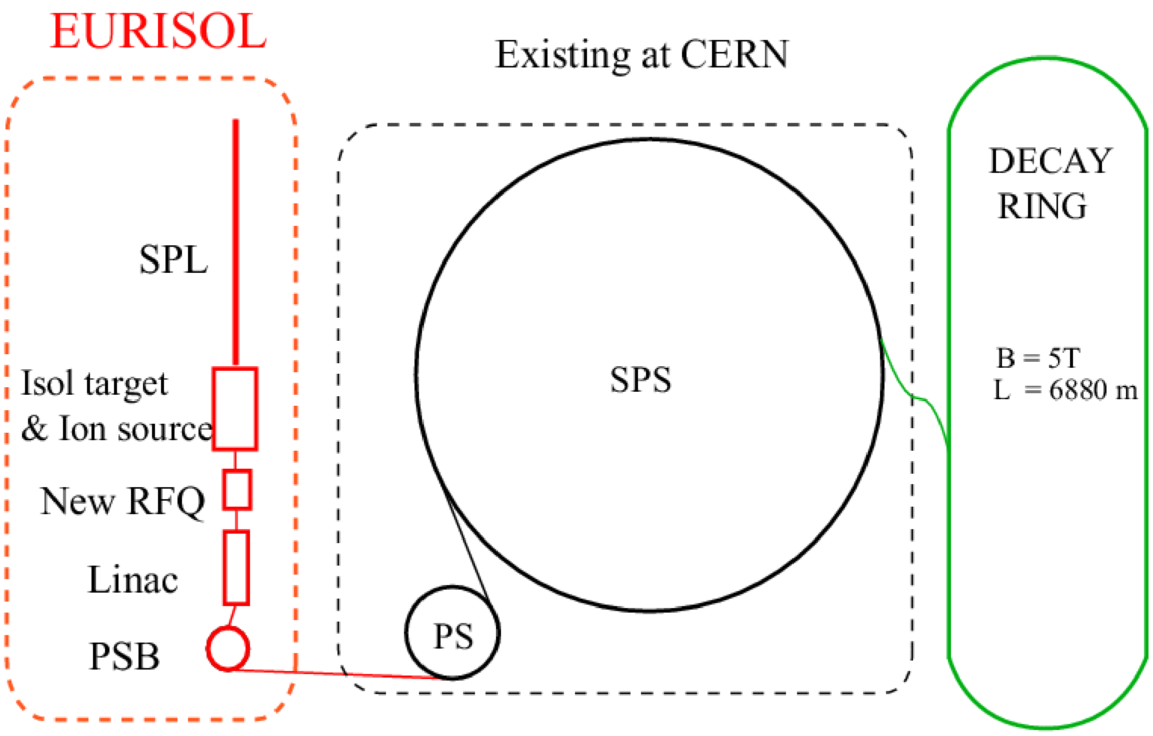
Importance of neutrino oscillation parameter measurements

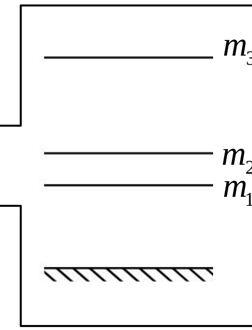


Neutrino mixing

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Standard Model states

Neutrino mass states



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 0 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} e^{i\beta_1} & 0 & 0 \\ 0 & e^{i\beta_2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Atmospheric angle | Reactor angle and CP phase | Solar angle | Majorana phases

Exact analytical formula for neutrino oscillations in matter

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{j<k} \Re\left(\tilde{X}_j^{\alpha\beta} \tilde{X}_k^{\alpha\beta *}\right) \sin^2\left(\frac{\Delta \tilde{E}_{jk} L}{2}\right)$$

Kimura, Takamura, Yokomakura 02

$$+ 2 \sum_{j<k} \Im\left(\tilde{X}_j^{\alpha\beta} \tilde{X}_k^{\alpha\beta *}\right) \sin\left(\Delta \tilde{E}_{jk} L\right),$$

where $\Delta \tilde{E}_{jk} \equiv \tilde{E}_j - \tilde{E}_k$. $\quad \tilde{X}_j^{\alpha\beta} \equiv \tilde{U}_{\alpha j} \tilde{U}_{\beta j}^*$

Eigenvalues of the matrix below:

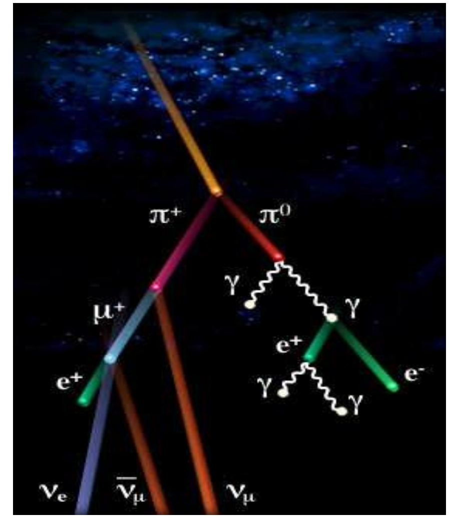
$$U \,\mathrm{diag}(E_1, E_2, E_3) U^{-1} + \mathrm{diag}(\sqrt{2} G_F N_e, 0, 0), \text{ where } E_j \equiv \sqrt{p^2 + m_j^2}.$$

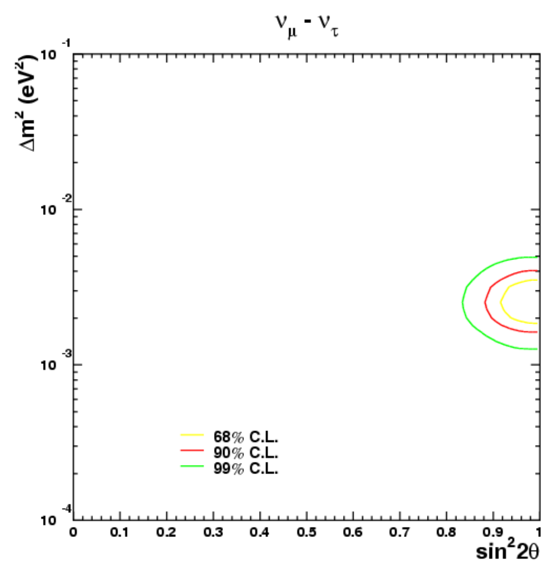
Super-Kamiokande: Atmospheric Neutrinos and Theta_23

- Production of neutrinos in the atmosphere (expected neutrino flux ratio: mu: e = 2 : 1)

- detection (sensitive to direction) in SuperKamikande (Cerenkov, 50000 t water in Kamioka mine, Japan)

- atmospheric neutrino deficit





Explanation by neutrino oscillations with:
Theta_23 ~45°
Delta m^2_{atm} ~2.10^{-3} eV^2

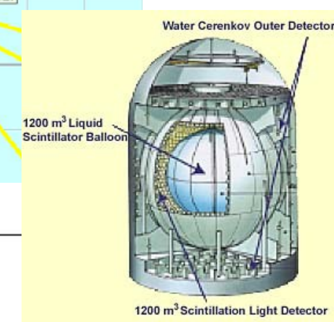
KamLAND: Large Mixing Angle (LMA) MSW

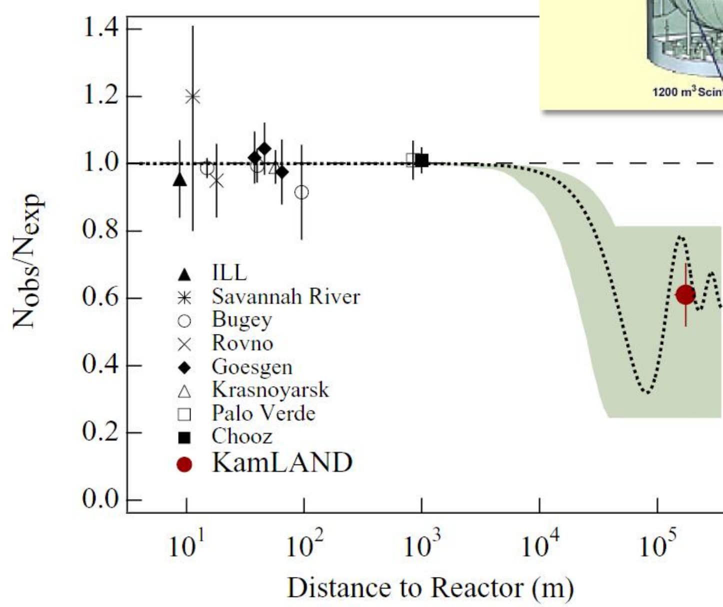
- electron antineutrinos from reactors (flux quite well known) mainly in Japan

- average distance to detector (baseline) ~250 km

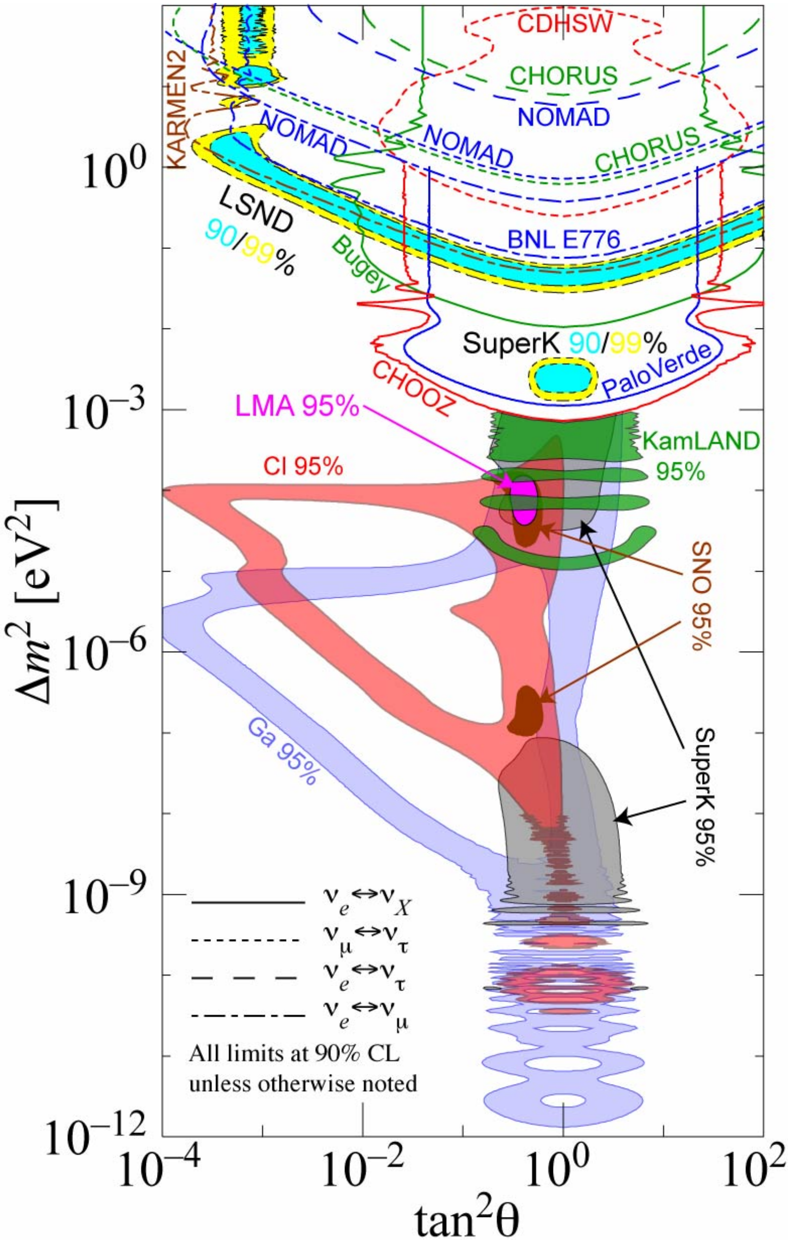
- search for antineutrino disappearance (conversion into different flavour)

Results compatible with neutrino oscillations (LMA MSW solution confirmed):
Theta_12 ~30°
Delta m^2_{sol} ~ 7.10^{-5} eV^2



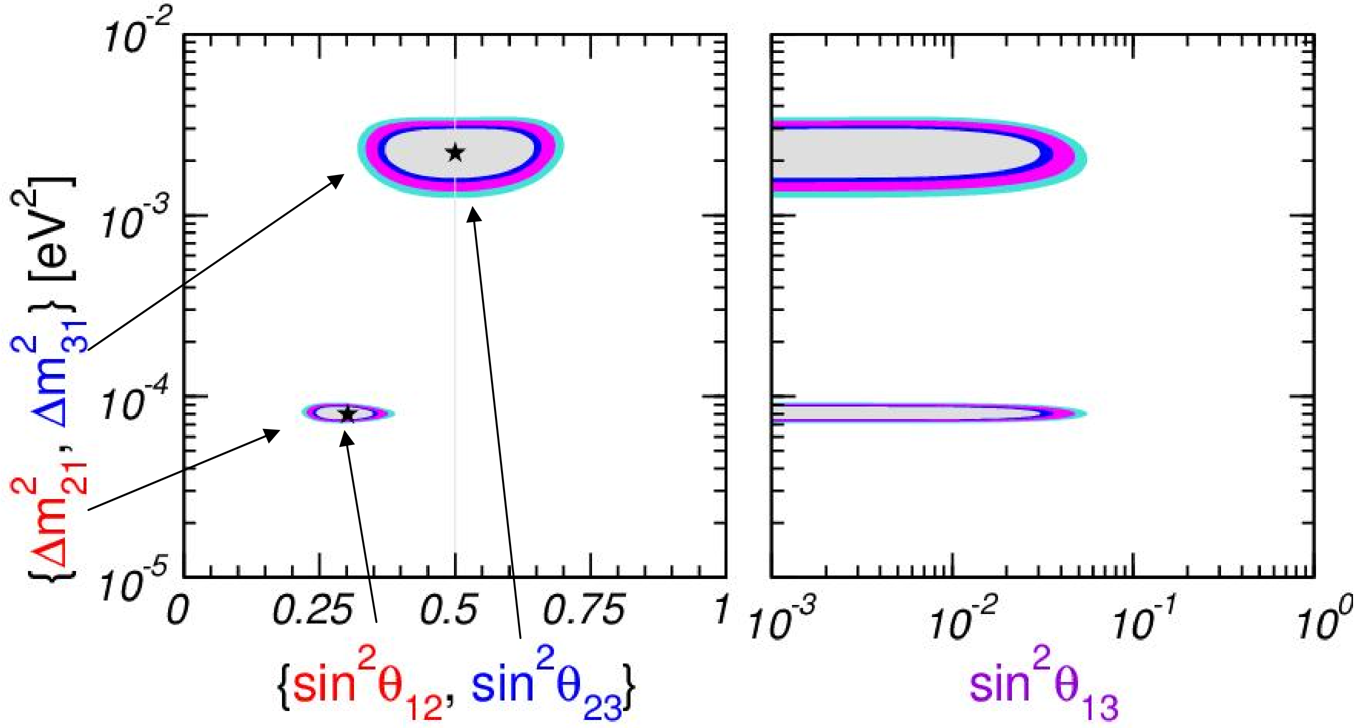


Neutrino oscillations c.2003



For a review see
SFK hep-ph/0310204

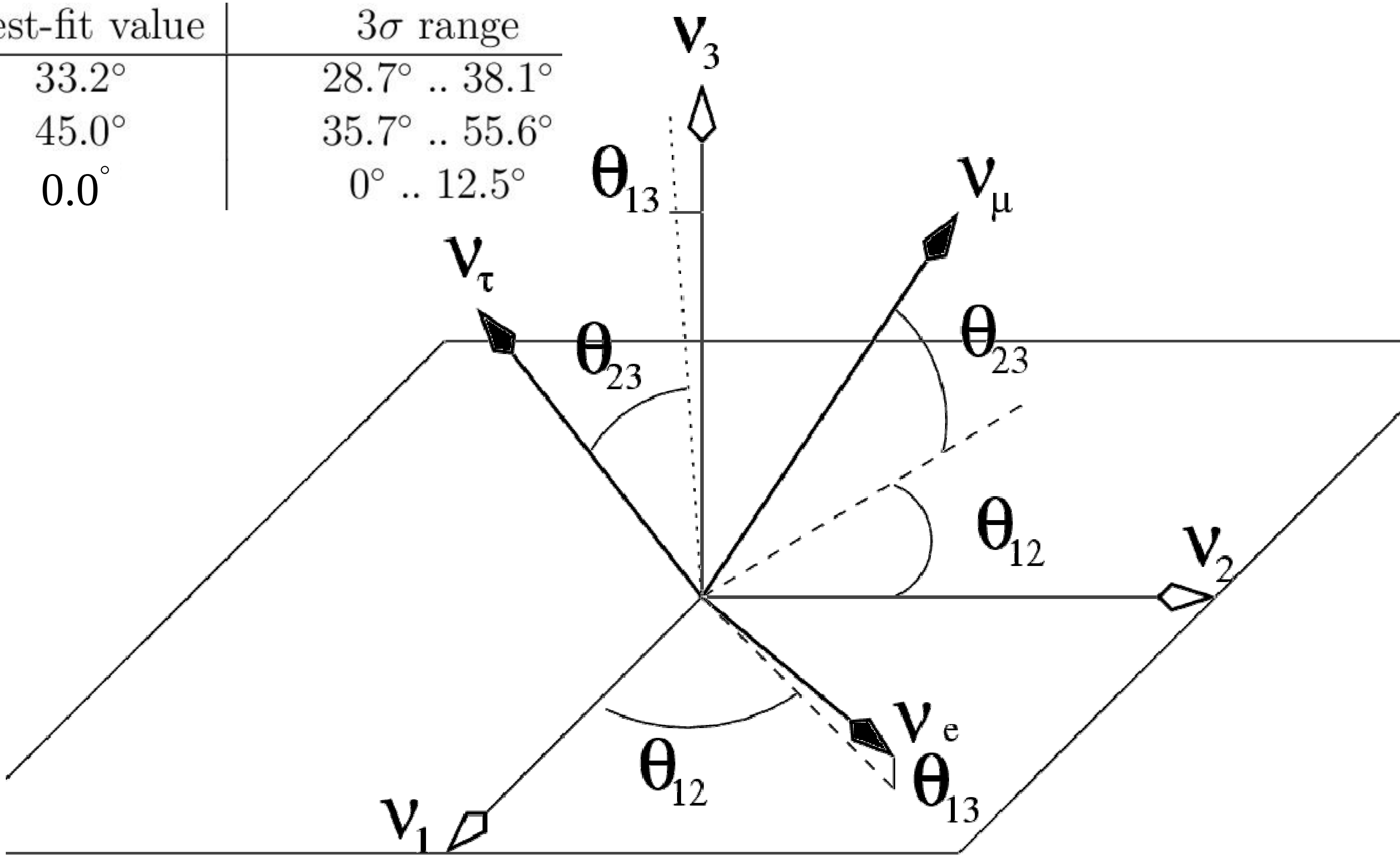
Detailed fits c.2004



from: Maltoni, Schwetz, Tortola, Valle ('04)

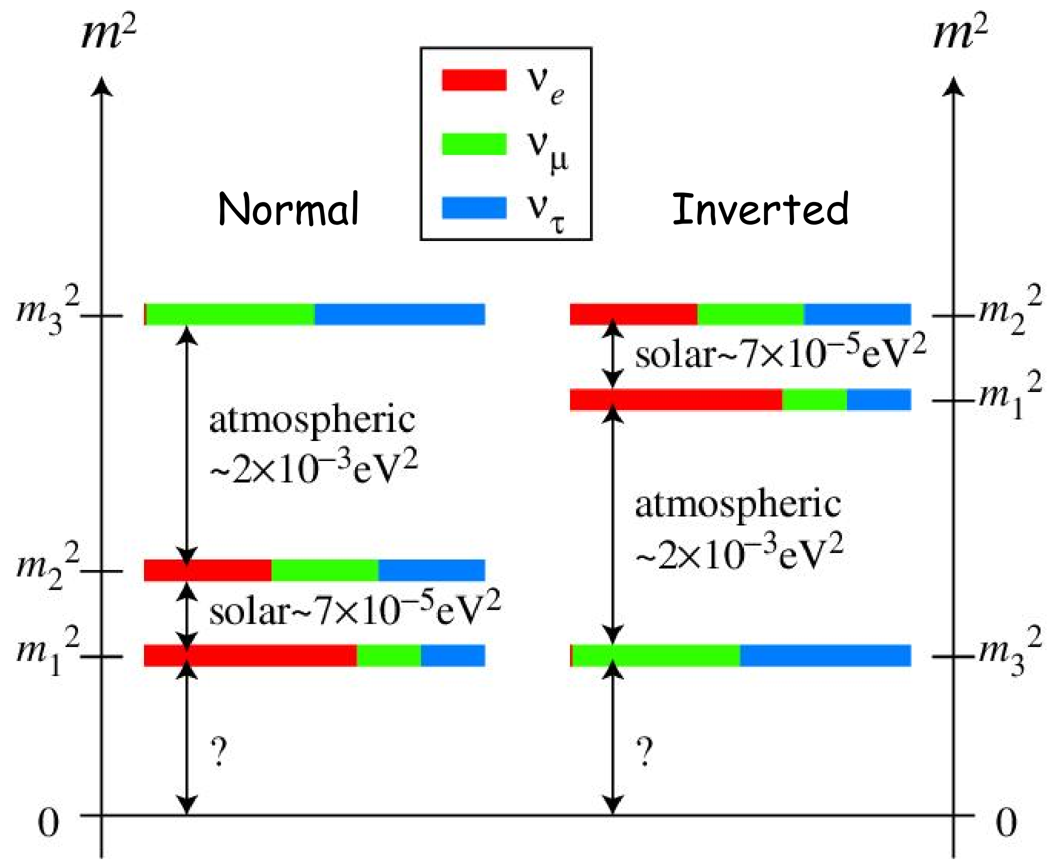
Neutrino Mixing Angles

Parameter	Best-fit value	3σ range
θ_{12}	33.2°	28.7° .. 38.1°
θ_{23}	45.0°	35.7° .. 55.6°
θ_{13}	0.0°	0° .. 12.5°



Three Neutrino Mass Patterns

parameter	best fit	2σ	3σ	4σ
Δm^2_{21} [10^{-5}eV^2]	7.9	7.3–8.5	7.1–8.9	6.8–9.3
Δm^2_{31} [10^{-3}eV^2]	2.2	1.7–2.9	1.4–3.3	1.1–3.7



The Unanswered Questions

APS study Mohapatra et al hep-ph/0412099

- Are neutrinos Dirac or Majorana?
- What is the absolute mass scale of neutrinos?
- How small is θ_{13}?
- How "maximal" is θ_{23}?
- Is there CP Violation in the neutrino sector?
- Is the mass hierarchy inverted or normal?
- Is the LSND evidence for oscillation true? Are there sterile neutrino(s)?

Amenable to LBL neutrino oscillation experiments

How we could learn about the nature and pattern of neutrino masses?

APS study Mohapatra et al hep-ph/0412099

$\beta\beta_{0\nu}$	Δm^2_{13}*	KATRIN	Conclusion
yes	> 0	yes	Degenerate, Majorana
yes	> 0	No	Degenerate, Majorana
yes	< 0	no	Inverted, Majorana
yes	< 0	yes	Degenerate, Majorana
no	> 0	no	Normal, Dirac or Majorana
no	< 0	no	Dirac
no	< 0	yes	Dirac
no	> 0	yes	Dirac

*Amenable to LBL neutrino oscillation experiments

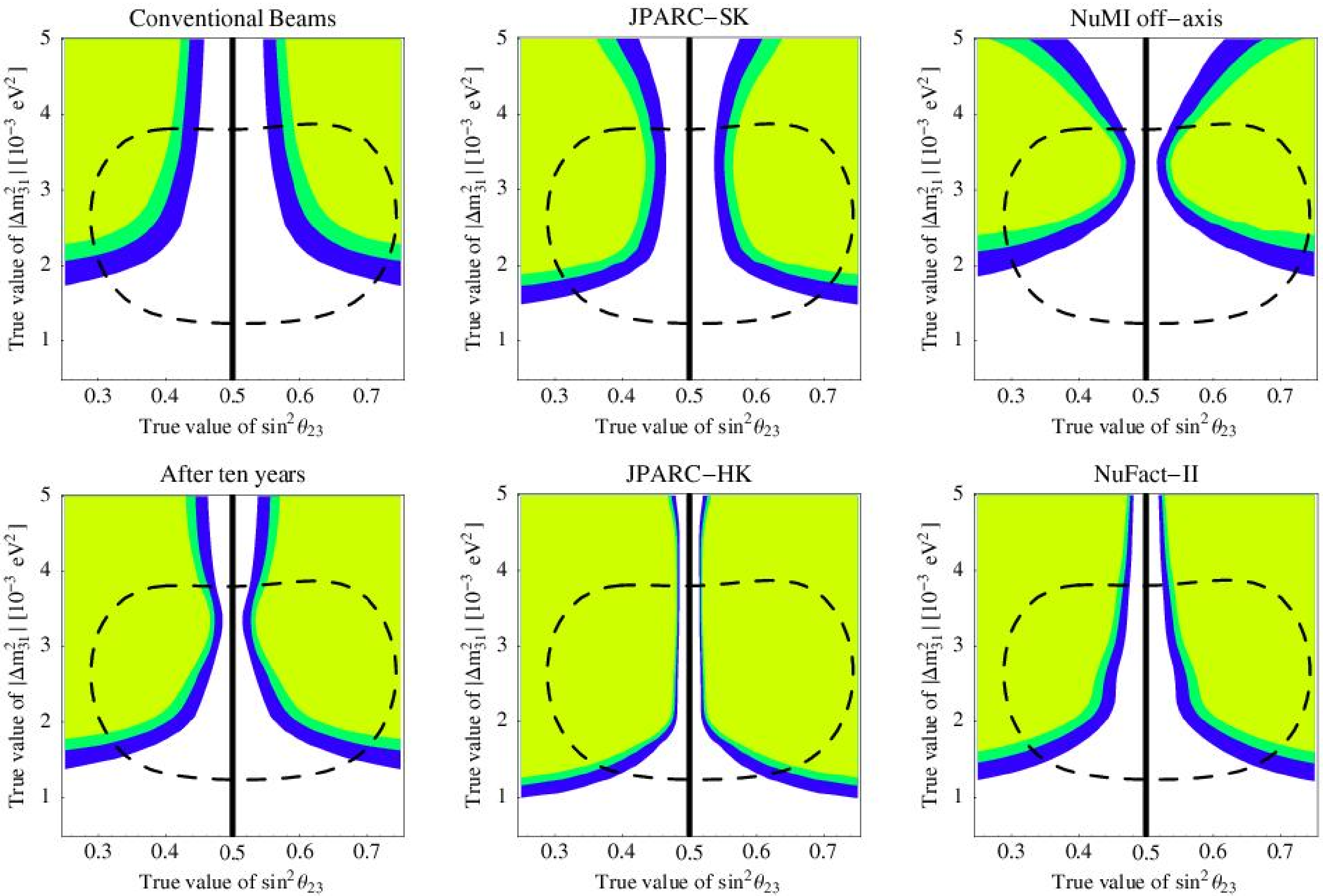
Compilation of theoretical predictions for deviations from maximal atmospheric mixing

Model(s)	Refs.	$\lvert 0.5 - \sin^2\theta_{23} \rvert$
Minimal SO(10)	[14]	> 0.16
SO(10) + flavour symmetry	[15–17]	$\lesssim 0.05$
SO(10) + texture	[18]	$\lesssim 0.11$
Flavour symmetries	[19–25]	0
	[26]	0.02
	[27]	0.04
Sequential RH neutrino dominance	[28, 29]	0.1
+ Flavour symmetries	[30–32]	0.1
+ Type II see-saw upgrade	[33]	0.01 .. 0.1
Texture zeros	[34]	0.07
	[35]	> 0.1
Perturbations of textures	[36]	$\lesssim 0.16$
	[37, 38]	0.005 .. 0.1

TABLE II: Selection of theoretical expectations for $\lvert 0.5 - \sin^2\theta_{23} \rvert$ at tree level. The numbers should be considered as order of magnitude statements.

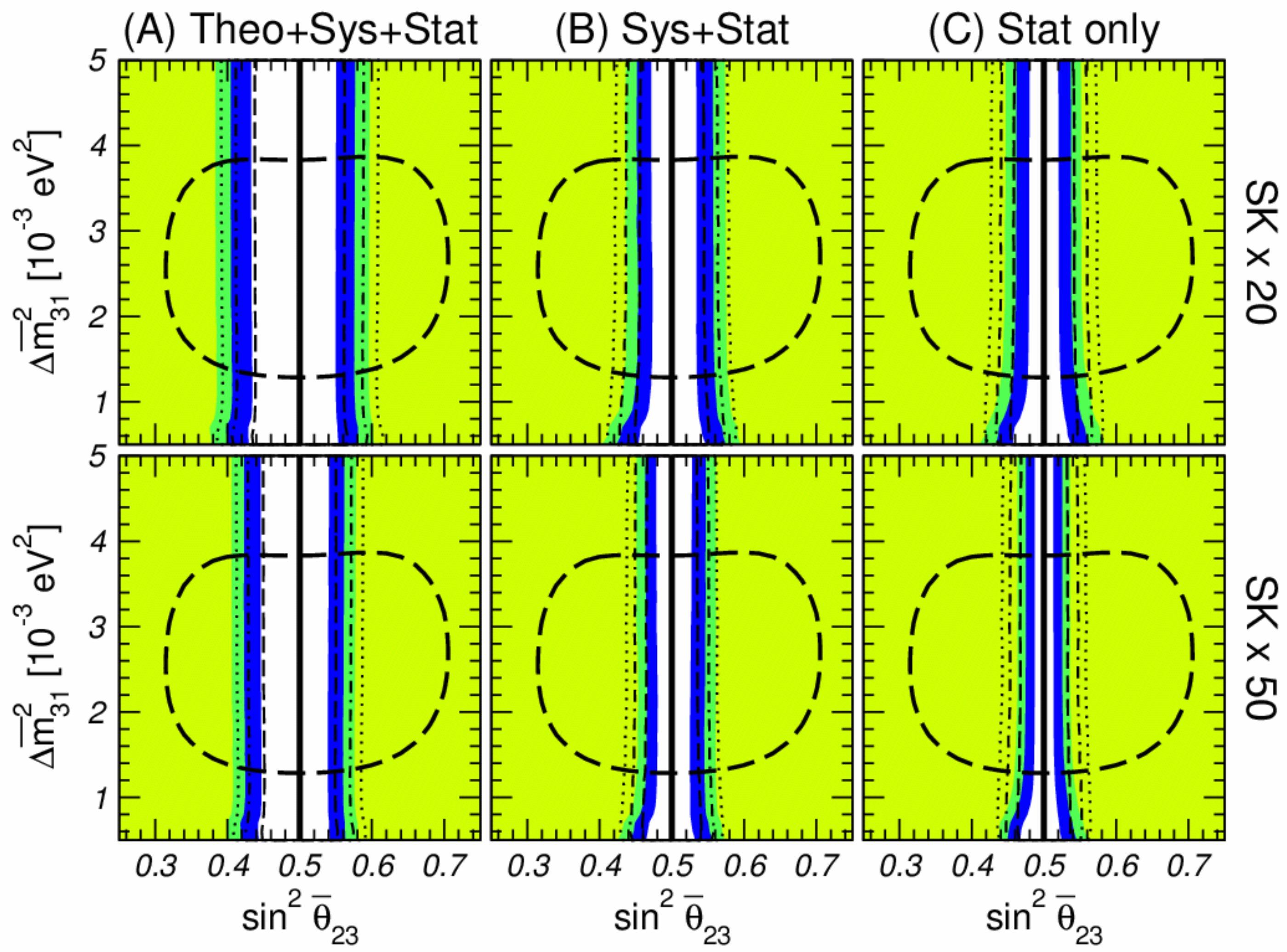
S. Antusch, M. Huber, J. Kersten, T. Schwetz, W. Winter (hep-ph/0404268)

Sensitivity for Excluding Maximal Atmospheric Mixing
I. Long Baseline Experiments



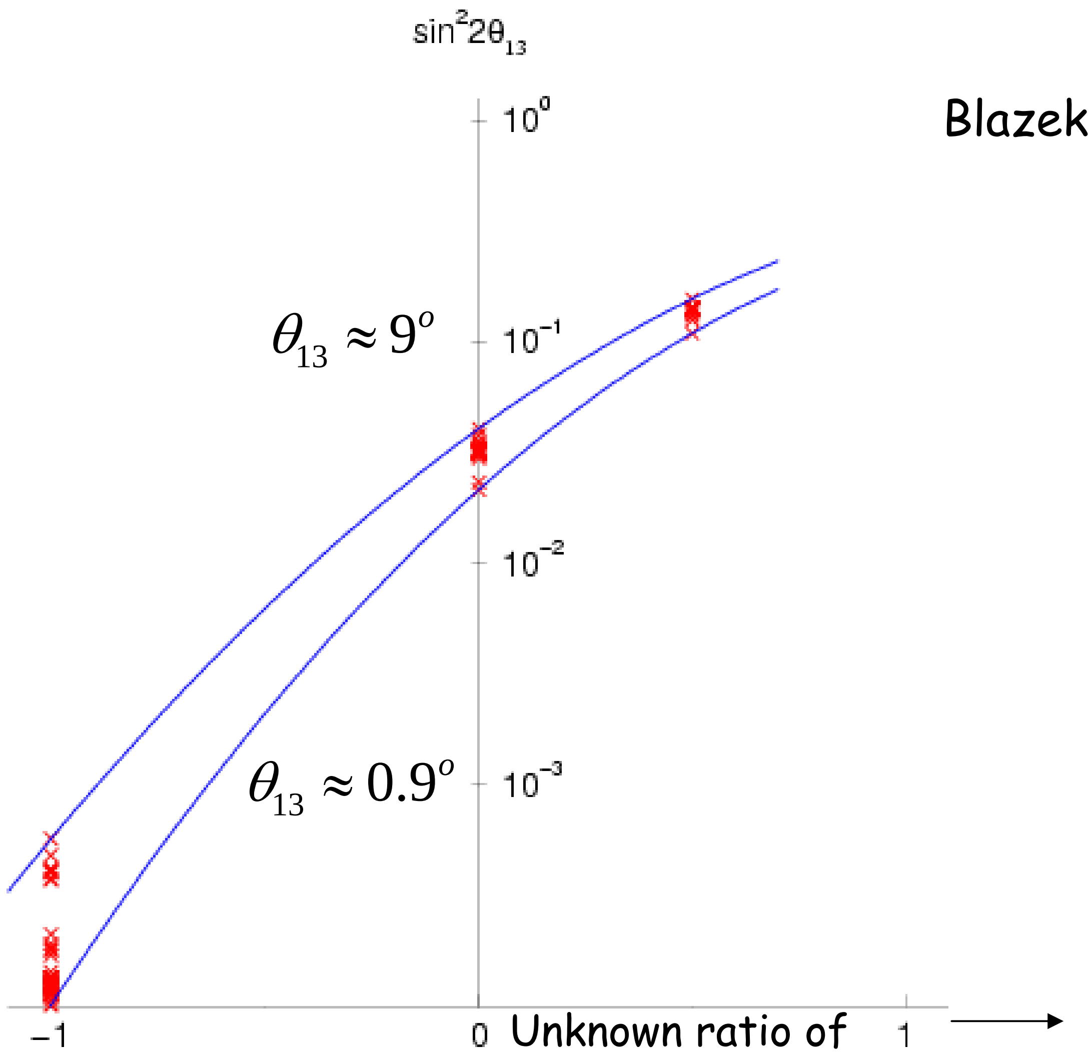
S. Antusch, M. Huber, J. Kersten, T. Schwetz, W. Winter (hep-ph/0404268)

Sensitivity for Excluding Maximal Atmospheric Mixing
II. Atmospheric Neutrino Oscillations



Gonzalez-Garcia, Maltoni, Smirnov, hep-ph/0408170

Expectation for Theta_13 for a natural neutrino mass hierarchy



Blazek,SFK 00

Unknown ratio of Yukawa couplings r

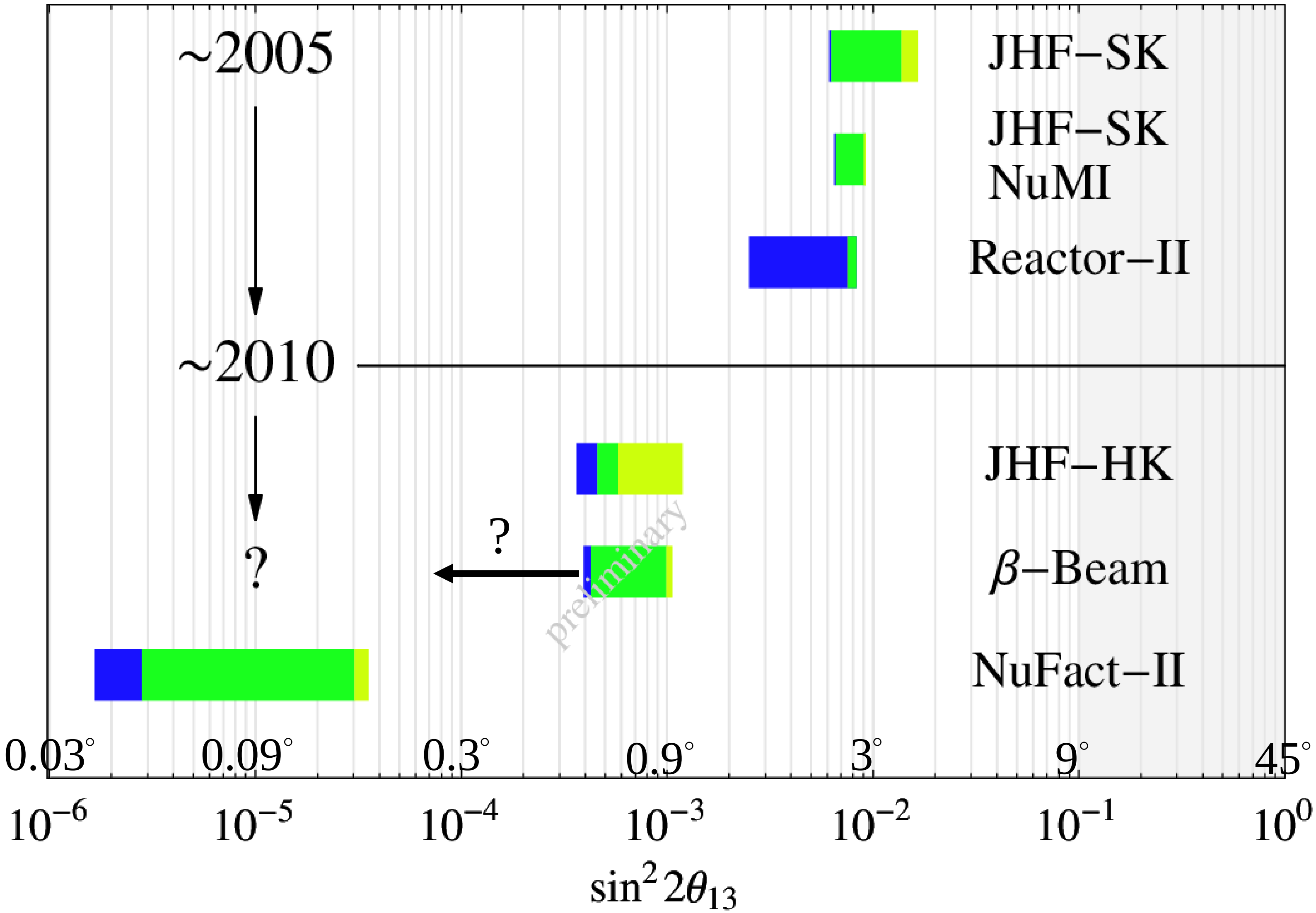
Compilation of Theoretical predictions for Theta_13

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3×2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

From hep-ex/0402041

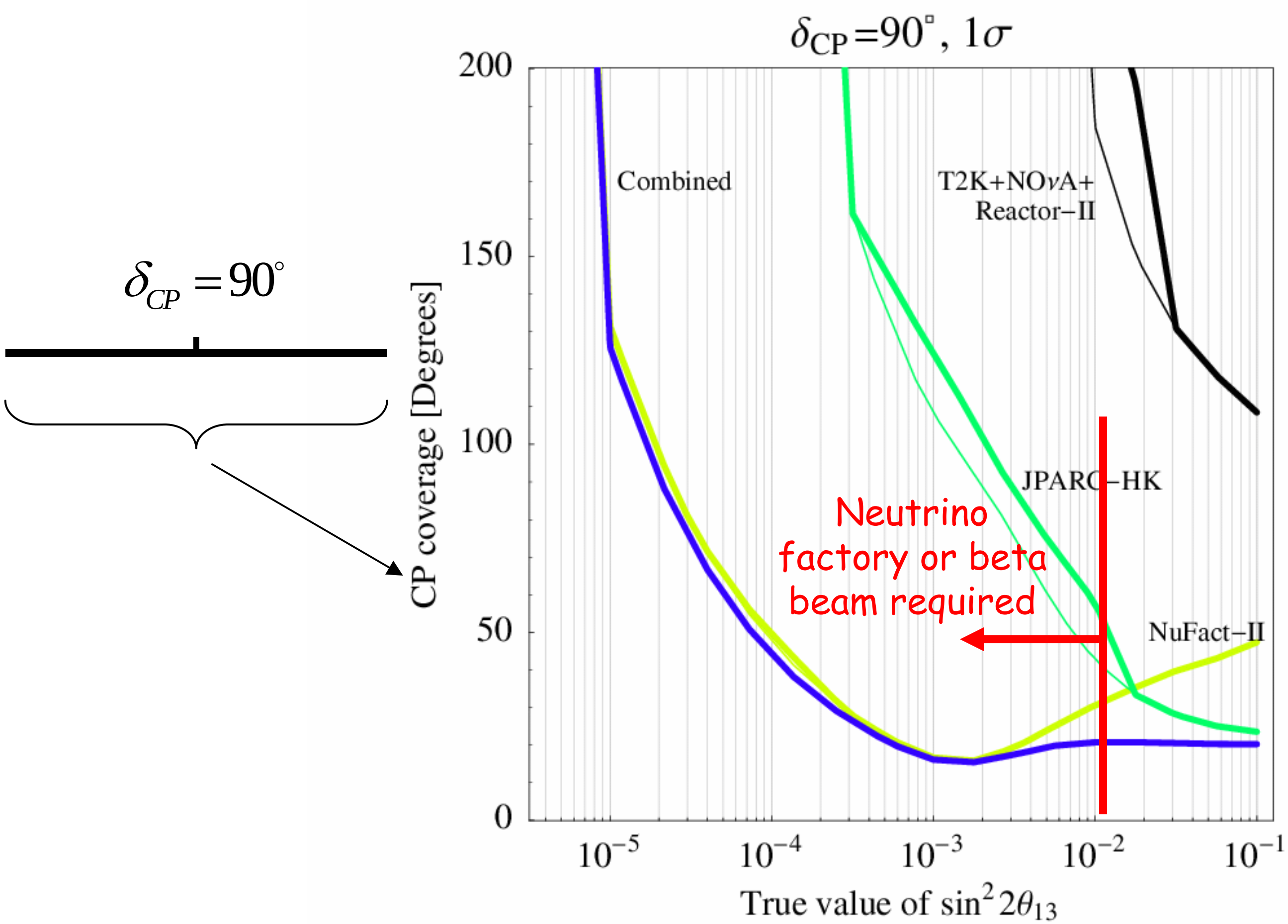
Experimental prospects for Theta_13

APS study Albright et al, physics/0411123



Prospects for measuring CP Violation if $\delta_{CP} = 90^\circ$.

APS study Albright et al, physics/0411123



Quark-Lepton Complementarity?

Lepton mixings

Parameter	Best-fit value	3σ range
θ_{12}	33.2°	28.7° .. 38.1°
θ_{23}	45.0°	35.7° .. 55.6°
θ_{13}	2.6°	0° .. 12.5°

Quark mixings

Parameter	Best-fit value	2σ range
θ_{12}^q	12.88°	12.75° .. 13.01°
θ_{13}^q	0.21°	0.17° .. 0.25°
θ_{23}^q	2.36°	2.25° .. 2.48°

Present experimental data allows for relations like:

$$\theta_{12} + \theta_{12}^q = 45^\circ$$

...SFK ('02), Raidal ('04)
Smirnov, Minakata ('04),
Mohapatra, Frampton ('04)

'Quark-lepton complementarity' –
clues to quark-lepton unification?

This motivates measurements of neutrino mixing angles to at least the accuracy of the measured quark mixing angles

Summary and Conclusion

Recall the unanswered questions amenable to LBL experiments:

- How small is θ_{13}?
- How "maximal" is θ_{23}?

No theoretical consensus – accurate measurements would provide a good discriminator between models.

- Is there CP Violation in the neutrino sector?

Probably yes, need a nufact or beta beam if $\sin^2 2\theta_{13} < 10^{-2}$.

- Is the mass hierarchy inverted or normal?

Need very LBL→ matter effects.

Are accurate measurements of neutrino oscillation parameters important to theorists?

YES!

How accurate?

To at least the accuracy as quark mixing angles to test ideas about quark-lepton unification – maybe more accurate measurements possible since lepton parameters are not subject to QCD corrections.