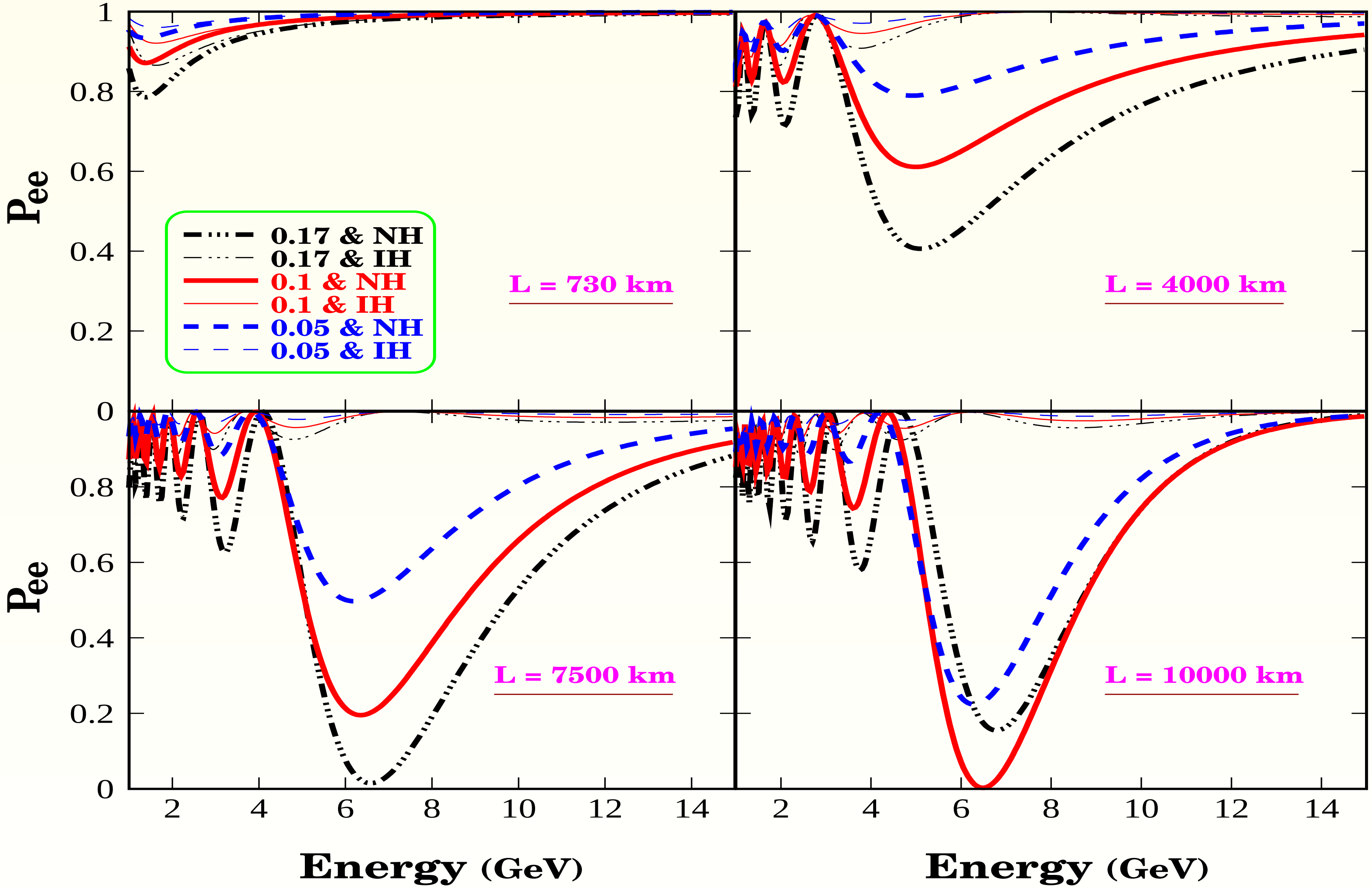
$$\lim_{\Delta m^2_{21} \to 0} P_{e\tau} = \cos^2\theta_{23} \sin^2 2\theta^m_{13} \sin^2 \frac{(\Delta m^2_{31})^m L}{4E}$$

Large Matter Effects in P_{ee}

$$\lim_{\Delta m^2_{21} \to 0} P_{ee} = 1 - \sin^2 2\theta^m_{13} \sin^2 \frac{(\Delta m^2_{31})^m L}{4E}$$



Agarwalla, S.C., Goswami, Raychaudhuri, hep-ph/0611233

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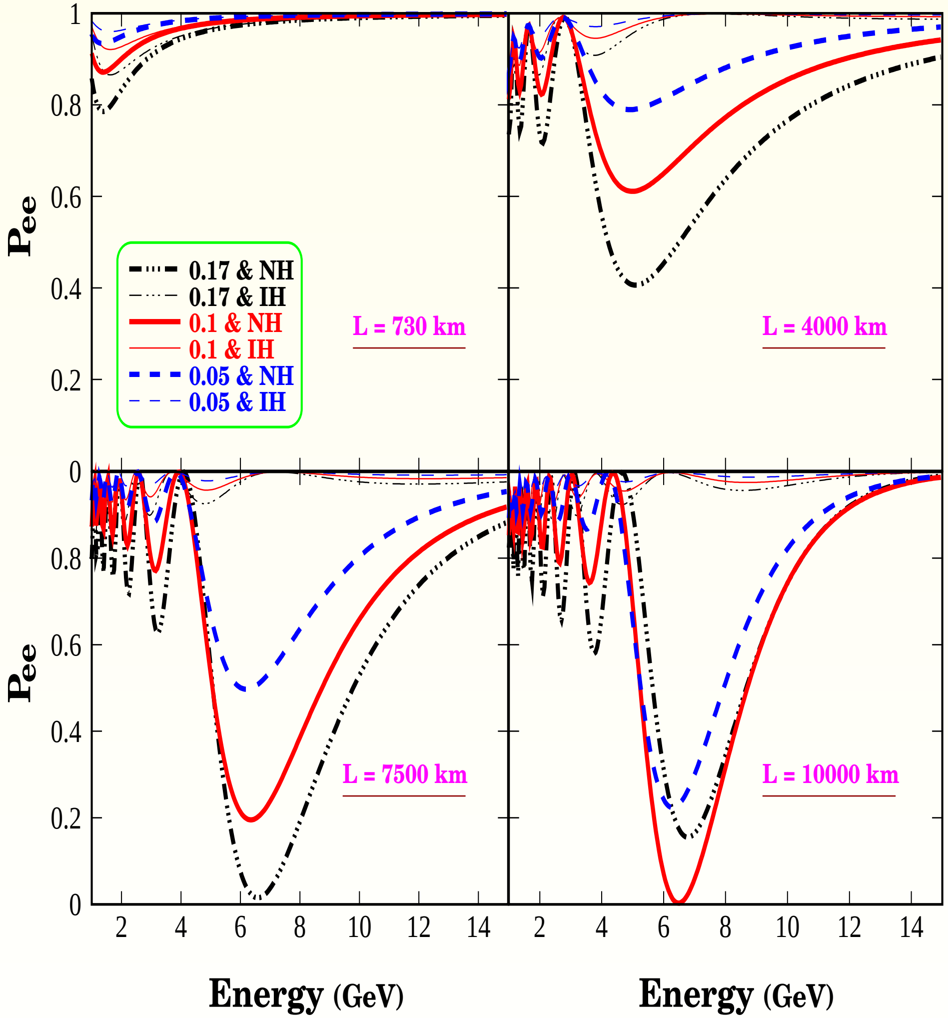

Agarwalla, S.C., Goswami, Raychaudhuri, hep-ph/0611233

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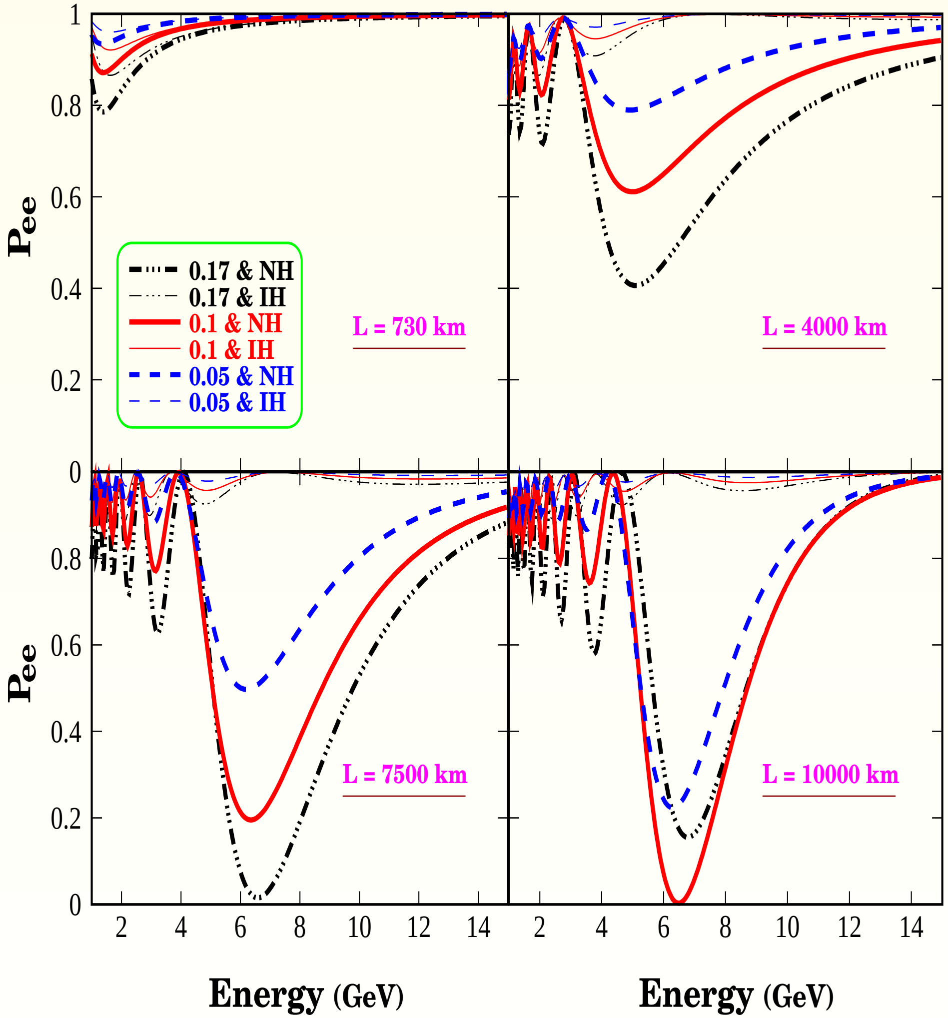

- Matter effects large: almost 2 times
- No dependence on δ_{CP} and θ_{23}
- No parameter degeneracies!!

Agarwalla, S.C., Goswami, Raychaudhuri, hep-ph/0611233

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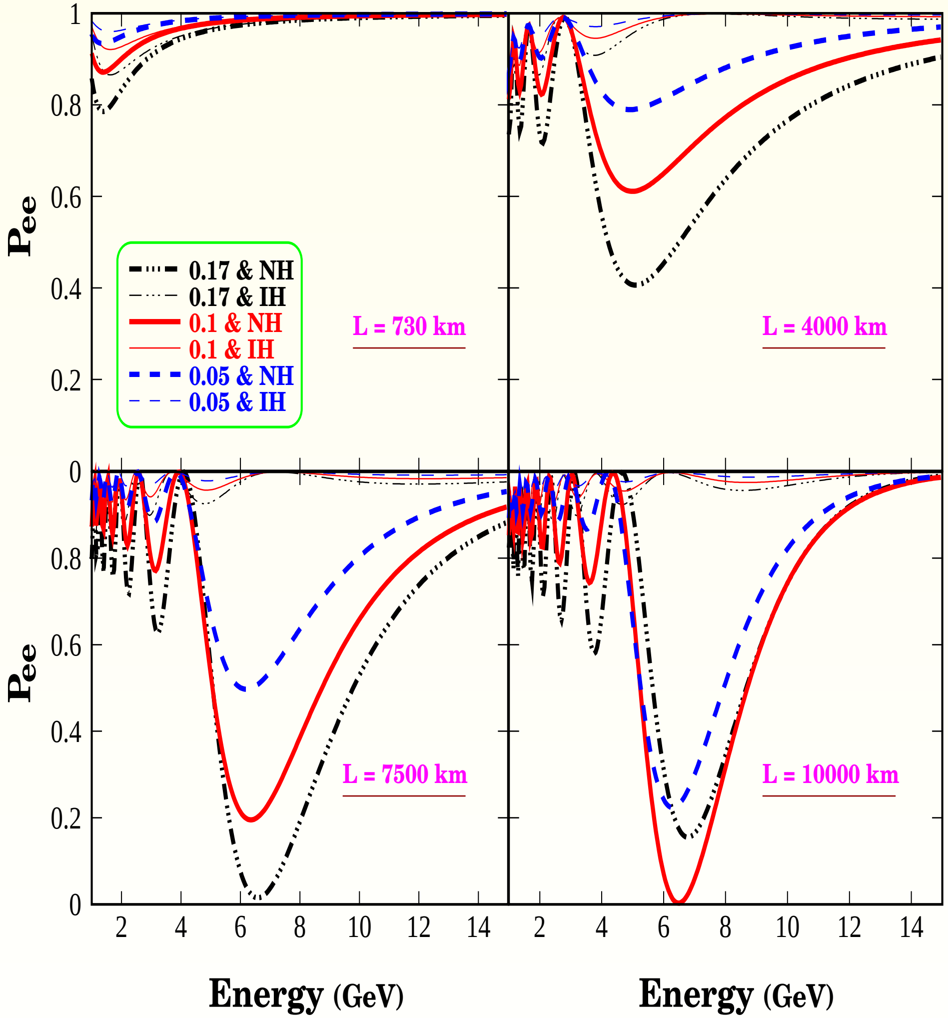

- Pure $\nu_e/\bar{\nu}_e$: Beta Beams

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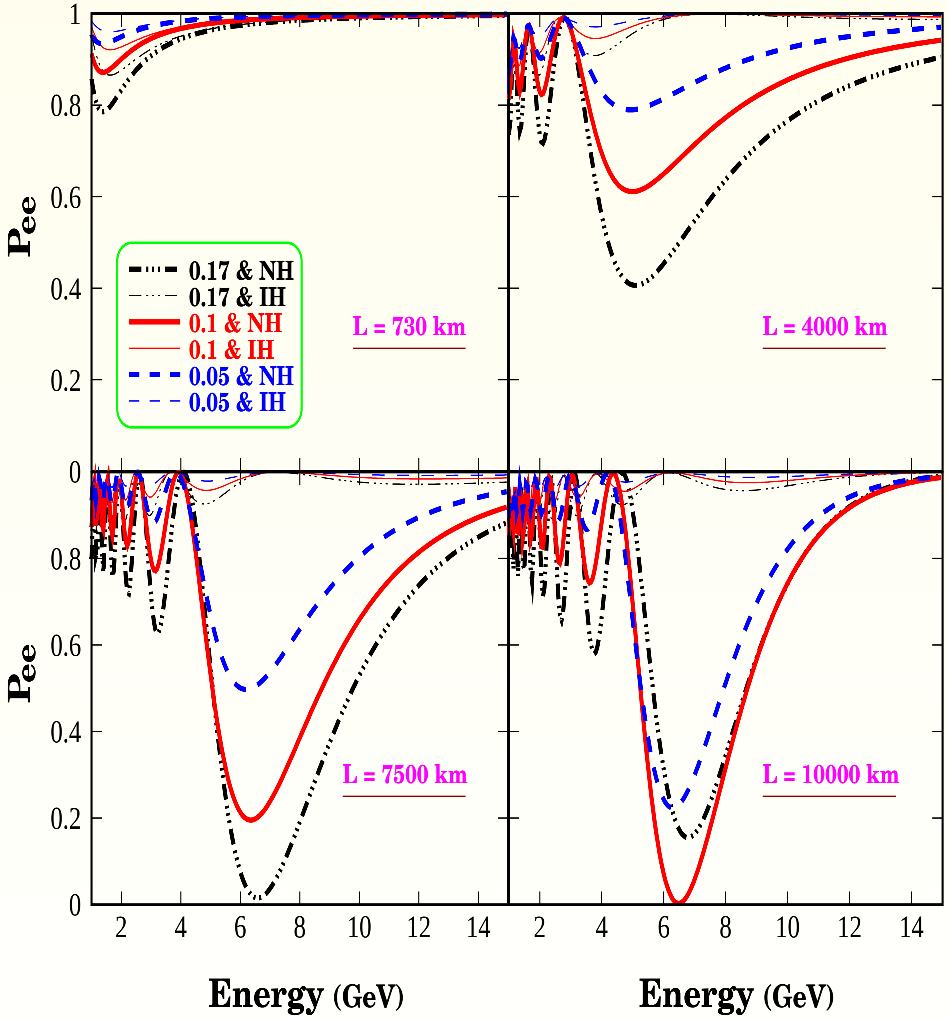

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- $E \sim 6$ GeV: ^8B and ^8Li

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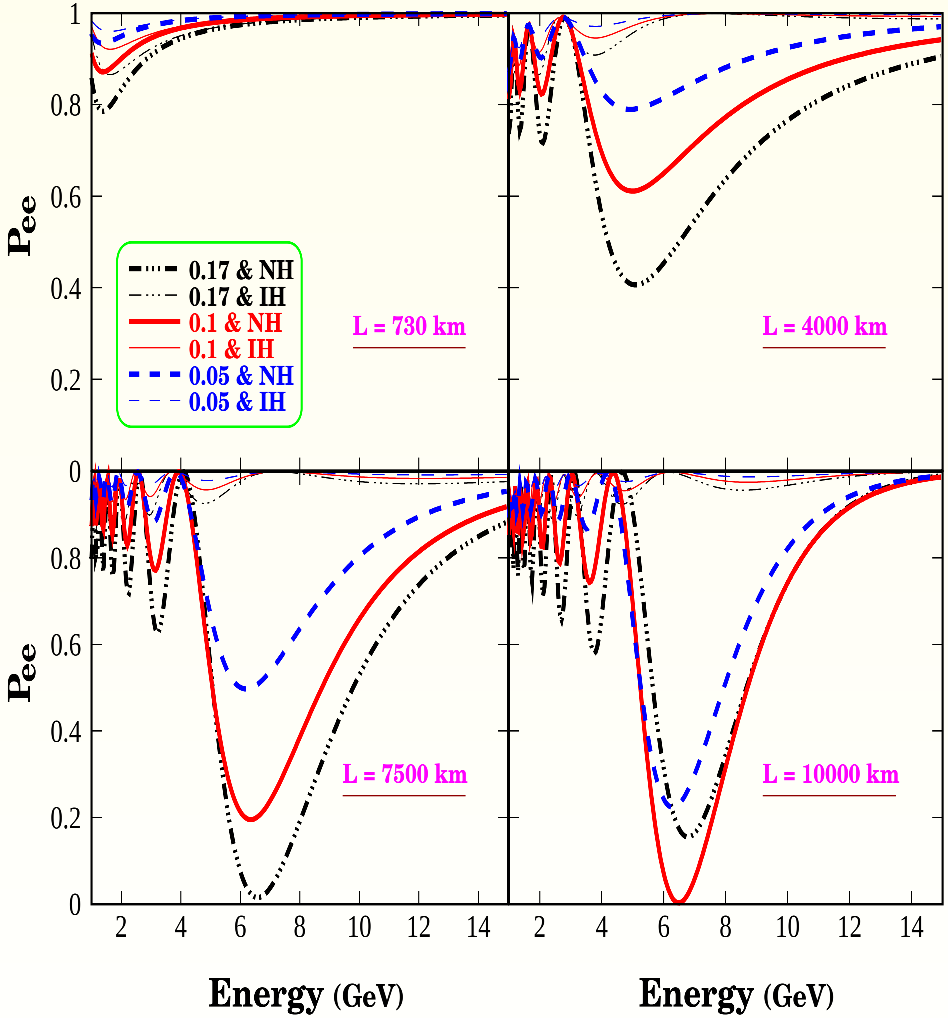

- Pure $\nu_e/\bar{\nu}_e$: Beta Beams
- $E \sim 6$ GeV: ^8B and ^8Li
- Very long baselines:

CERN-UNO: $L = 7000 - 8600$ km

FNAL-MEMPHYS: $L = 7313$ km

FNAL-HK: $L = 10184$ km

CERN-HK: $L = 9647$ km

Agarwalla, S.C., Goswami, Raychaudhuri, hep-ph/0611233

CP Discovery Reach with Beta-Beams ($P_{e\mu}$)

- At magic baseline CP sensitivity is smothered

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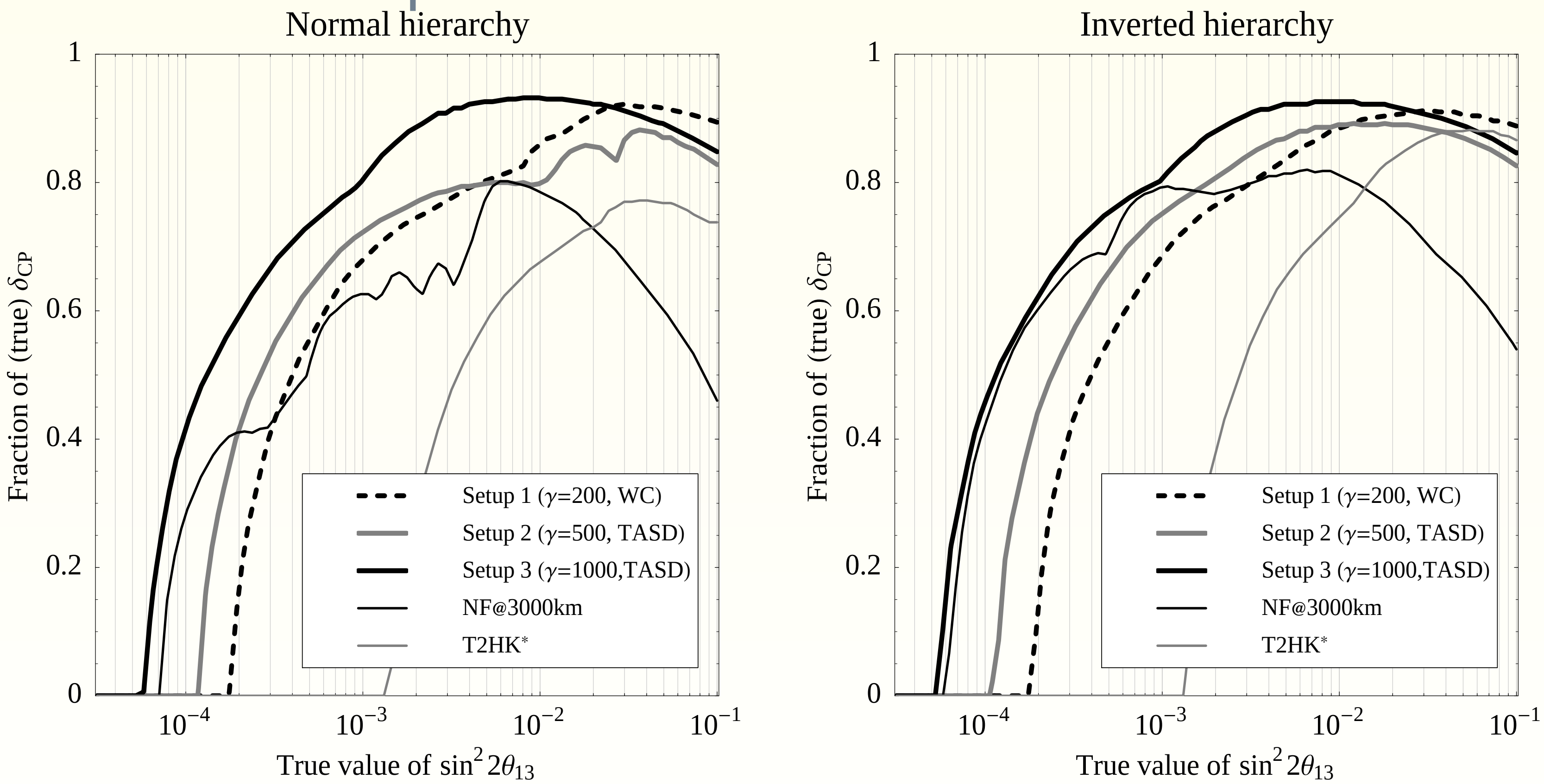
#	1	2	3
type	WC	TASD	TASD
m [kt]	500	50	50
γ	200	500	1000
L [km]	520	650	1000
ν signal	1983	2807	7416
ν background	105	31	95

The following results are taken from PH, M. Lindner, M. Rolinec, W. Winter, hep-ph/0506237.

CP Discovery Reach with Beta-Beams ($P_{e\mu}$)

- At magic baseline CP sensitivity is smothered
- Must move away from the magic baseline
- Which set-up could be best?

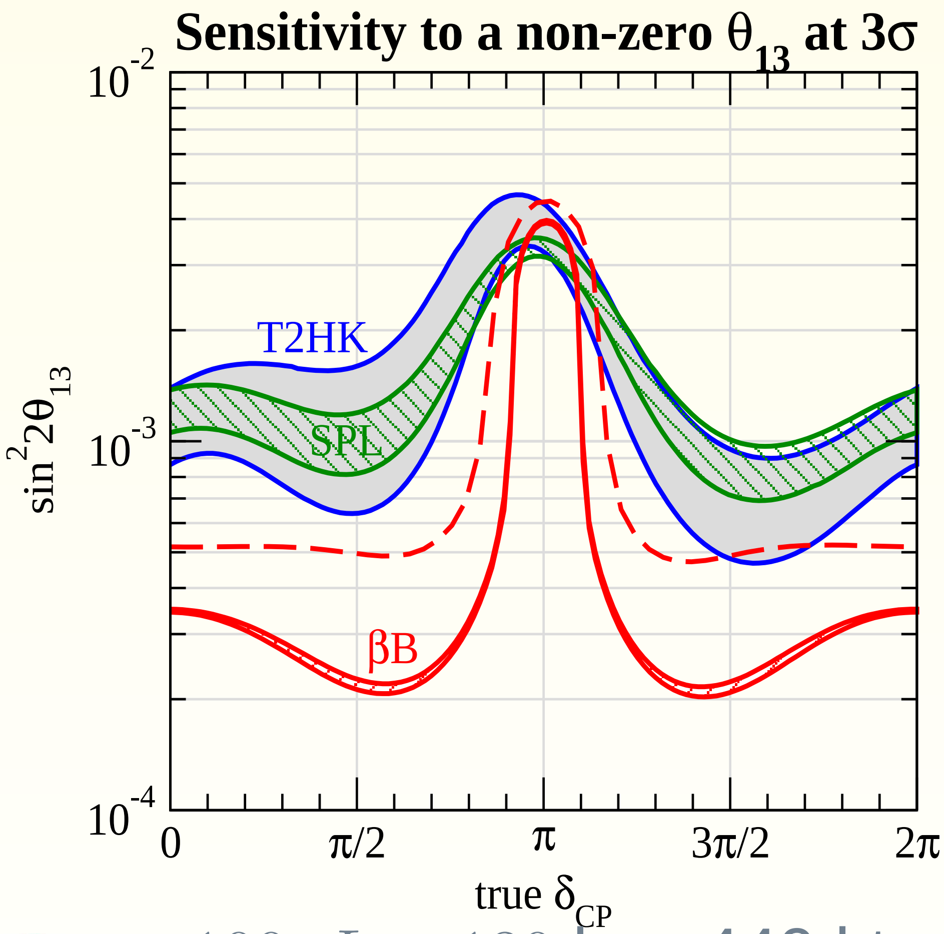


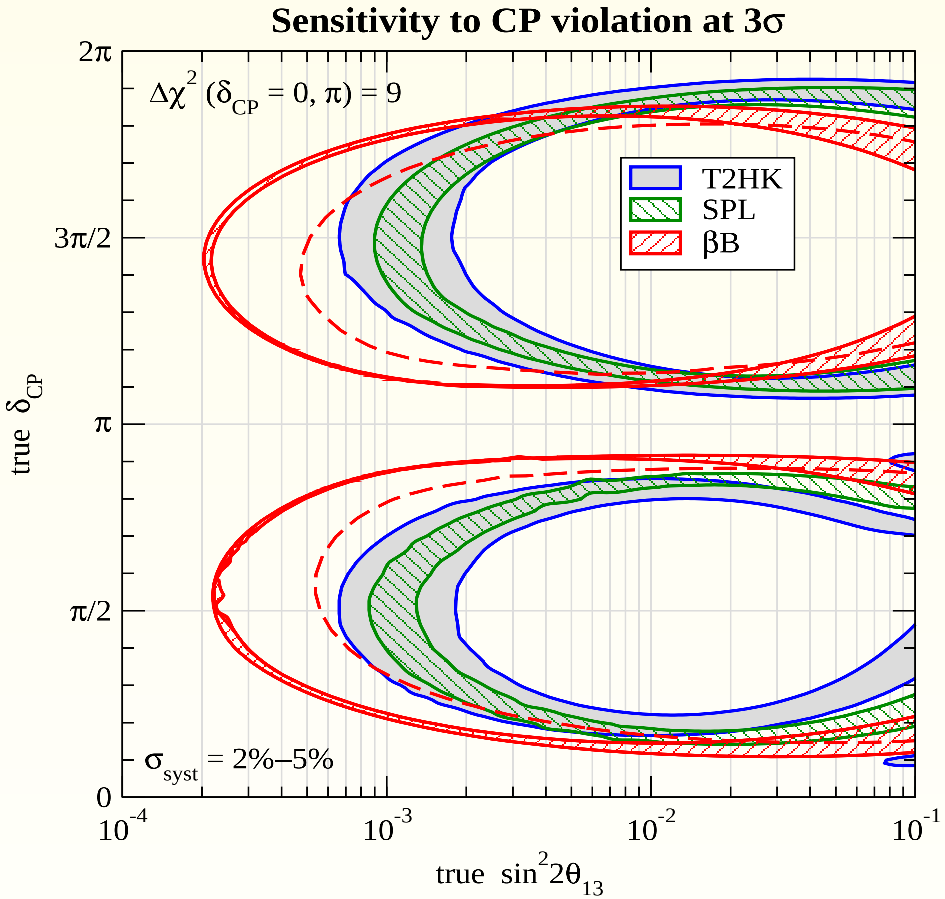
Huber *et al.*, hep-ph/0506237

- Beta-Beams CP sensivity is similar to NuFacts

Physics Potential of CERN-MEMPHYS

Campagne *et al.*, hep-ph/0603172



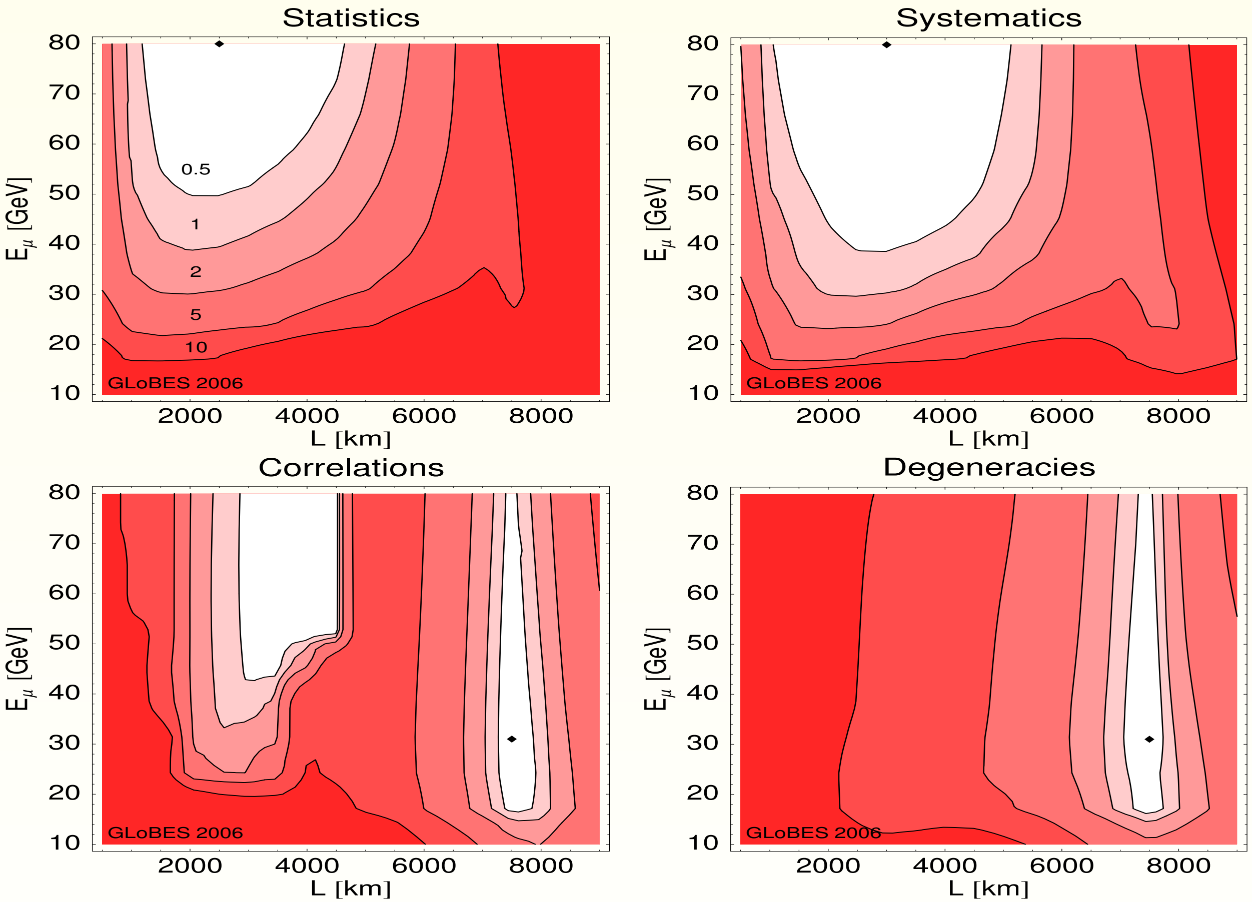


- $\gamma = 100$, $L = 130$ km, 440 kton WC detector
- Combined βB and SPL in only ν mode takes 5 yrs only
- The megaton water detector will also collect atm data

– helps in determining $sgn(\Delta m^2_{31})$ and octant of θ_{23}

Physics Reach of Neutrino Factory

- Sensitivity to $\sin^2 2\theta_{13} \lesssim 5.0 \times 10^{-4}$ (5σ)

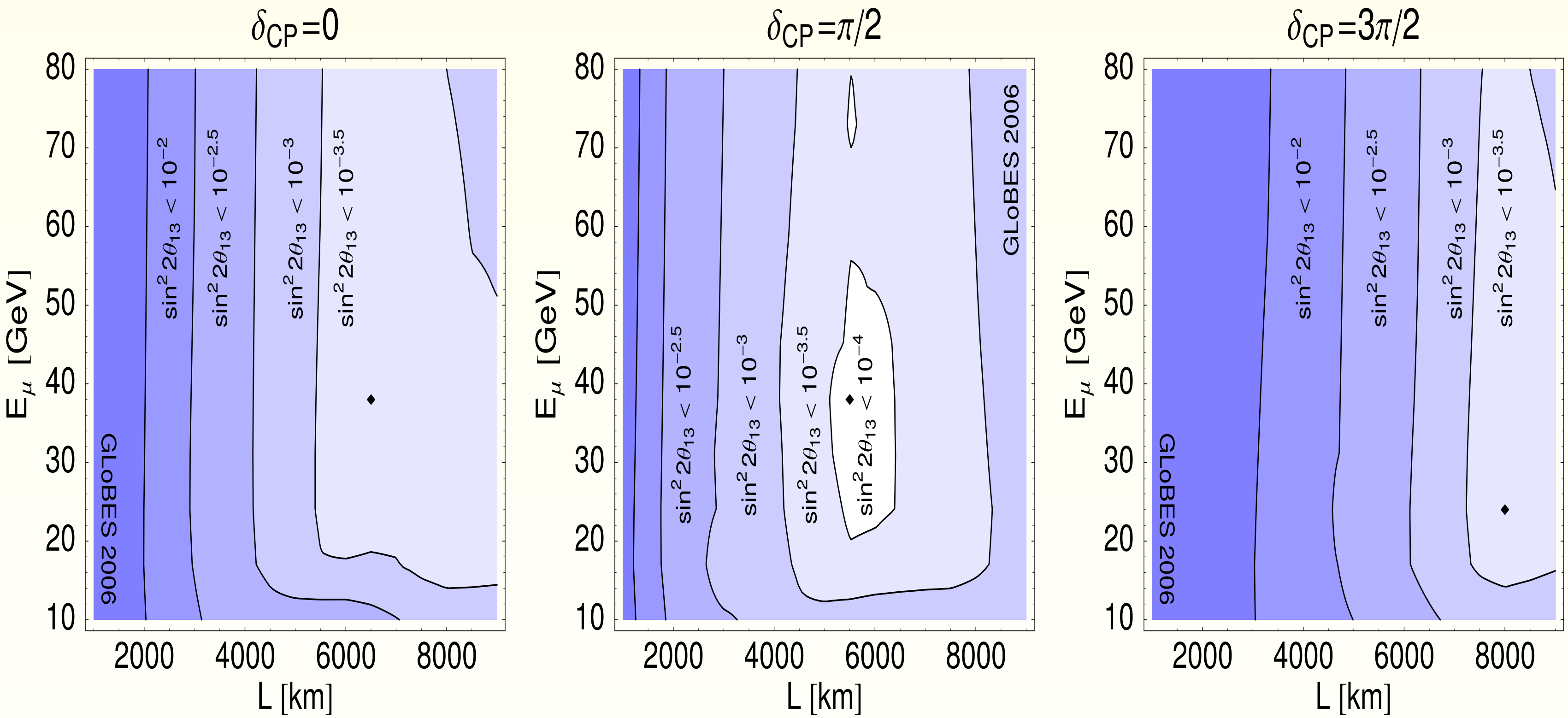


Huber *et al.*, hep-ph/0606199

- Best around $E_\mu = 30$ GeV and close to magic baseline

Physics Reach of Neutrino Factory

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

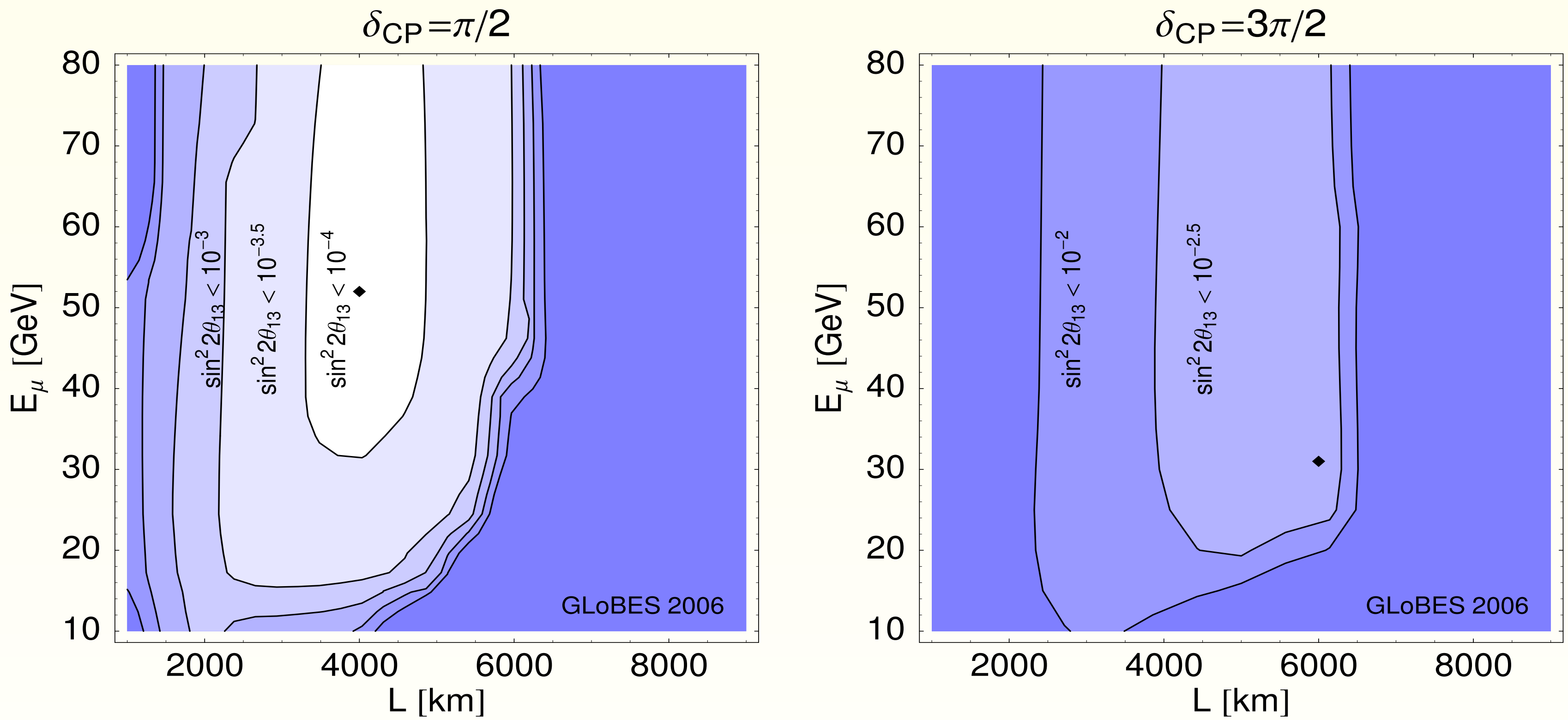


Huber *et al.*, hep-ph/0606199

- Best around $E_\mu = 20 - 40$ GeV and close to magic baseline

Physics Reach of Neutrino Factory

- CP Discovery Reach (3σ)

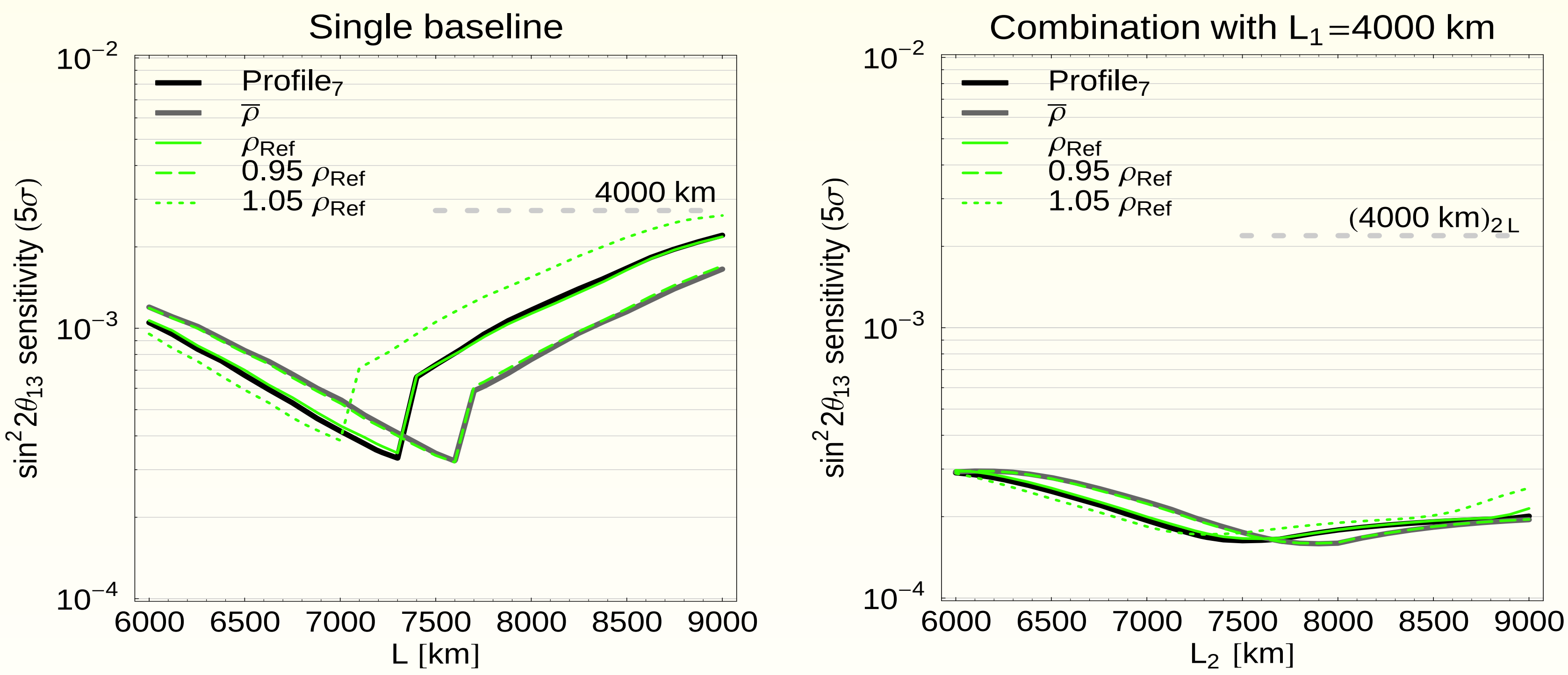


Huber *et al.*, hep-ph/0606199

- Best at around $L = 4000$ km

Physics Reach of Neutrino Factory

- Combining baselines for best θ_{13} sensitivity



Gandhi, Winter, hep-ph/0612158

- With two detectors, one at $L = 4000$ km and another farther away, the range of “optimal” baselines widens