Testing Neutrino CP Violation with Oscillations:

Stephen Parke

Fermilab

Outline:

- Leptonic CP Violation:
- Highlights of Neutrino Oscillations:
- "The Key Process" - $\nu_\mu \to \nu_e$:
  - Theory:
  - Possible Near Term Experiments:

    JHF, NuMI, BNL, ...
- Summary

Leptonic CP and T Violation in Oscillations

CP

$$\nu_\mu \leftrightarrow \nu_e \qquad \Longleftrightarrow \qquad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$$

T $\qquad \Updownarrow \qquad\qquad\qquad \Updownarrow \qquad$ T

$$\nu_e \leftrightarrow \nu_\mu \qquad \Longleftrightarrow \qquad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$$

CP

IN GENERAL (in vacuum):

CP Violation:

$$\alpha \neq \beta \qquad P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

T Violation:

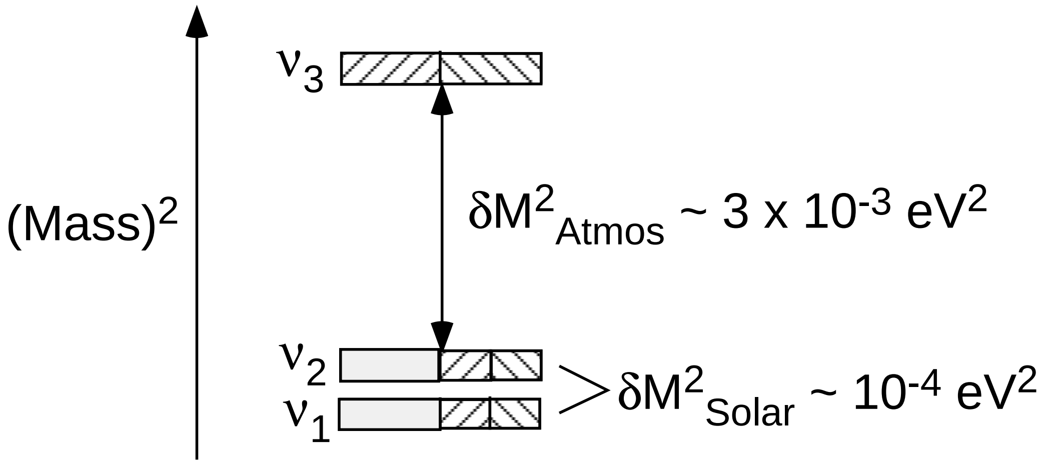
$$\alpha \neq \beta \qquad P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\nu_\beta \rightarrow \nu_\alpha)$$

$$\text{and} \qquad P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$$

CPT Violation:

$$\text{any } \alpha, \beta \quad P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$$

Notation:



3 active flavors

(but can be easily modified to accommodate 3+1)

flavors $\alpha = e, \mu, \tau$ and mass eigenstates i=1, 2, 3

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

The parameterization used for the unitary MNS matrix, $U_{\alpha i} =$

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

where $c_{jk} \equiv \cos\theta_{jk}$ and $s_{jk} \equiv \sin\theta_{jk}$.

Oscillation Highlights:

With three neutrinos we can access: two δm^2, three mixing angles, θ and one CP or T violating phase, δ.

(Majorana neutrinos have two more CP phases inaccessible in oscillations. These effect neutrinoless double beta decay.)

ATMOSPHERIC:

$$|\delta m^2_{atm}| = 3 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} \approx 1.0 \qquad \theta_{23} \sim \frac{\pi}{4} = 45^\circ \quad |U_{\mu 3}|^2 \approx \frac{1}{2}$$

SOLAR: assuming LMA

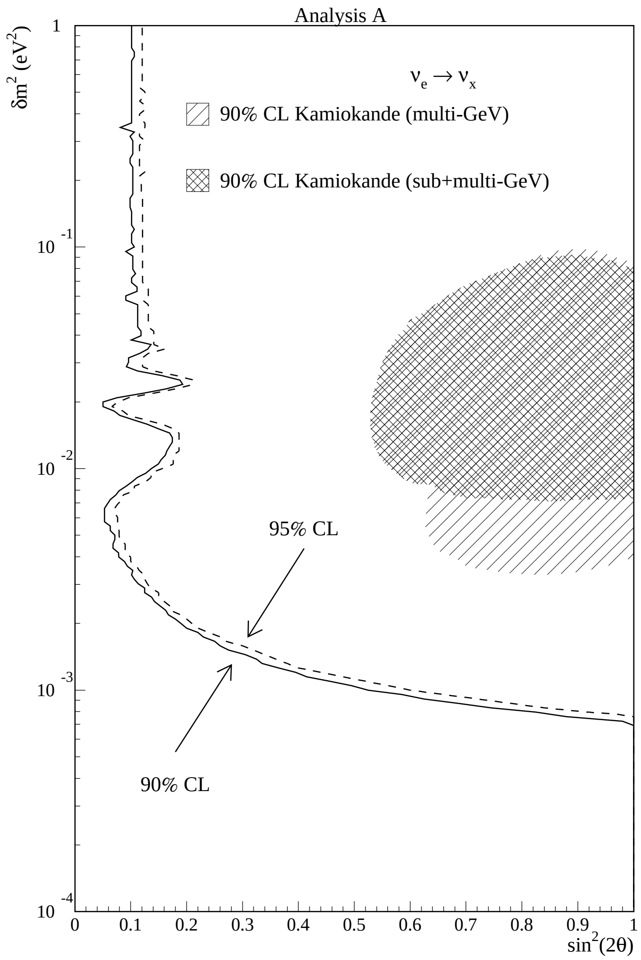
$$\delta m^2_{\odot} = +5 \times 10^{-5} eV^2$$

$$\sin^2 2\theta_{12} = 0.8 \qquad \theta_{12} \sim \frac{\pi}{6} = 30^\circ \quad |U_{e2}|^2 \approx \frac{1}{4}$$

REACTOR: (Chooz)

$$\sin^2 2\theta_{13} < 0.1 \qquad \theta_{13} < \frac{\pi}{20} = 9^\circ \quad |U_{e3}|^2 < 2.5\%$$

Chooz: ν_e Disappearance

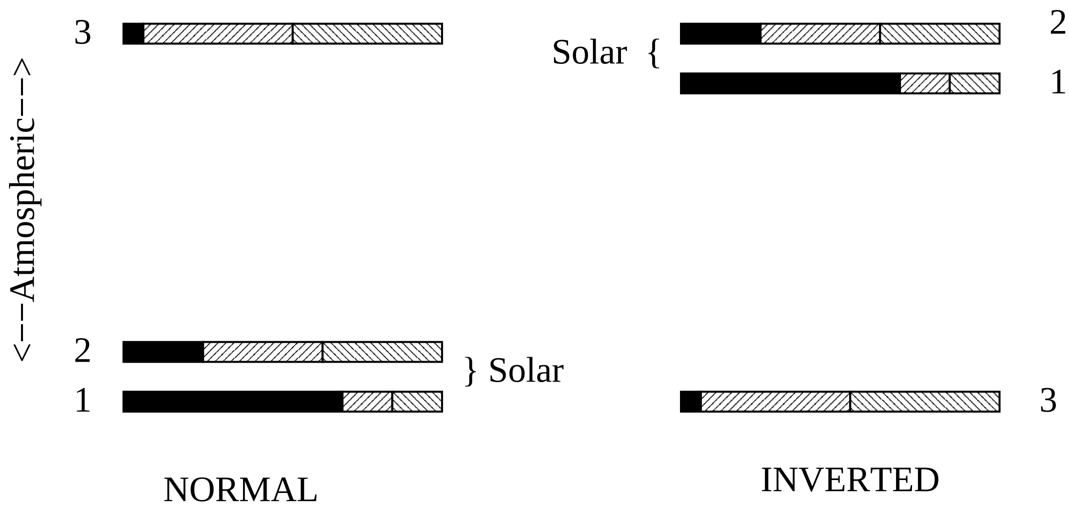


- at $|\delta m^2_{atm}| = 3 \times 10^{-3} eV^2$

$$\sin^2 2\theta_{13} < 0.1$$

- for all $|\delta m^2_{atm}|$ $\sin^2 2\theta_{13} < 0.05$

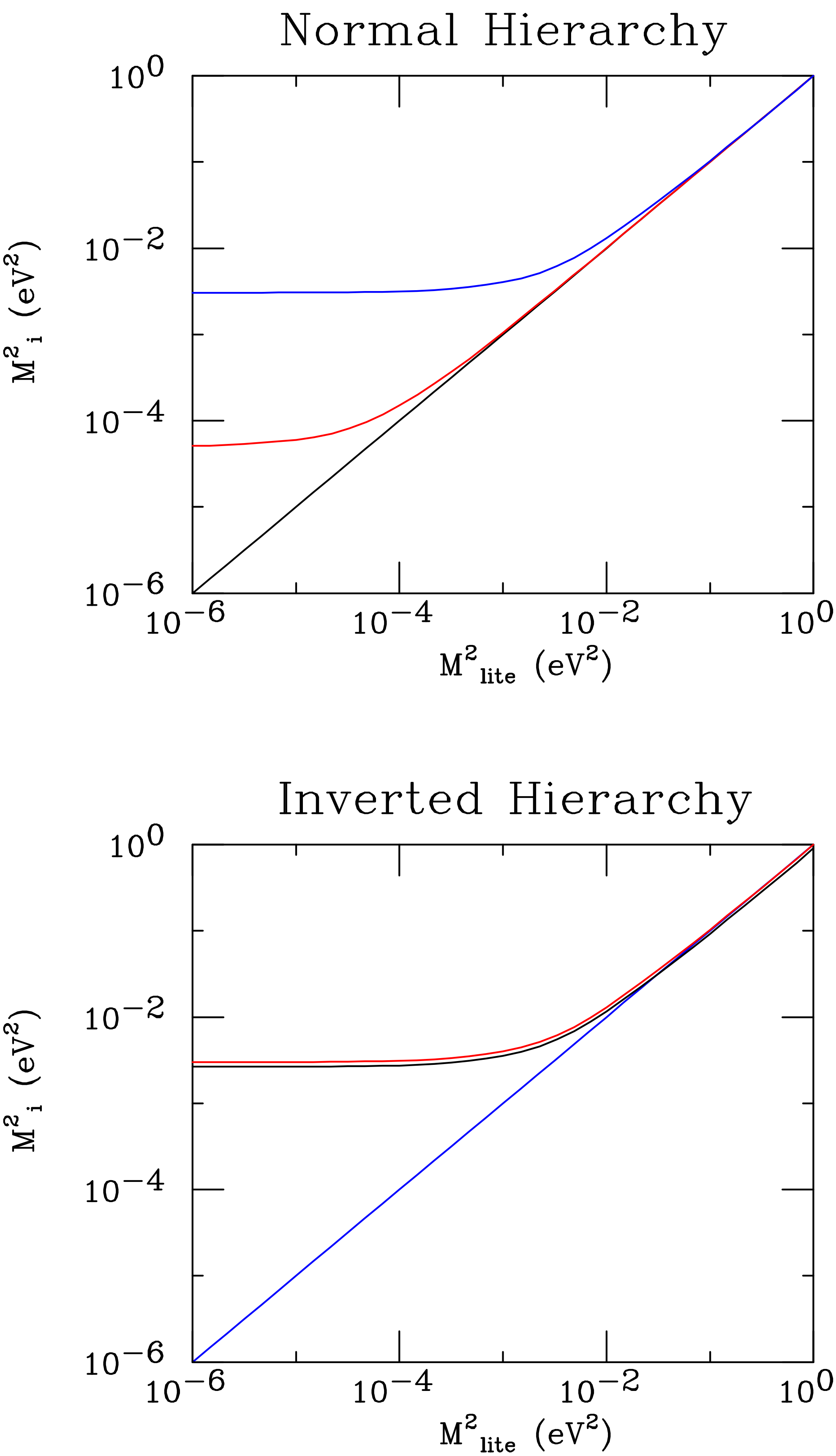
The Neutrino Picture:



$\delta m^2_{atm} > 0$: $\delta m^2_{atm} < 0$

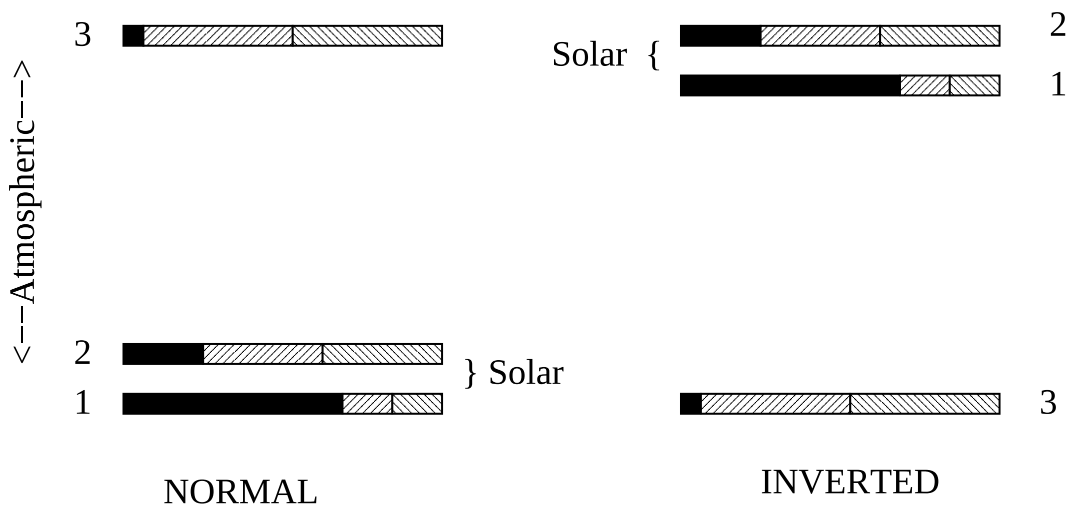
Wish List:

- Sign of δm^2_{atm}: normal verses inverted
- Size of θ_{13}: ν_e in "single" state
- Value of δ: CP violation
- Value of $\frac{\pi}{4} - \theta_{23}$: $\mu \leftrightarrow \tau$ sym breaking



Normal Hierarchy
$M^2{}_i$ (eV^2)
$M^2{}_{lite}$ (eV^2)
10^0
10^{-2}
10^{-4}
10^{-6}
Inverted Hierarchy
$M^2{}_i$ (eV^2)
$M^2{}_{lite}$ (eV^2)
10^0
10^{-2}
10^{-4}
10^{-6}

The Neutrino Picture:



$$\delta m^2_{atm} > 0 \quad : \quad \delta m^2_{atm} < 0$$

- Sign of δm^2_{atm}: Determined via Matter Effects

Important for

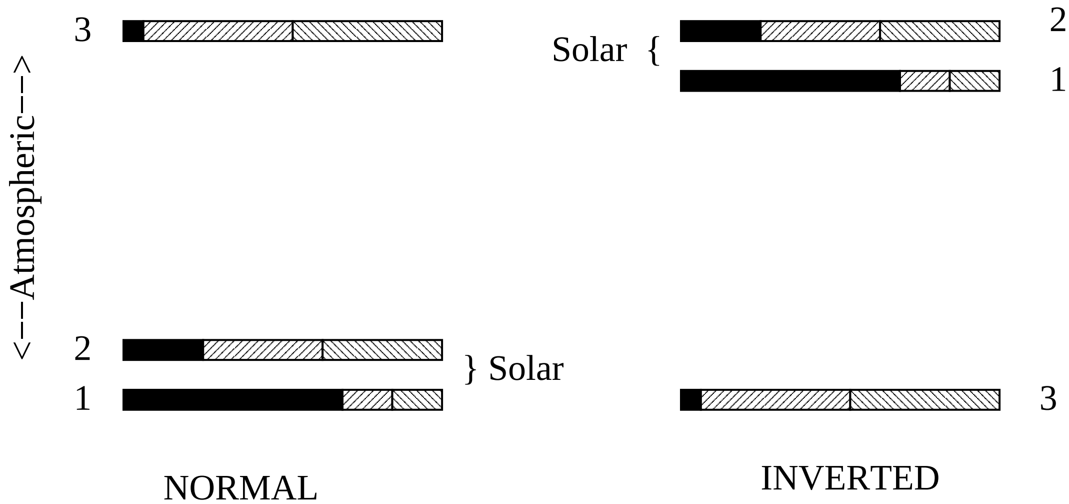
▷ Tritium β Decay

▷ ν-less $\beta\beta$ decay

▷ large scale structure 1 verses 2 neutrinos with

$$m > \sqrt{|\delta m^2_{atm}|}$$

The Neutrino Picture:



$$\delta m^2_{atm} > 0 \quad : \quad \delta m^2_{atm} < 0$$

- Size of θ_{13}:

▷ Long Baseline $\nu_\mu \to \nu_e$ and/or $\nu_e \to \nu_\mu$ at atmospheric L/E $\approx$ 500km/GeV.

For normal hierarchy important for

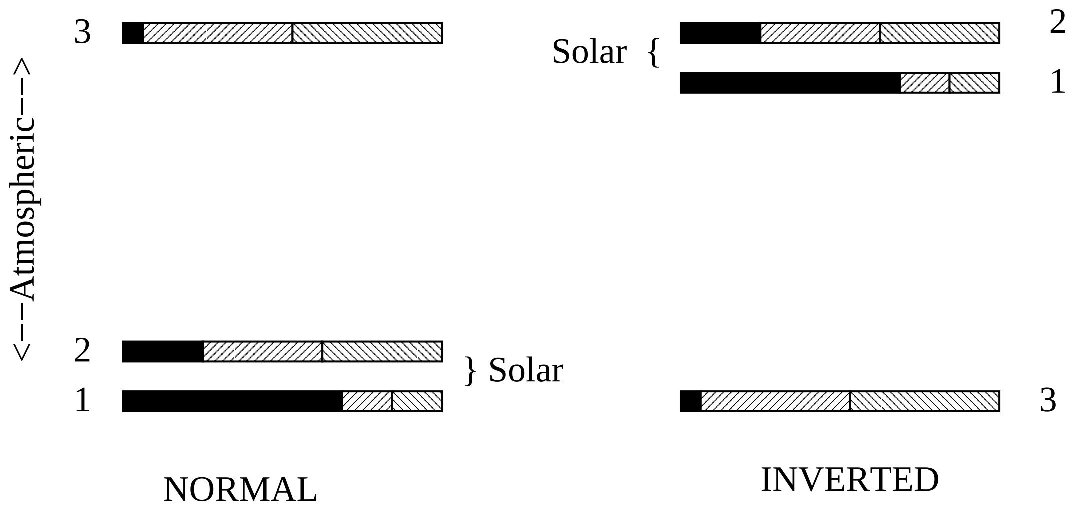
▷ Tritium β Decay

$$\begin{aligned} '' \; m^2_{\nu_e} \; '' &= |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2 \\ &\approx m_1^2 + |U_{e2}|^2 \delta m^2_\odot + |U_{e3}|^2 \delta m^2_{atm} \\ &\sim m_1^2 + 10^{-5} \; eV^2 + < 10^{-4} \; eV^2 \end{aligned}$$

▷ ν-less $\beta\beta$ decay

$$m_3 U^2_{e3} + \cdots$$

The Neutrino Picture:



$$\delta m^2_{atm} > 0 \quad : \quad \delta m^2_{atm} < 0$$

- Value of δ:

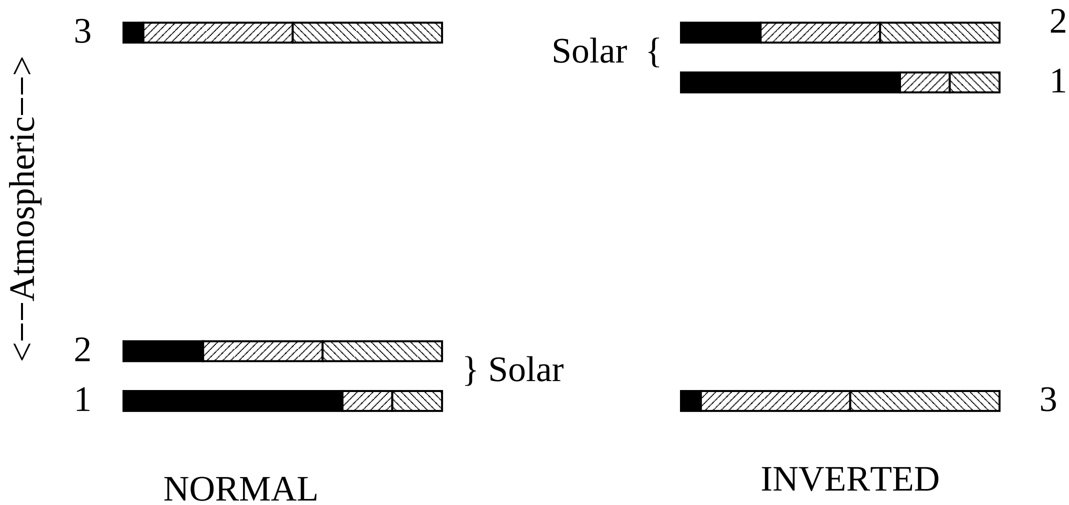
▷ CP Violation!

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

$$\begin{aligned} \Delta P_{viol} = \quad & \sin\delta \\ * \quad & (\sin 2\theta_{13} \ \sin\Delta_{13}) \cos\theta_{13} \\ * \quad & (\sin 2\theta_{23} \ \sin\Delta_{23}) \\ * \quad & (\sin 2\theta_{12} \ \sin\Delta_{12}) \end{aligned}$$

where $\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E}$

The Neutrino Picture:



$$\delta m^2_{atm} > 0 \quad : \quad \delta m^2_{atm} < 0$$

- Also value of $\frac{\pi}{4} - \theta_{23}$

Numerical Fact:

If $0.97 < \sin^2 2\theta_{23} < 1.0$ then $40^\circ < \theta_{23} < 50^\circ$ or $0.41 < \sin^2\theta_{23} < 0.59$. So the fraction of ν_μ in 3 mass state can be 50 ± 9 %.

If $\theta_{23} = \frac{\pi}{4}$ then there is a $\mu \leftrightarrow \tau$ symmetry. The departure from $\frac{\pi}{4}$ tells us the SIZE and the SIGN of the symmetry breaking. Very Important for model building.

"The Key Process"

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

In vacuum

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \sin^2(\Delta_{atm})$$

$$+ J_r\, \Delta_\odot\ \sin\Delta_{atm}\,(\cos\delta\cos\Delta_{atm}\ \pm \sin\delta\sin\Delta_{atm})$$

plus for ν's and minus for $\bar{\nu}$'s.

$$\Delta_{atm} = \frac{\delta m^2_{atm} L}{4E} \quad \& \quad \Delta_\odot = \frac{\delta m^2_\odot L}{4E} \approx \frac{1}{60}\ \Delta_{atm}$$

$$(\sim 1.27\ \frac{\delta m^2 L}{E} \quad \text{in } eV^2\ km\ GeV^{-1})$$

with

$$J_r = \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$

$$\approx 0.3\ \sqrt{\frac{\sin^2 2\theta_{13}}{0.1}}$$

At the first oscillation maximum and using $\sin^2 2\theta_{23} = 1$ then

$$P(\nu_\mu \to \nu_e) = 0.5 \ \sin^2 2\theta_{13} \ \pm 0.016 \ \sin\delta \sin 2\theta_{13}$$

at the upper bound on $\sin^2 2\theta_{13} = 0.1$ (Chooz).

$$\boxed{P(\nu_\mu \to \nu_e) = 5\% \ \pm 0.5\% \sin\delta}$$

- Matter Effects also split

  Neutrinos from Anti-Neutrinos.

can be used to distinguish

$\delta m^2_{atm} > 0$ from $\delta m^2_{atm} < 0$.

Matter Effects and the sign of δm^2_{atm}:

$$P_{mat}(\nu_\mu \to \nu_e) = \sin^2\bar\theta_{23}\ \sin^2 2\bar\theta_{13}\ \sin^2(\bar\Delta_{atm})$$

where the bar indicates that quantity (θ's and δm^2's) in matter.

$$P_{mat}(\nu_\mu \to \nu_e) = \sin^2\bar\theta_{23}\ \sin^2 2\bar\theta_{13}\ \bar\Delta^2_{atm}\ \frac{\sin^2(\bar\Delta_{atm})}{\bar\Delta^2_{atm}}$$

$$\Updownarrow$$

$$= \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \Delta^2_{atm}\ \frac{\sin^2(\bar\Delta_{atm})}{\bar\Delta^2_{atm}}$$

Now if $\bar\Delta = \Delta(1-\epsilon)$ then near $\Delta = \frac{\pi}{2}$

$$\left(\frac{\sin^2\bar\Delta}{\bar\Delta^2}\right) \approx \left(\frac{\sin^2\Delta}{\Delta^2}\right)(1+2\epsilon)$$

Thus near the Peak

$$P_{mat}(\nu_\mu \to \nu_e) \approx (1+2\epsilon)P_{vac}(\nu_\mu \to \nu_e)$$

with $\quad \epsilon \approx E_\nu/13GeV$

Possible Experiments:

The peaks occurs when $\Delta_{atm} = (2n-1)\frac{\pi}{2}$:

JHF to SK n=1

$E = 0.72\ GeV\ (\frac{\delta m^2_{atm}}{3\times10^{-3} eV^2})\ (\frac{L}{295 km})$

NuMI n=1

$E = 1.8\ GeV\ (\frac{\delta m^2_{atm}}{3\times10^{-3} eV^2})\ (\frac{L}{732 km})$

BNL to Homestake n=1, 2, 3

$E = 6.16,\ 2.05,\ 1.25\ GeV\ (\frac{\delta m^2_{atm}}{3\times10^{-3} eV^2})\ (\frac{L}{2540 km})$

Marciano

Bi-Probability Plots:

$P(\nu_\mu \to \nu_e)$ verses $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
holding all parameters fixed except the CP phase, δ, which varies from 0 to 2π.

Minakata and Nunokawa hep-ph/0108085

JHF → Super-Kamiokande

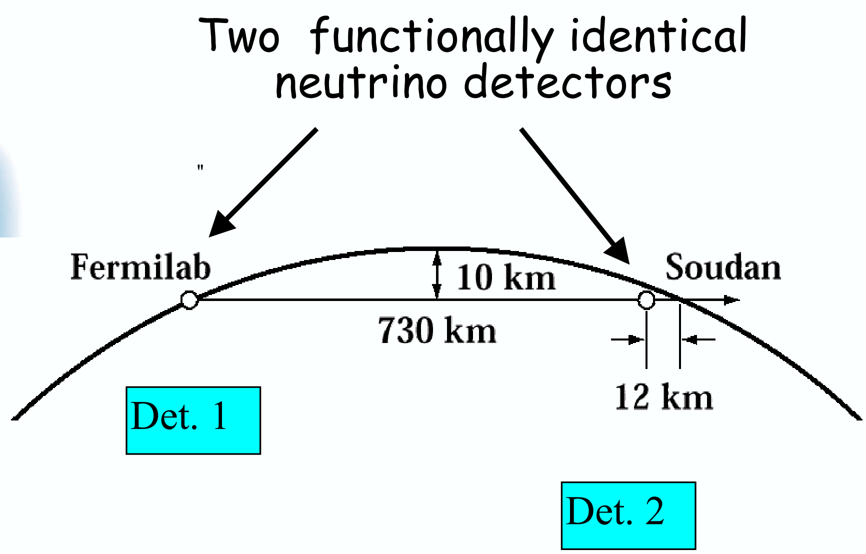
- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID
  - Additional π^0/e ID
- Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- Matter effects small
- Study using fully simulated and reconstructed data

Requires New Beamline:

http://www-off-axis.fnal.gov/

LOI: hep-ex/0106019

The NUMI Beamline



New Detector Required:

http://www-off-axis.fnal.gov/

LOI: hep-ex/0210005

Brookhaven to Homestake OR WIPP

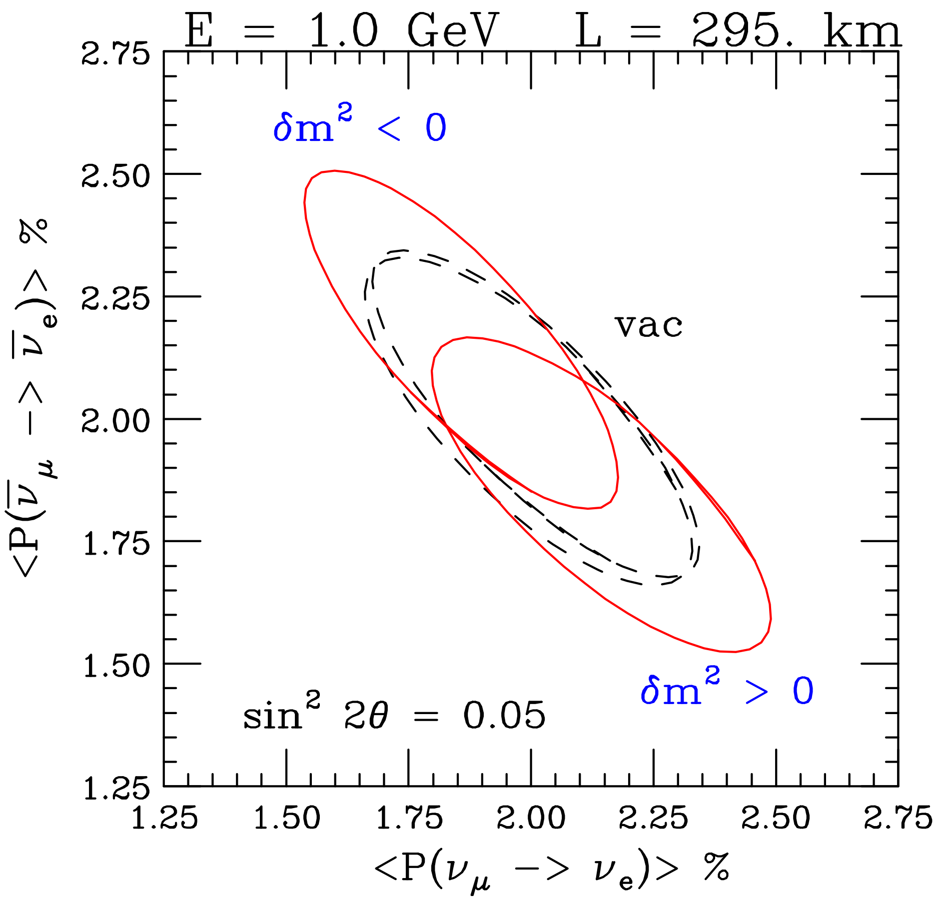
L= 2540 km or 2880 km

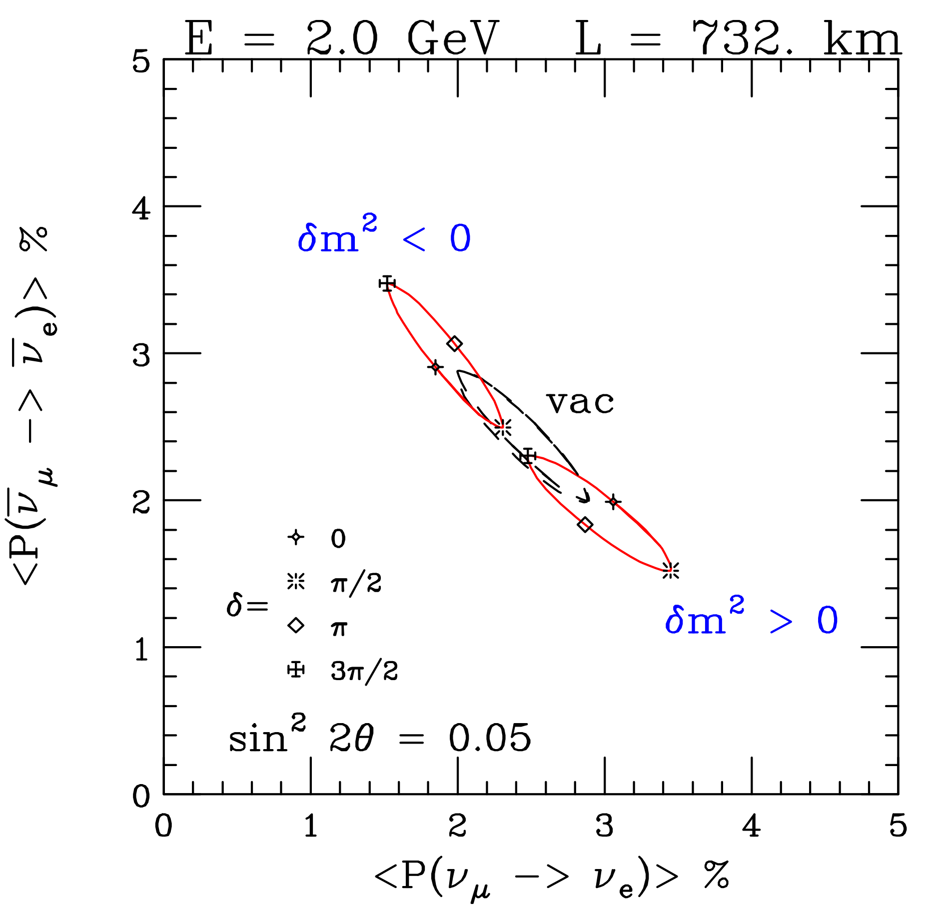
New Beamline, New Detector:

http://www.neutrino.bnl.gov/

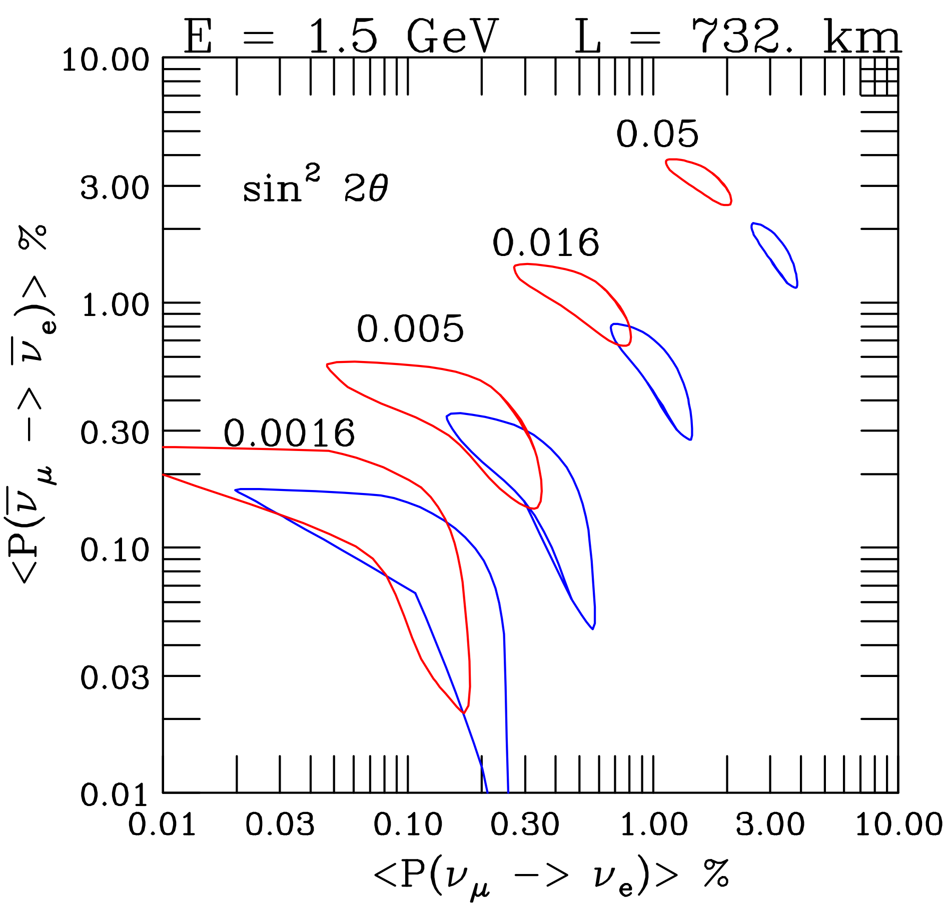
LOI: hep-ex/0205040

JHF to SK and NuMI to ???



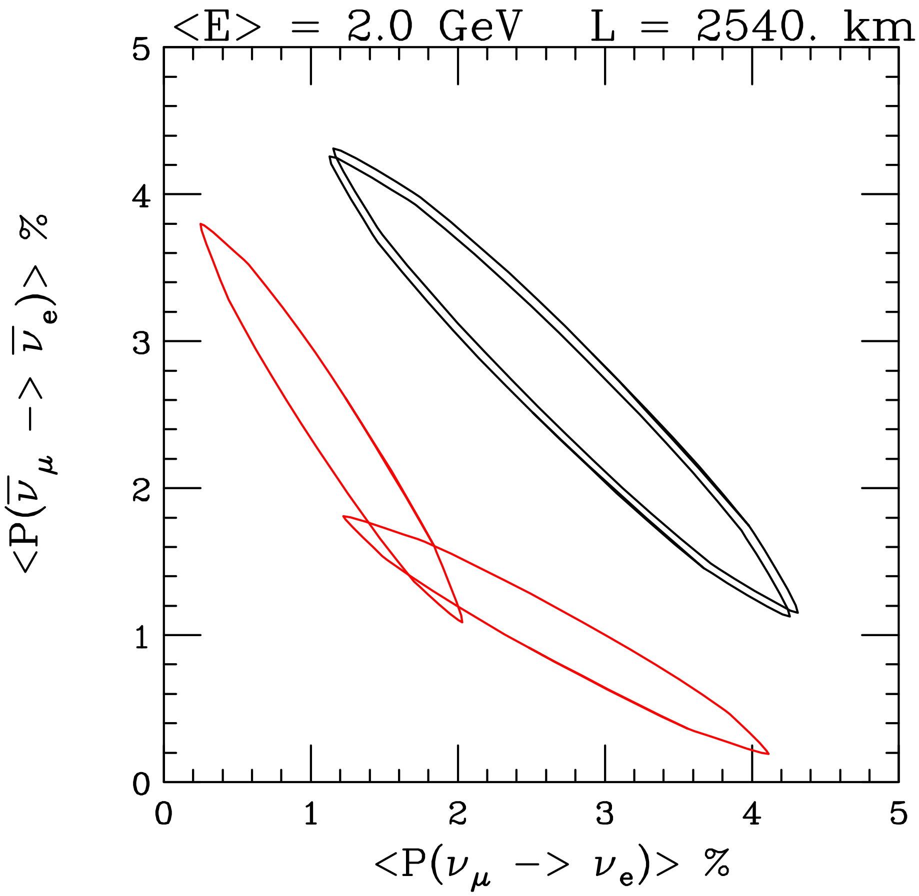


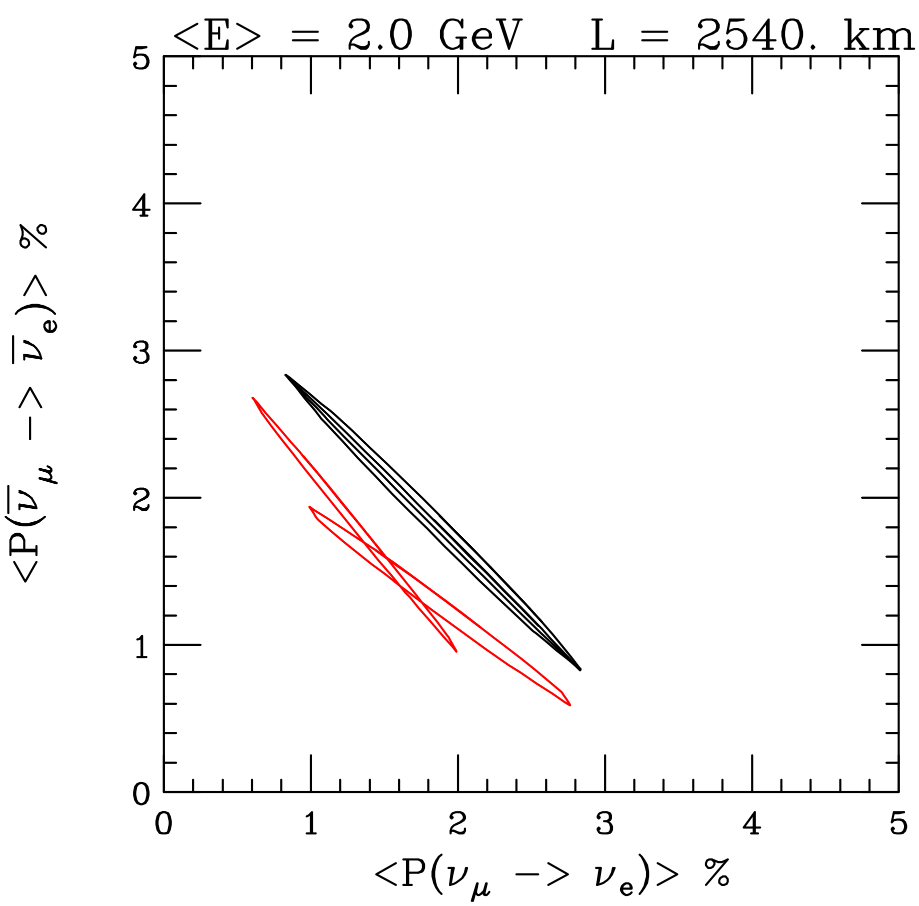
As $\sin^2 2\theta_{13}$ Varies:



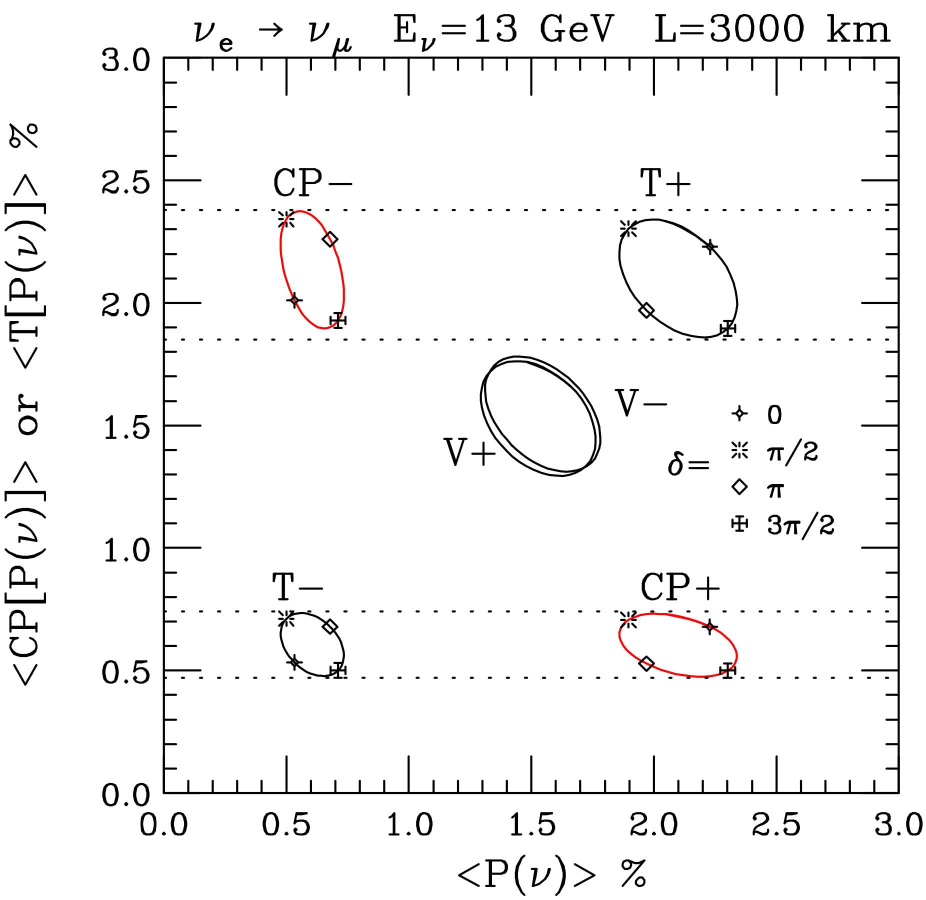
BNL to Homestake:

0% and 20% beam spread



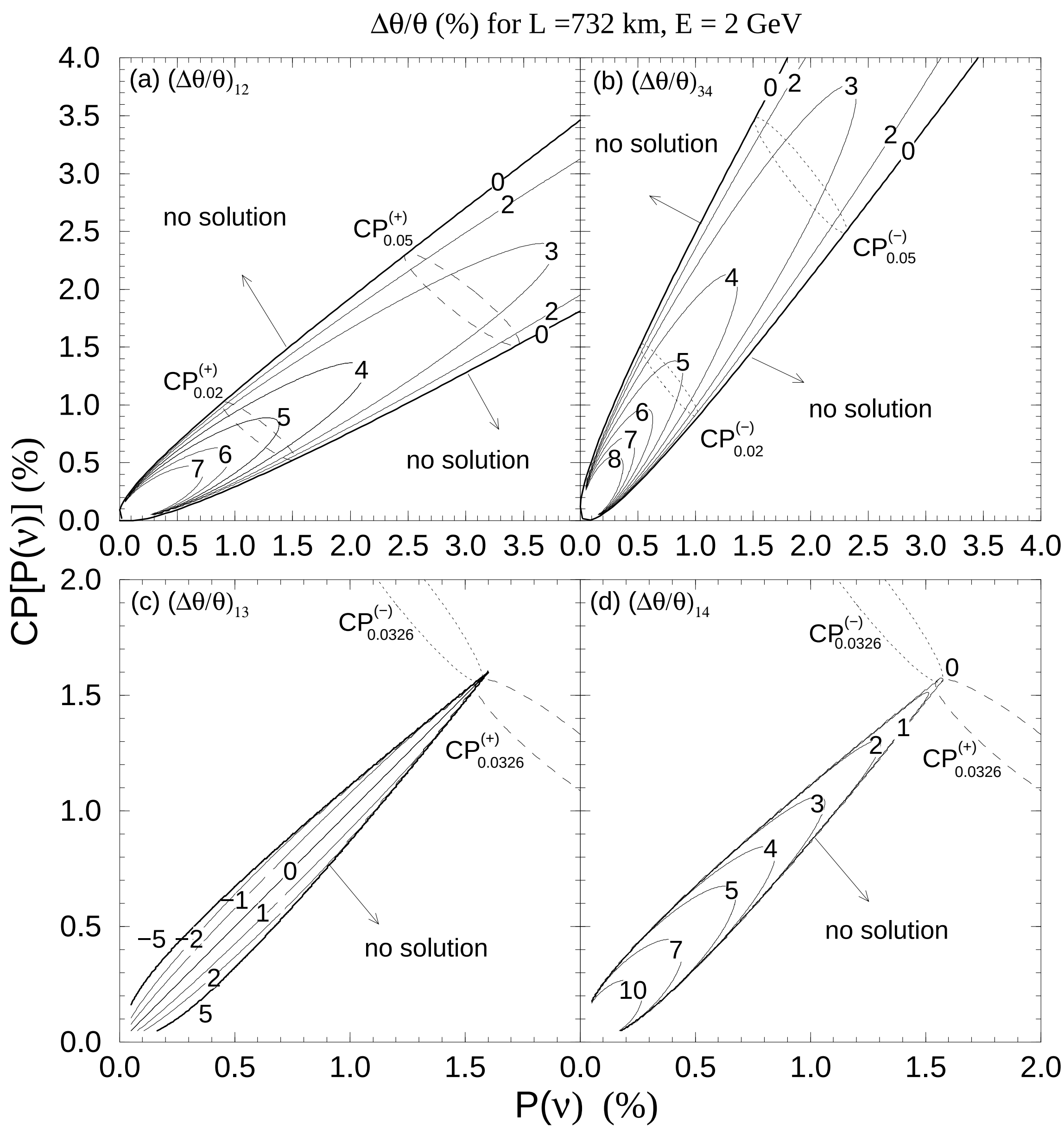


The Dream Machine: Neutrino Factory using a Muon Storage Ring



Parameter Degeneracies:

- In general there is an Eight Fold Degeneracy. two for θ_{23}, sign of δm^2_{13} and θ_{13}.



- Precision Determination will require experiments at more than one E and L.

SUMMARY:

- (If) Kamland confirms LMA

and

- θ_{13} is within a factor of 3 of the Chooz

bound: $(\sin^2 2\theta_{13} > 0.01)$

then

We have a great OPPORTUNITY!!!

CP Violation in the Lepton Sector is measureable in the near future as well as other neutrinos properties.

- Value of θ_{13},
- Normal verses Inverted hierarchy
- Deviation of θ_{23} from $\pi/4$.

and

- CP Violating phase δ.

Next Step: Understanding

Fermion Masses and Mixings