Questions:

- Majorana v. Dirac
  $\Rightarrow$ lepton # violation } B.K.

- # light neutrinos
  $\Rightarrow$ 3 + ...

- Masses & Mixings
  $\Rightarrow m^2_{\text{lightest}}$, δm^2's, θ's, δ's

Diamond in the rough ?!!

LSND: $\mu \to e \bar{\nu}_\mu \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_e$ at 0.3% level

with $\Delta m^2 \sim 1\,eV^2$

$\sin^2 2\theta \sim 10^{-2\pm0.5}$

muon decay

DAR

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} = 0.264 \pm 0.067 \pm 0.045\%$$

$$\left(P_{\nu_\mu \to \nu_e} = 0.10 \pm 0.16 \pm 0.04\% \right)$$

DIF

More light neutrinos

OR.

violate CPT

(ν spectrum $\neq \bar{\nu}$ spectrum)

Are there any light sterile neutrinos?

δm^2_{atm} scale:

SK { matter effects in atmospheric ν's
$< 20\%$ ν_s

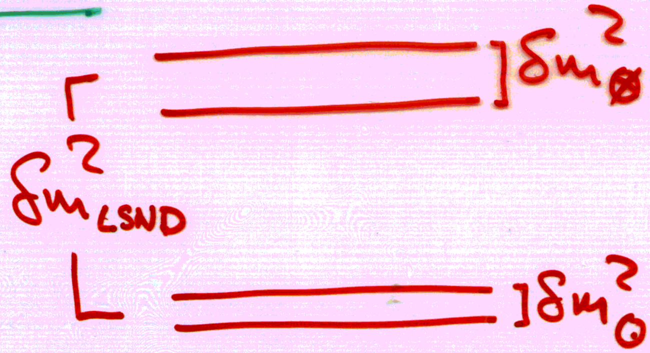
MINOS (NC/CC ratio)

δm^2_{solar} scale:

SNO $< 50\%$ ν_s

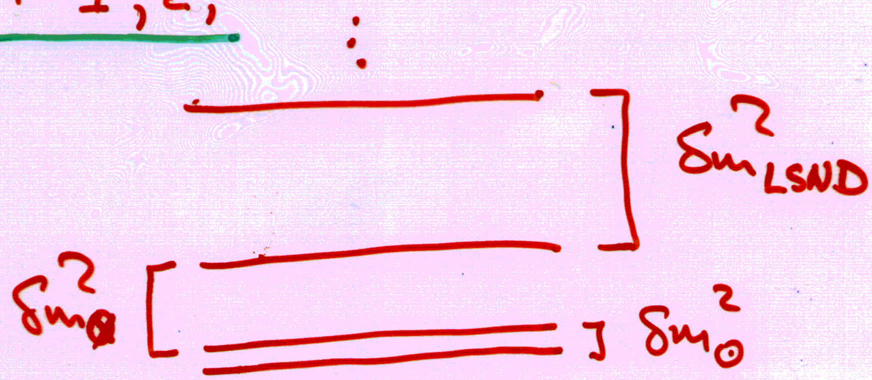
- comes from theoretical uncertainty in ^8B flux
- D/N asymmetry may improve this

2 + 2



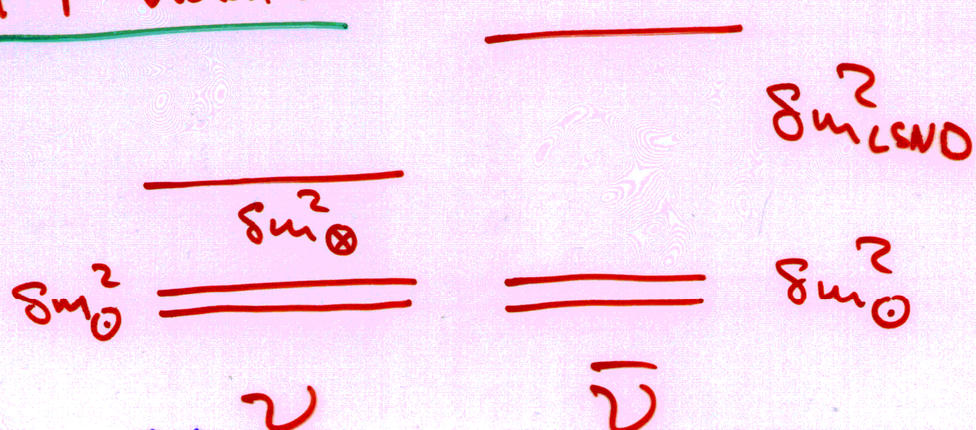
1 ν_s in solar + atmospheric ~ marginal
Weiler etal

3 + 1, 2, ...



Constrainted by ν_μ , ν_e dissappearance
3+2 Sorel eta

CPT Violation



Barenboim etal

MINOS atmospheric ν υ $\bar{\nu}$

mini-BOONE: $\pi \to \mu \, \nu_\mu$

Suppose mini-BOONE sees a convincing signal, consistent with LSND.

How many δm^2 involved?

What are their mixings, $\sin^2 2\theta_{eff}$?

Do we need a NEAR Detector (FINeSE)

or a FAR Detector (BOONE)

or BOTH ???

What about CP violation?

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

How is ν_τ involved?

Can FERMILAB response in a timely fashion? Brookhaven CERN Japan

◆ Number of light Neutrinos

If mini BOONE confirms LSND then Fermilab must exploit this opportunity in a timely fashion:

- new detector(s)
- sufficient P.O.T.
- maybe even new ν beamlines

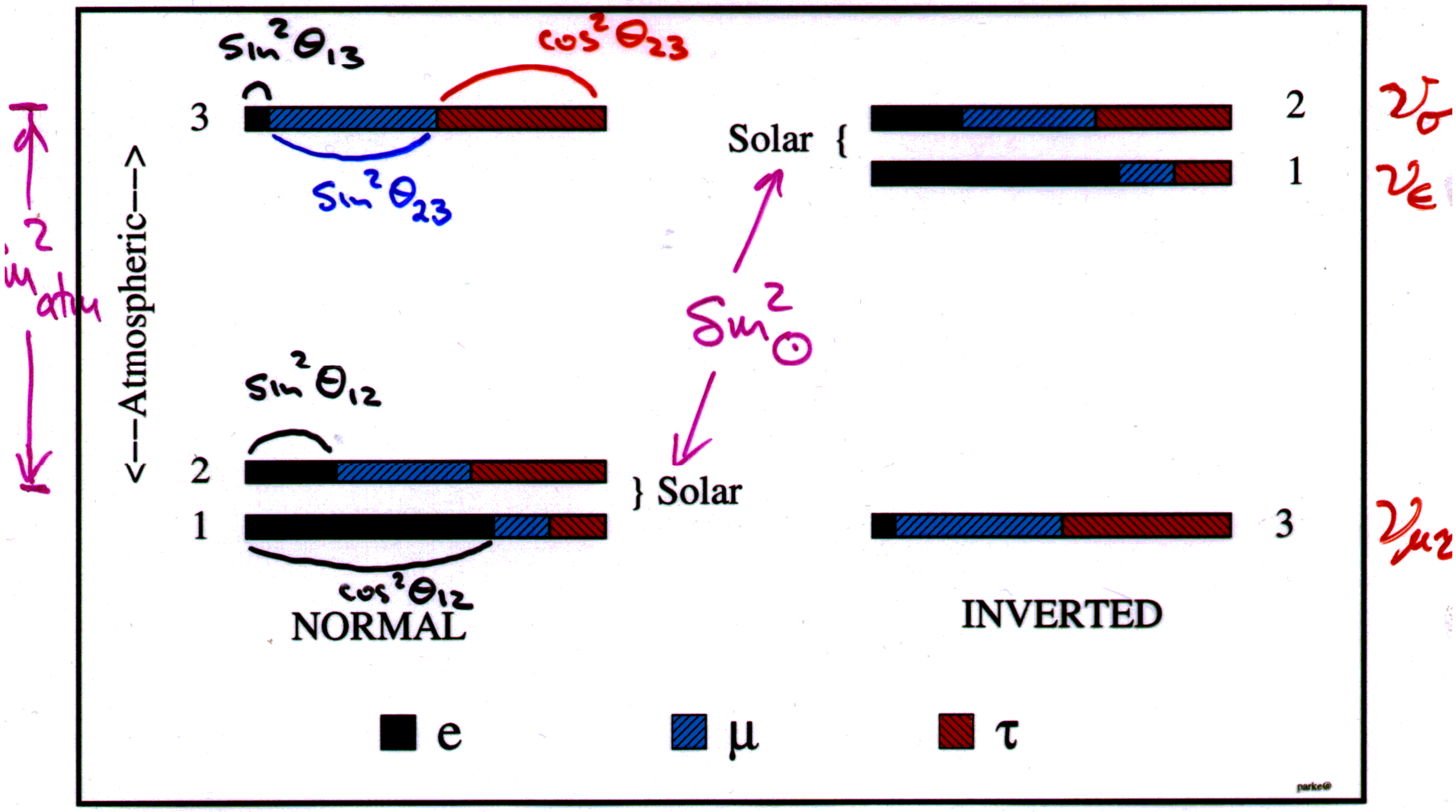
δm^2's , $\sin^2 2\theta_{eff}$'s

also

CP violation and role of ν_τ

Sans LSND

and $\cos^2\theta_{13} \approx 1$



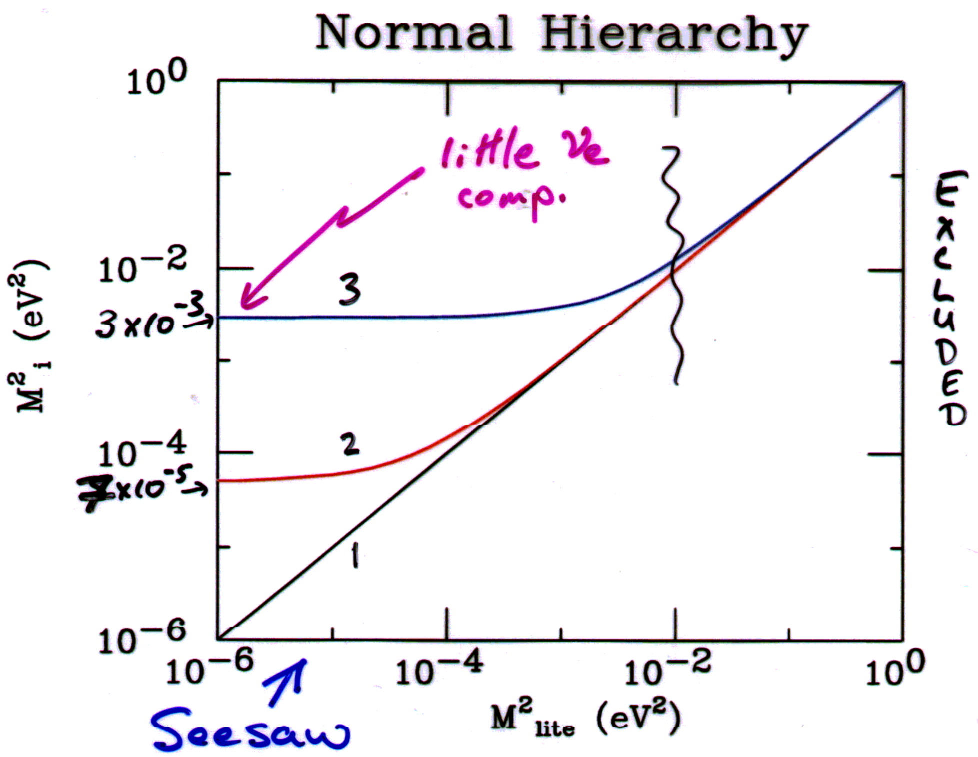
δm^2_{atm} ; δm^2_{solar}

$\sin^2\theta_{23}$; $\sin^2\theta_{12}$

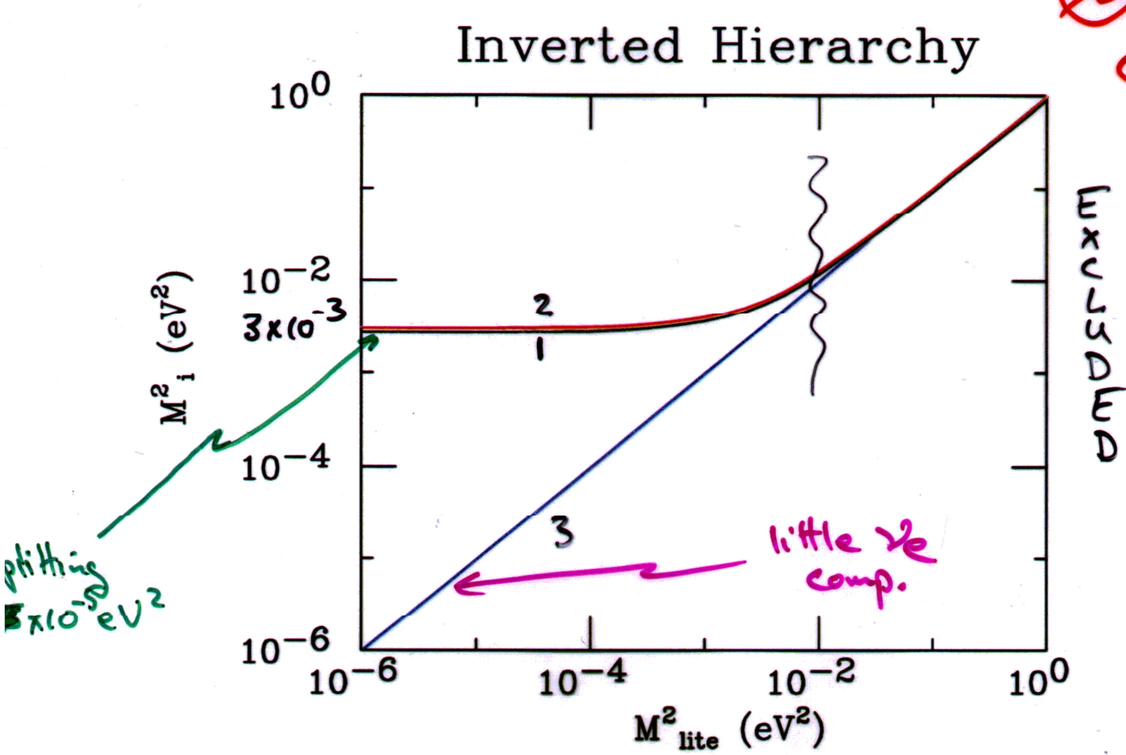
$\sin^2\theta_{13}$ and phase $\delta_{CP}\left\{\begin{matrix}\sin\delta\\ \cos\delta\end{matrix}\right.$

and m^2_{lite}

MASS SPECTRUM: $n = 3$

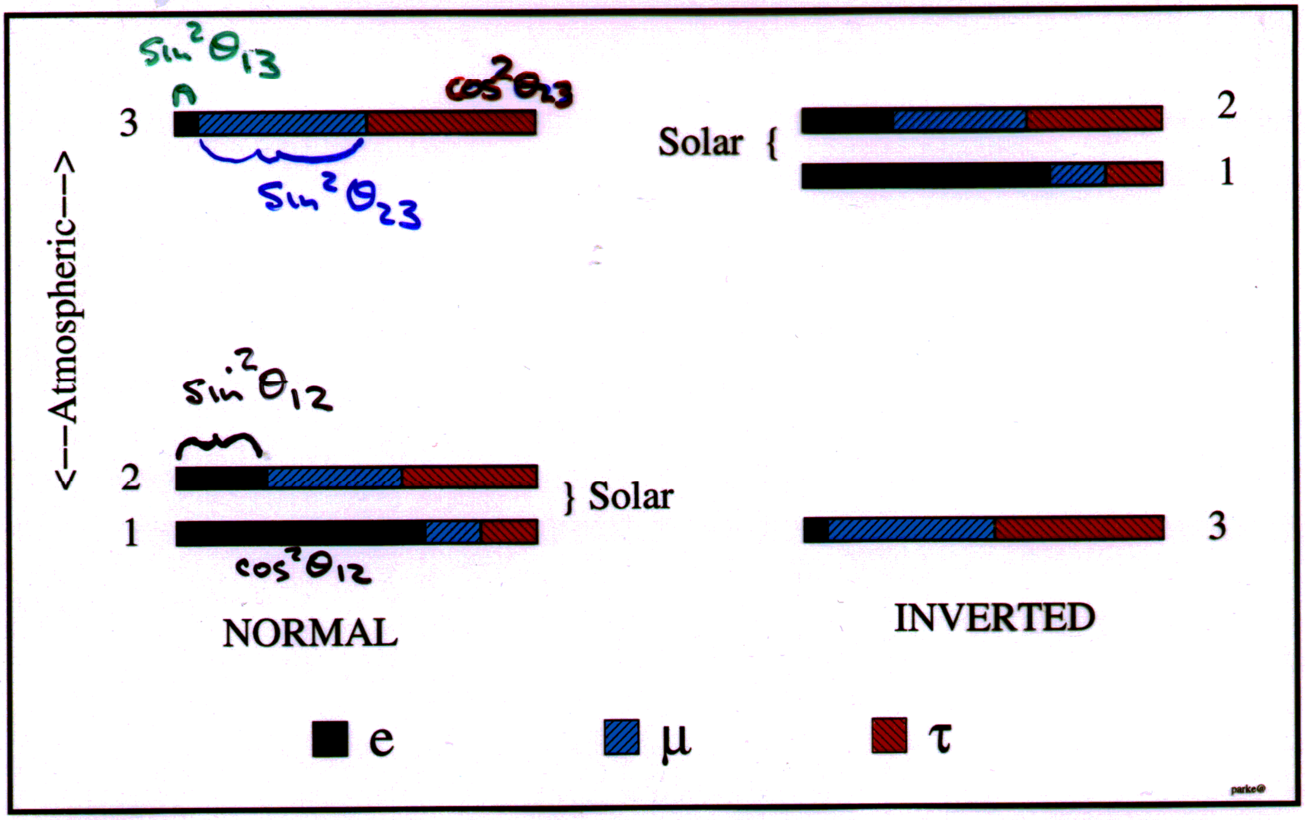


tritium
0νββ decay
cosmology



Beacon + Bell

Sans LSND



SOLAR: (SNO, KamLAND, SK, ...)

$$\delta m^2_{solar} = +7.1 \pm 2.0 \times 10^{-5}\,eV^2$$

$$0.23 < \sin^2\theta_{12} < 0.35 \quad \left(\tfrac{1}{2} \text{ excluded at } 5.4\sigma\right)$$

ATMOSPHERIC: (SK, K2K, ...)

$$|\delta m^2_{atm}| = 1.5 - 3.5 \times 10^{-3}\,eV^2$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

CHOOZ: (+SK)

$$\sin^2\theta_{13} < \begin{cases} 0.03 & \delta m^2_{atm} = 3\times10^{-3}\,eV^2 \\ 0.05 & \delta m^2_{atm} = 2\times10^{-3}\,eV^2 \end{cases}$$

Solar Parameters:

$$\delta m^2_{21}, \quad \sin^2\theta_{12}$$

SNO, KamLAND, SK ....

$$\delta m^2_{21} = +7.1 \times 10^{-5}\, eV^2$$

$$0.23 < \sin^2\theta_{12} < 0.35$$

[0.5 excluded at $> 5\sigma$

LBL need δm^2_{21}, $\sin 2\theta_{12}$

— precision measurement

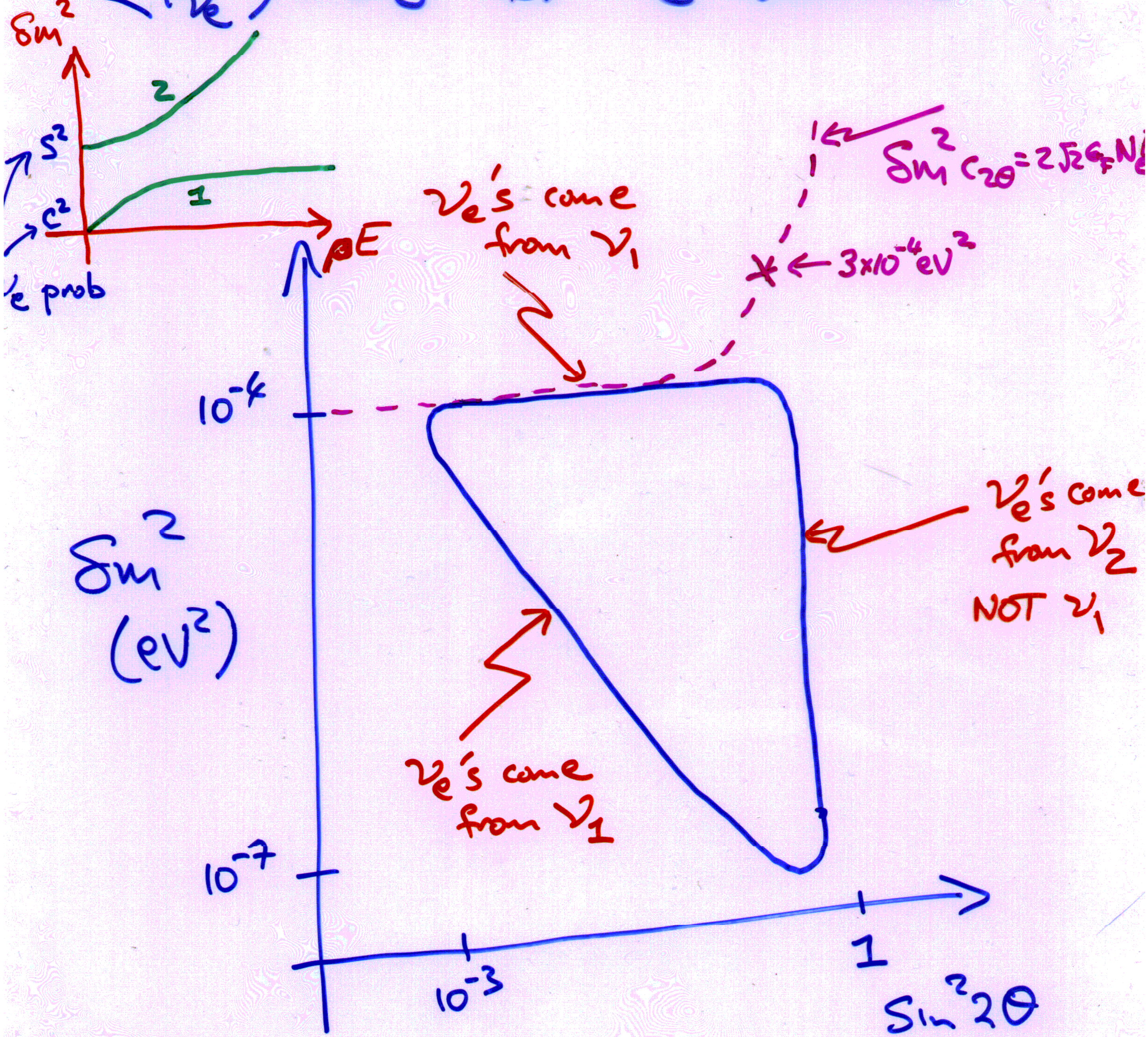
— D/N asymmetry, Spectral Distortion ✓✓✓

— Subleading effects, θ_{13}

— ν_s component

— Inconsistencies and Surprises !

$\langle P_{\nu_e} \rangle = 0.3$ for ^8B Neutrinos



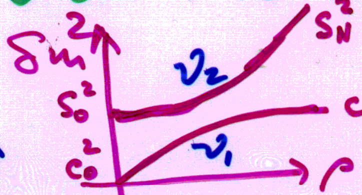
$$\langle P_{\nu_e} \rangle = \frac{1}{2} + \left(\frac{1}{2} - P_{jump}\right) \cos 2\theta_{VAC} \cos 2\theta_{MATT}$$

SP PRL 57, 1275 ('86)

ELECTRON NEUTRINO SURVIVAL

$P^{^8B}_{SNO} = 0.306 \pm 0.026 \pm 0.024$ ← solar ν_e

$P^{Reac}_{Kam} = 0.611 \pm 0.085 \pm 0.041$ ← Reactor $\bar{\nu}_e$



Solar: Matter

$$\langle P^{^8B}_{\nu_e \to \nu_e} \rangle = \sin^2\theta_{12}^{VAC} \underbrace{\sin^2\theta_{12}^{MAT}}_{\approx 1} + \cos^2\theta_{12}^{VAC} \underbrace{\cos^2\theta_{12}^{MAT}}_{\approx 0}$$

$$\simeq \sin^2\theta_{12}^{VAC} = 0.3$$

$\theta_{12}^{MAT} = \frac{\pi}{2}$?

Reactor: VACUUM

$$\langle P^{Reac}_{\bar{\nu}_e \to \bar{\nu}_e} \rangle \simeq \sin^4\theta_{12}^{VAC} + \cos^4\theta_{12}^{VAC}$$

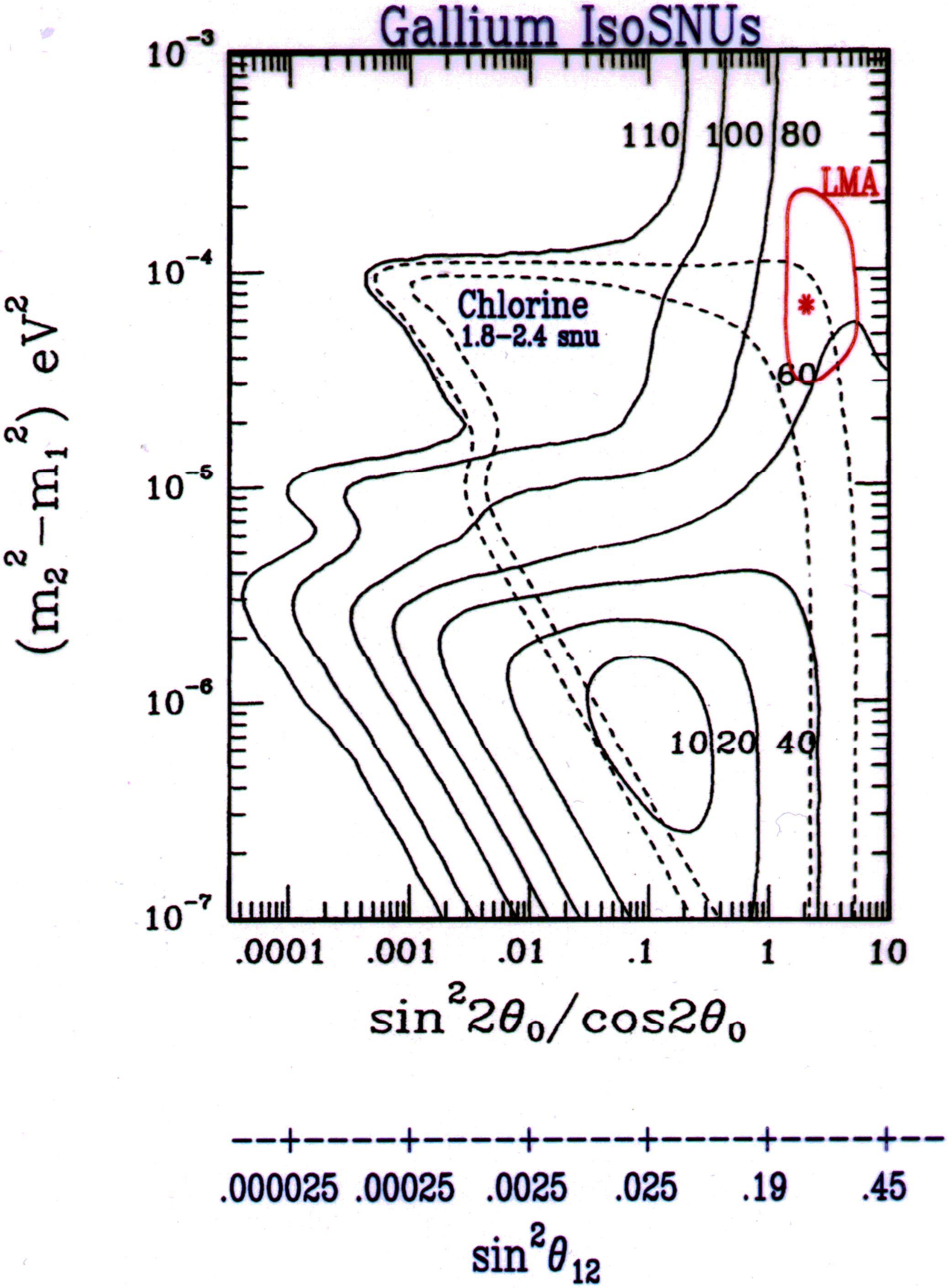
(same as $1 - \frac{1}{2}\sin^2 2\theta_{12}^{VAC}$)

$$= 0.3^2 + 0.7^2$$

$$= 0.58$$

KAMLAND = 0.61 ✓

Energy Average?

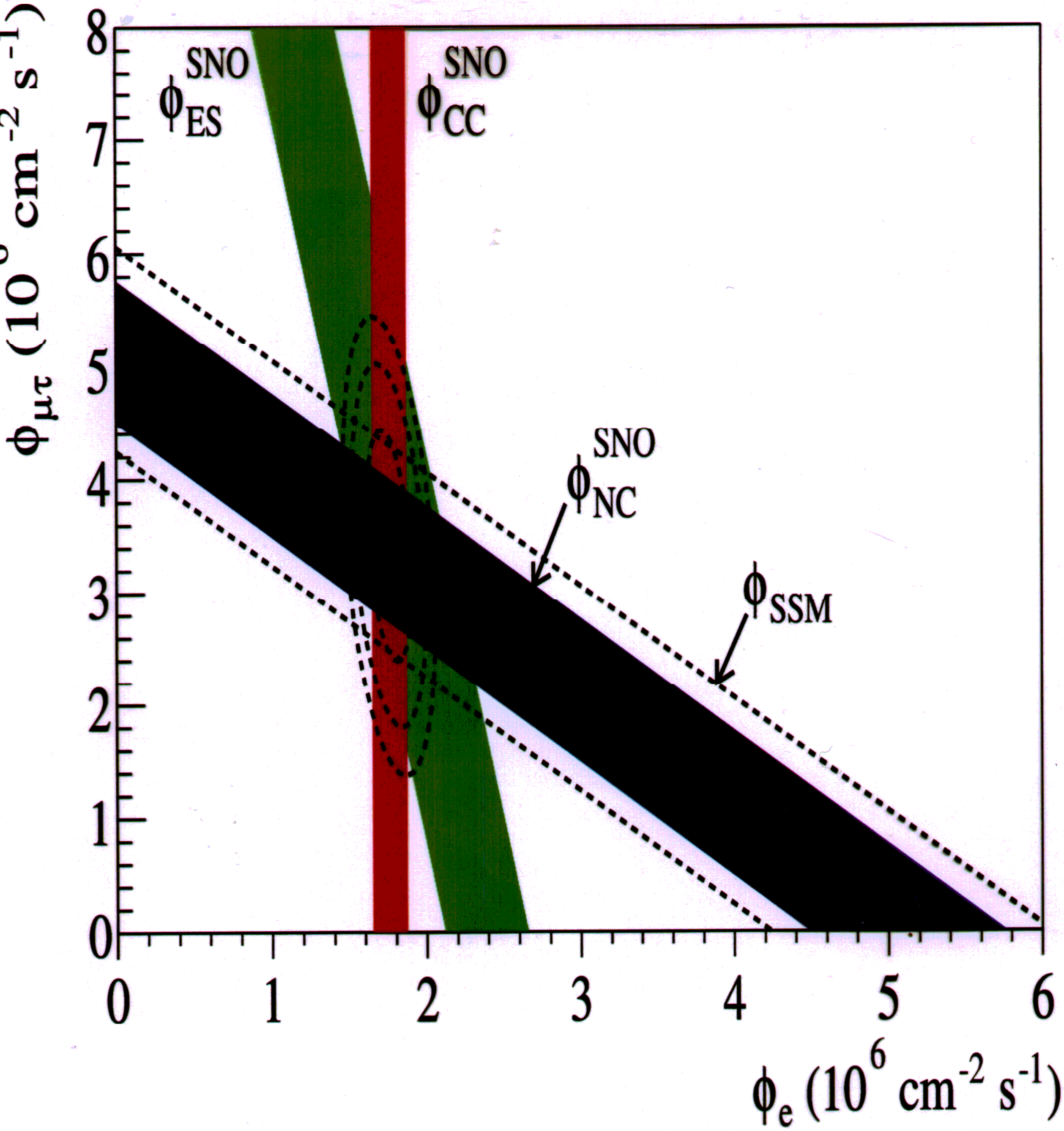


S. Parke and T. Walker – PRL 57, 2322 (1986)

--based on analytic results of

S. Parke – PRL 57, 1275 (1986)

— SNO —



works because
Spectral distortion
is small

Atmospheric Parameters:

$$\delta m^2_{32}\ ,\ \sin^2\theta_{23}$$

SK, K2K, ...

$$|\delta m^2_{32}| = 1.5 - 3.5 \times 10^{-3}\ eV^2$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

$|\delta m^2_{32}|$

- improve marginally with more K2K running
- MINOS 10% measurement
  - oscillations
- JPARC – NuMI-Off-Axis
  uncertainty of $1 \times 10^{-4}\ eV^2$

$$\Delta m^2_{32}\Big| \simeq c^2_{12}\,\delta m^2_{32} + s^2_{12}\,\delta m^2_{31}$$

ν_μ dissappearance experiment

$$= \delta m^2_{32}\left(1 + s^2_{12}\frac{\delta m^2_{21}}{\delta m^2_{32}}\right)$$

1% effect

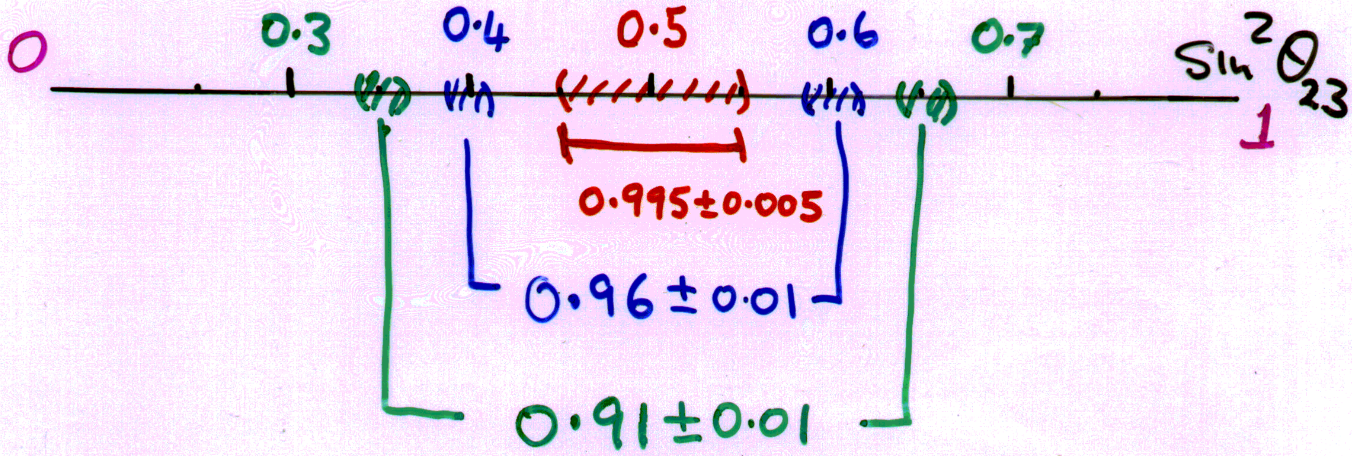
$\sin^2 2\theta_{23} > 0.91$

$$0.35 < \sin^2\theta_{23} < 0.65$$

$\theta_{23} = \pi/4$ μ-τ symmetry point

JParc + NuMI-Off-Axis: $\sin^2 2\theta_{23}$ to 1%

$$\sin^2\theta_{23} = (1 \pm \epsilon)/2$$



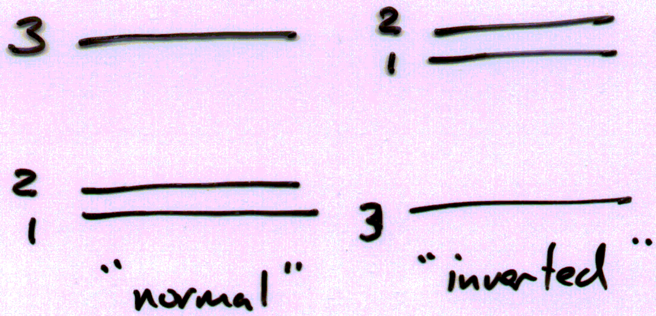
$$\sin^2 2\theta_{23} = 1 - \epsilon^2$$

$\nu_\mu \to \nu_\mu$ poor way to measure $\sin^2\theta_{23}$ near $\pi/4$

A Reactor measurement of θ_{13} can help!

magnitude and sign of breaking:

Sign δm^2_{32}



- $\not{\nu}$ $\beta\beta$ decay with $m_{\beta\beta} \sim 10\,\text{meV}$
- Supernova ?
- Cosmology 1 v 2 ν at 50meV
- Reactors:
  interference of solar + atmospheric
  at intermediate distances:
  20-30km (Shape!)
- Matter Effects in LBL:

$\sin^2\theta_{13}$

Current bound from Chooz Reactor:

$$\sin^2\theta_{13} < 3-4 \times 10^{-2}$$

depending δm^2_{atm}

- subleading effects solar
- atmospheric especially $\cos\theta_{zenith} \simeq -1$
- Supernova ?
- Reactors:

sensitivity down to

$$\sin^2\theta_{13} \sim 3-4 \times 10^{-3}$$

systematics + statistics (shape)

Independent of θ_{23}, sign δm^2_{32} and δ_{CP}: Pure θ_{13} measurement

- Long Baseline: $\nu_\mu \to \nu_e$ or $\nu_e \to \nu_\mu$

Super beams ... ν factory

at (vacuum) Oscillation Maximum:

$$E_{OM} = \frac{2}{\pi}\, 1.27\, \delta m^2_{32} L$$

) JParc

LBL $\nu_\mu \to \nu_e$ + $\bar{\nu}_\mu \to \bar{\nu}_e$ measures

$\sin\theta_{23} \sin\theta_{13}$ ← nearly indep of sign δm^2_{32}

$\cos\theta_{23} \sin\delta$ ← depends somewhat on sign δm^2_{32}

precision?

Combined with Reactor measurement of $\sin\theta_{13}$ determines which $\sin^2\theta_{23} = (1 \mp \epsilon)/2$ is correct.

<u>Breaks</u> the θ_{23} ; $\pi/2 - \theta_{23}$ degeneracy!

$$|U_{\mu 3}|^2 \gtrless |U_{\tau 3}|^2$$

hep-ph/0211111

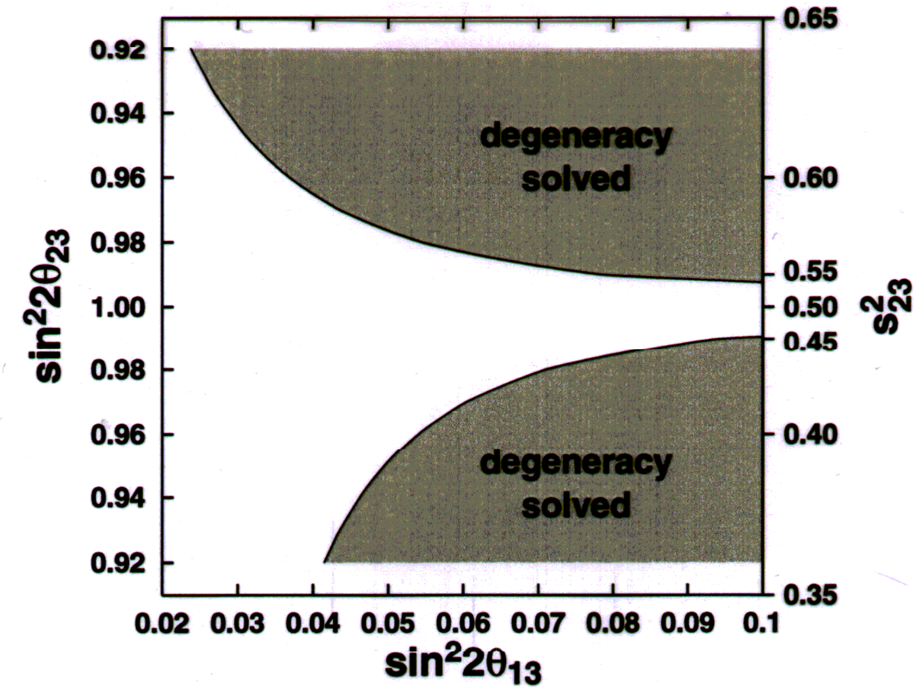
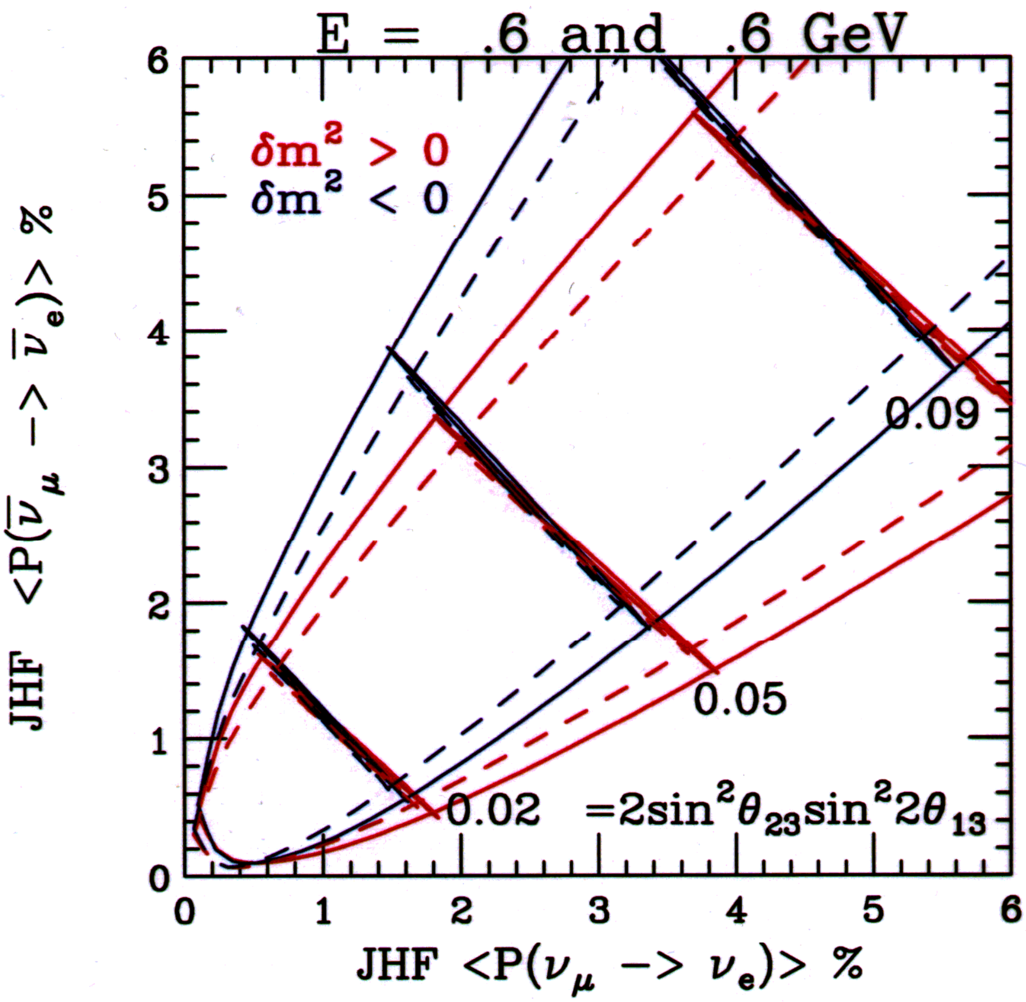


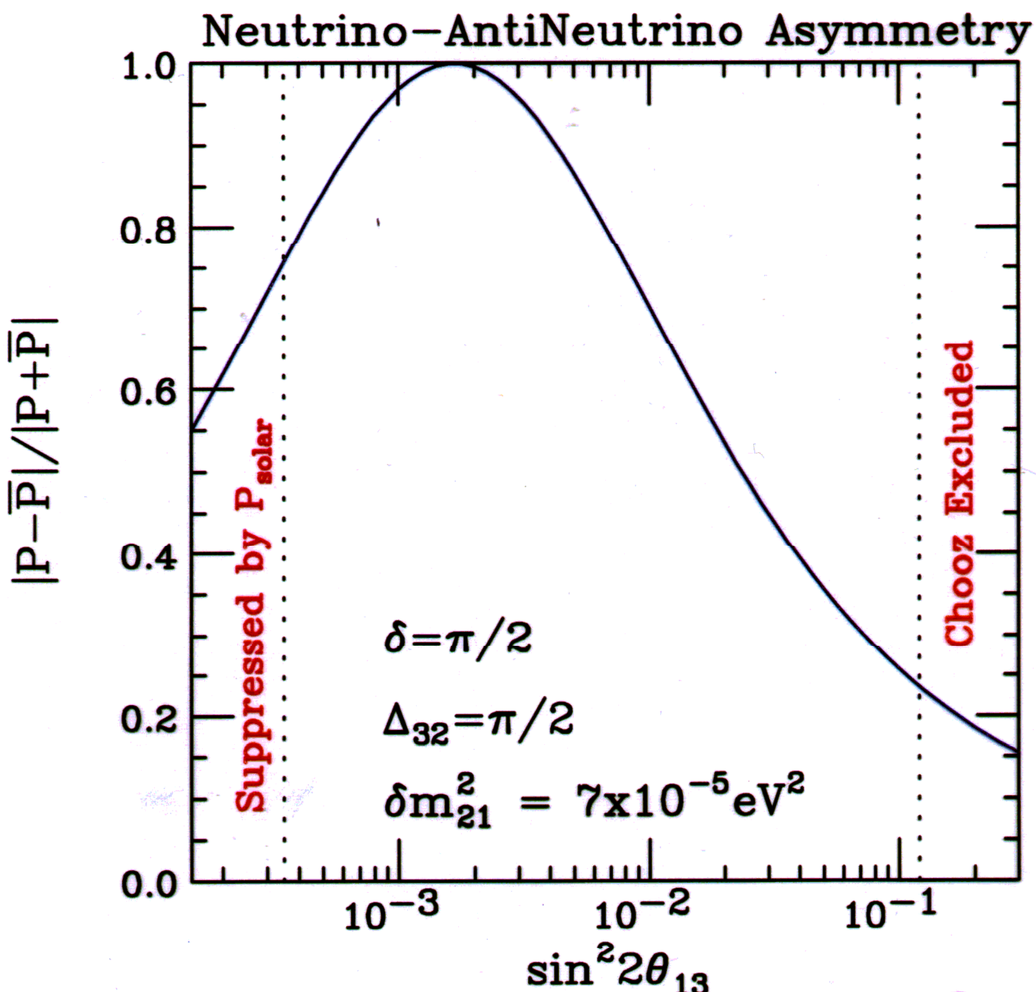
FIG. 7: The shadowed area stands for the region in which $\delta_{\rm re}(\sin^2 2\theta_{13}) < \delta_{\rm de}(\sin^2 2\theta_{13})$ is satisfied for $\sigma_{\rm sys}$=0.8 %, 40 t·yr, d.o.f.=1 and for the best fit values of the solar and atmospheric oscillation parameters. In this shadowed region, the $(\theta_{13}, \theta_{23})$ degeneracy may be solved. The vertical axis is the same as the horizontal axis of Fig. 6(b).



E = .6 and .6 GeV
δm² > 0
δm² < 0
0.09
0.05
0.02 =2sin²θ₂₃sin²2θ₁₃
JHF <P(ν̄μ −> ν̄e)> %
JHF <P(νμ −> νe)> %
0
1
2
3
4
5
6

at Osc. Max and Maximal CP violation

$$\overset{(-)}{P} = \left| \sqrt{P_\otimes} \pm \sqrt{P_\odot} \right|^2$$



$$\Delta_{ij} = 1.27 \frac{\delta m^2_{ij}}{E}$$

$$P_{\mu \to e} = \left| e^{-i(\Delta_{32} \pm \delta)} \sqrt{P_\otimes} + \sqrt{P_\odot} \right|^2$$

$$= P_\otimes + P_\odot + 2\sqrt{P_\otimes P_\odot} \cos(\Delta_{32} \pm \delta)$$

$$\sqrt{P_\otimes} = \sin\theta_{23} \sin 2\theta_{13} \sin \Delta_{31}$$

$$\sqrt{P_\odot} = \cos\theta_{23} \cos\theta_{13} \sin 2\theta_{12} \sin \Delta_{21}$$

MATTER EFFECTS in LBL:

use 2x2 $\delta m^2 \sin 2\theta$ is INVARIANT:

$$\sin\Delta \longrightarrow \frac{\Delta}{(\Delta \mp aL)} \sin(\Delta \mp aL)$$

for (31) and (21) but not (32):

where $\Delta_{ij} = 1.27\, \delta m^2_{ij} L/E$, $a^{-1} = \frac{\sqrt{2}}{G_F N_e} \simeq 3700\text{km} \left(\frac{2.8 g/cc}{\rho}\right)$

21 $\Delta_{21} \ll aL < 1$

$$\sin\Delta_{21} \to \Delta_{21} \frac{\sin aL}{aL} \approx \Delta_{21}$$

← not ν factory

31 $$\frac{\Delta_{31}}{\Delta_{31} \mp aL} \sin(\Delta_{31} \mp aL)$$

leading order $\xrightarrow{aL}$ $\left(1 \pm (\Delta_{31}^{-1} - \cot\Delta_{31})(aL)\right) \sin\Delta_{31}$

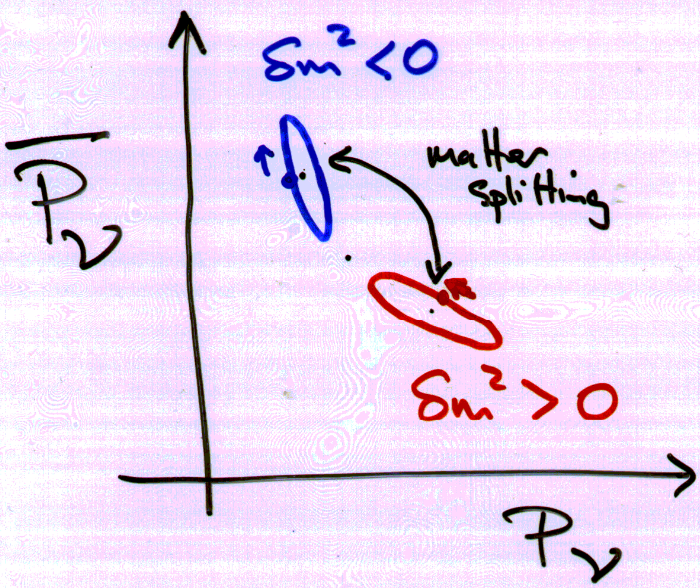
near Osc. Max, i.e. $\Delta_{31}^{OM} = \frac{\pi}{2}$

$$\approx \left[1 \pm \frac{E_{OM}}{E_R}\left(1 - \left(\frac{\pi^2}{4} - 1\right)\frac{(E - E_{OM})}{E_{OM}}\right)\right] \sin\Delta_{31}$$

↑ suppression above Osc. Max

$E_R \approx 12$ GeV

ν v $\bar{\nu}$



at Osc. Max.

Center of Ellipse moves

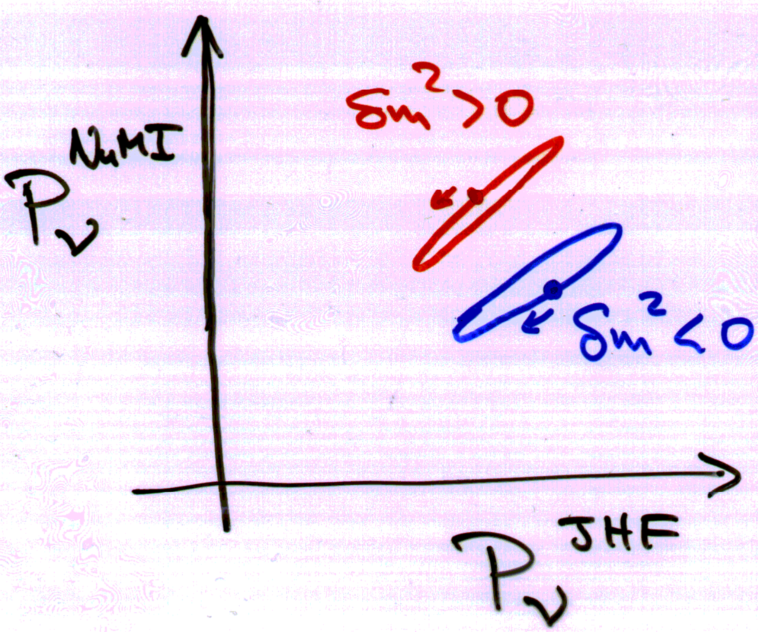
$$P^{mat} = \left(1 \pm 2\frac{E}{E_R}\right) P^{vac}$$

$E_R \approx 12\,\text{GeV}$

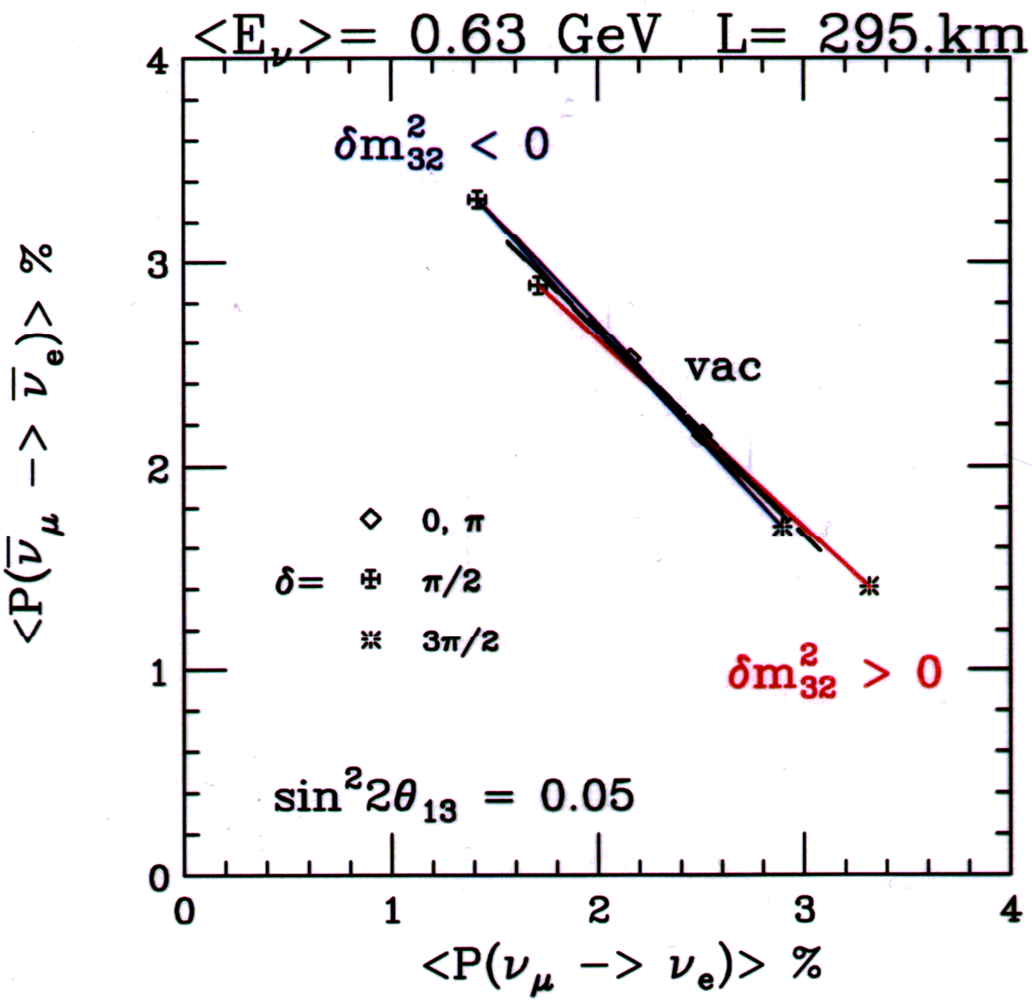
$$2\frac{E}{E_R} \sim \begin{array}{ll} 0.08 & \text{JHF} \\ 0.30 & \text{NuMI} \end{array}$$

ν v. ν

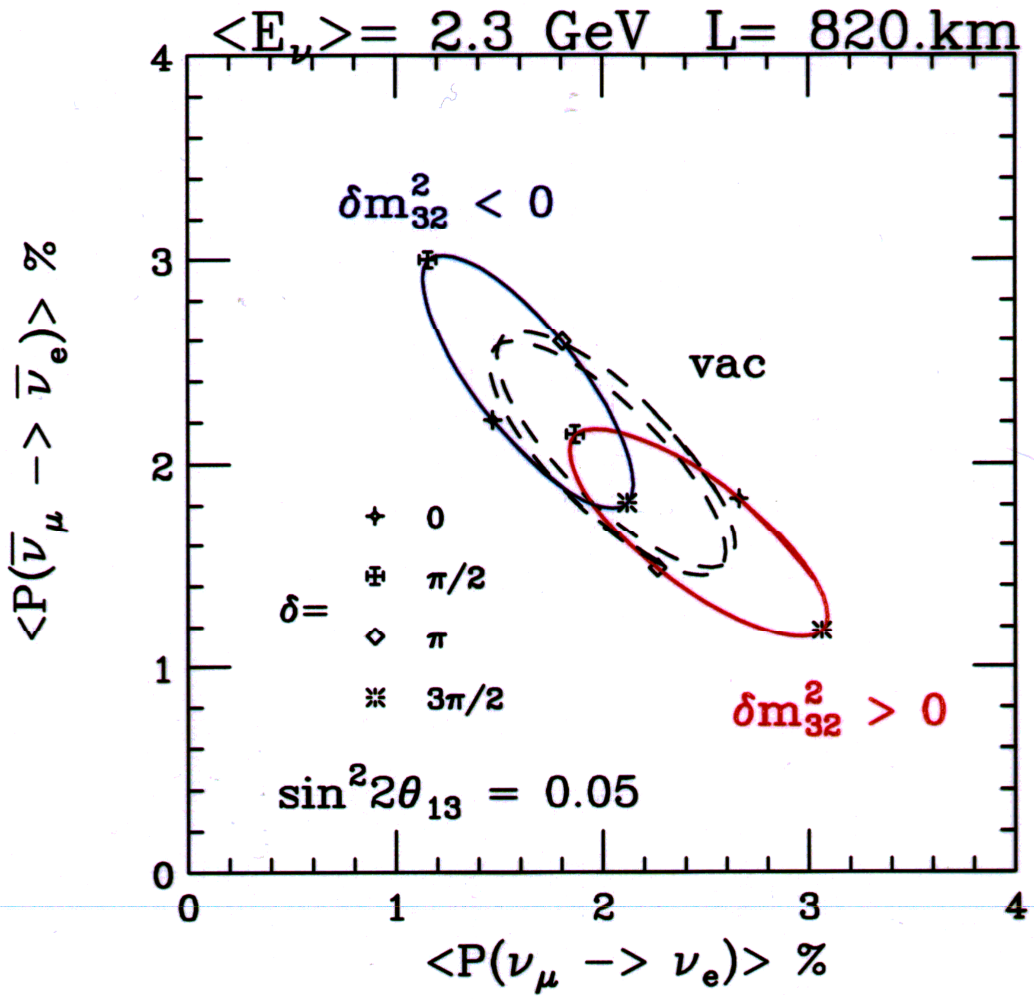
if both at OM.



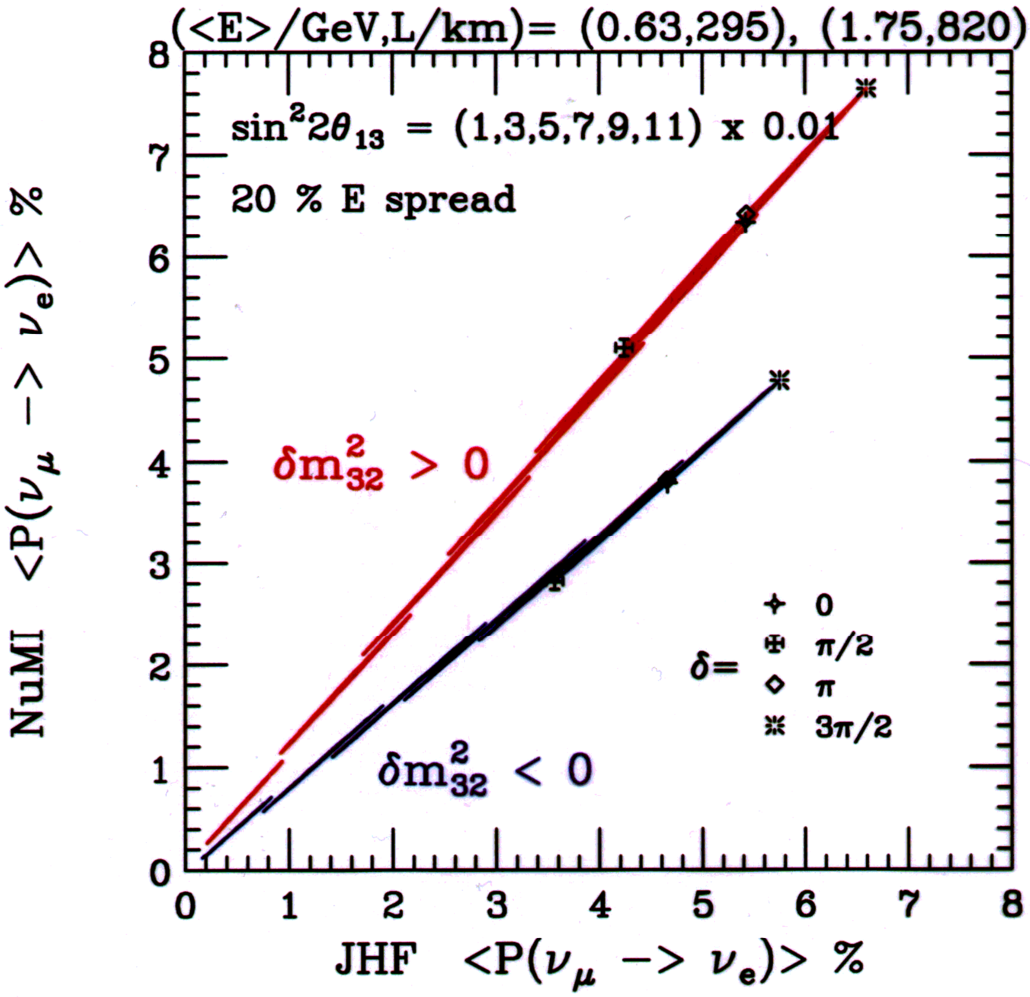
$$P_\nu^{NuMI} = \left(1 \pm 2\frac{(E^N - E^J)}{E_R}\right) P_\nu^{JHF}$$

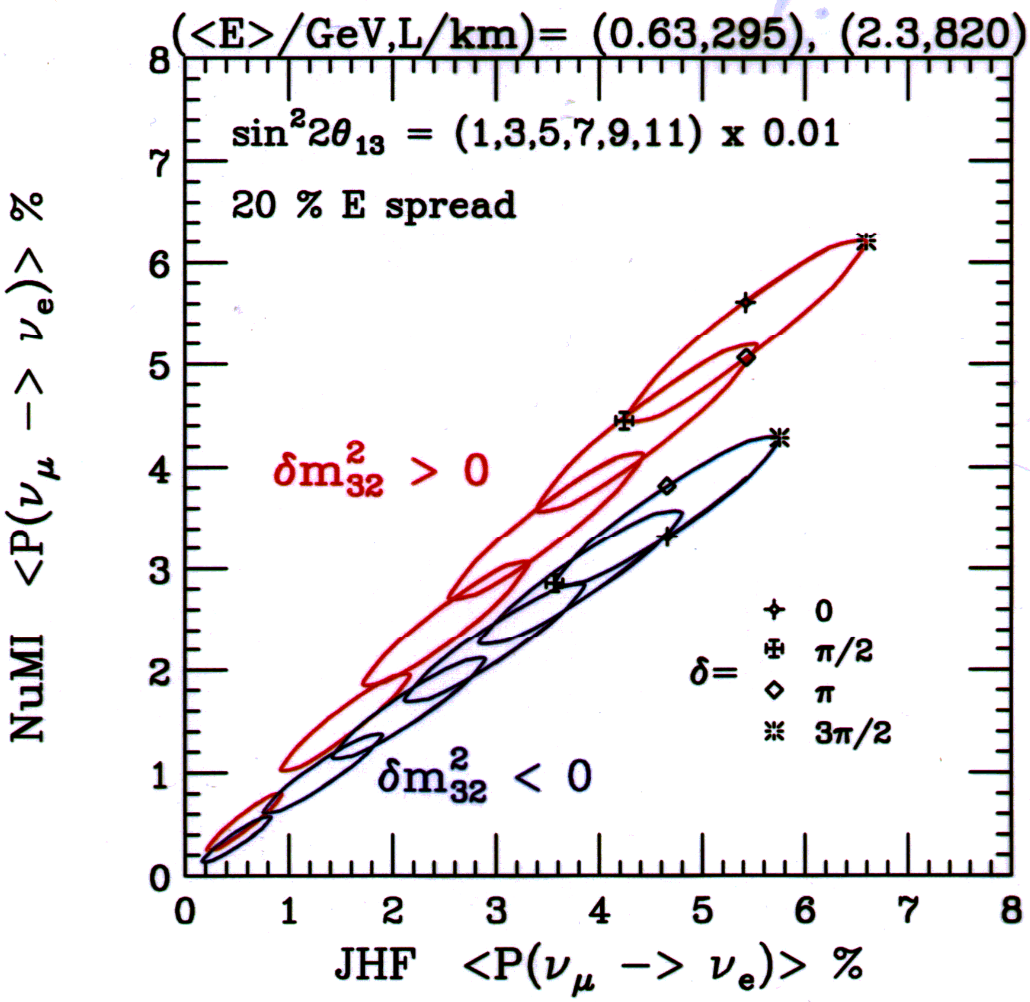


<E_ν>= 0.63 GeV L= 295.km
δm²₃₂ < 0
vac
δ=
0, π
π/2
3π/2
δm²₃₂ > 0
sin²2θ₁₃ = 0.05
<P(ν̄_μ -> ν̄_e)> %
<P(ν_μ -> ν_e)> %
0
1
2
3
4



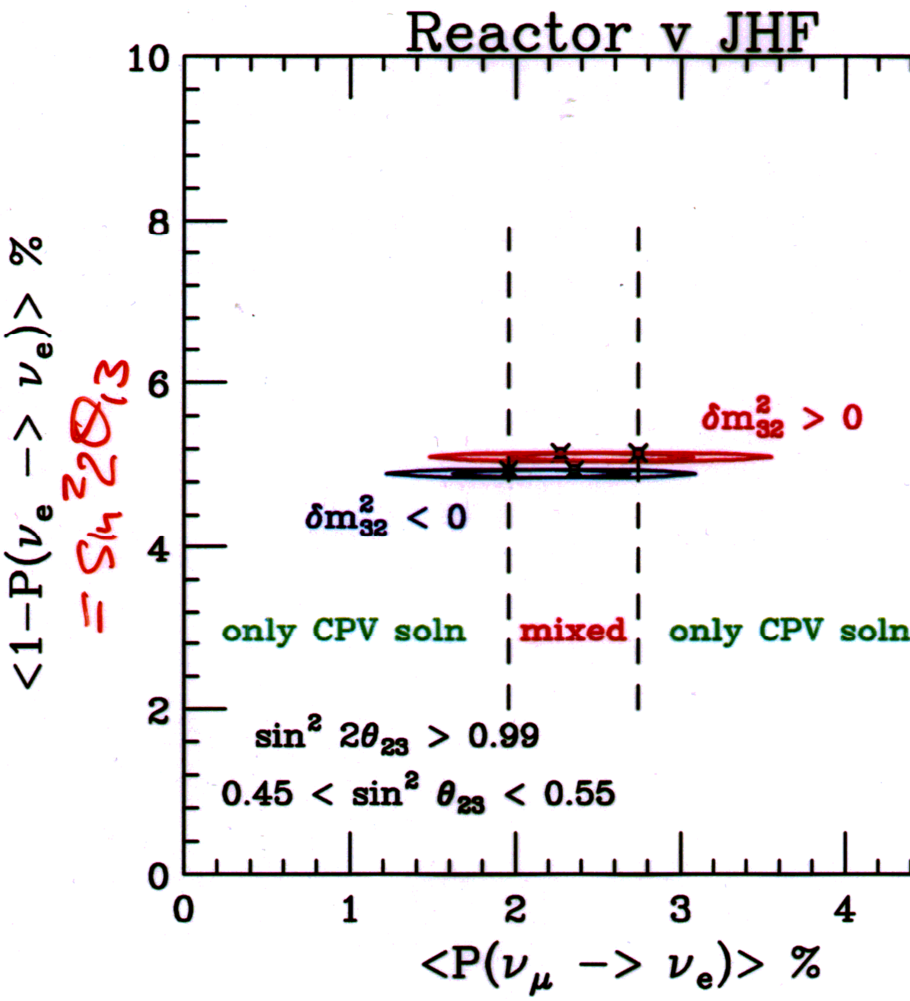
<E_ν>= 2.3 GeV L= 820.km
δm²₃₂ < 0
vac
δm²₃₂ > 0
δ=
0
π/2
π
3π/2
sin²2θ₁₃ = 0.05
<P(ν̄_μ -> ν̄_e)> %
<P(ν_μ -> ν_e)> %
0
1
2
3
4


(<E>/GeV,L/km)= (0.63,295), (1.75,820)
sin²2θ₁₃ = (1,3,5,7,9,11) x 0.01
20 % E spread
δm²₃₂ > 0
δm²₃₂ < 0
δ= 0
π/2
π
3π/2
NuMI <P(ν_μ −> ν_e)> %
JHF <P(ν_μ −> ν_e)> %
0
1
2
3
4
5
6
7
8



(<E>/GeV,L/km)= (0.63,295), (2.3,820)
$\sin^2 2\theta_{13}$ = (1,3,5,7,9,11) x 0.01
20 % E spread
$\delta m^2_{32} > 0$
$\delta m^2_{32} < 0$
δ=
0
$\pi/2$
π
$3\pi/2$
NuMI <P(ν_μ -> ν_e)> %
JHF <P(ν_μ -> ν_e)> %
0
1
2
3
4
5
6
7
8

Minakata + Sugiyama hep-ph/0309323



20% E spread

— One Possibility —

Minos, Icarus, ... sees hints of $\sin^2\theta_{13} \neq 0$

harder and harder ↓

Reactor Exp: measures $\sin^2\theta_{13}$

↑ probability of finding ν_e in isolated "3" state

JParc + NuMI-Off-Axis $\begin{pmatrix}\nu \\ \bar{\nu}\end{pmatrix}$:

$\sin^2\theta_{23}$ — ν_μ in "3" state

↑ breaks $\theta_{23}, \pi/2 - \theta_{23}$ degeneracy

$\sin\delta$ ← sensitive to sign δm^2_{32}

sign δm^2_{32}

$\cos\delta$ ← Above Osc. Max.

Leaving m^2_{lite} ???

if θ_{13} is tiny! $\sin^2 2\theta_{13} < 0.002$

we need
- β - Beams
- ν - factories
- ν - ideas

See Terranova + Mezzetto talks

Wish list:

harder and harder ↓

$\sin\theta_{13}$

sign δm^2_{32}

$\sin\delta$

$\theta_{23} \leftrightarrow \pi/2 - \theta_{23}$ i.e. $\sin^2\theta_{23}$

$\cos\delta$

m^2_{lite}

---

majorana v. dirac ⟵ Boris Please Rank

$n_{sterile}$ lite ν's ⟸ easy
miniBOONE

— lesson from japanese —

We need

"調査研究でなく実験"

"experiments NOT studies"

Question

What happens to ν oscillations in the limit $\hbar \to 0$ i.e. semi-classical limit?
(think about what happens to Oscillation Length.)

Is there an alternative way to describe the neutrino sector in this limit?

by S.P.