— Neutrinos —

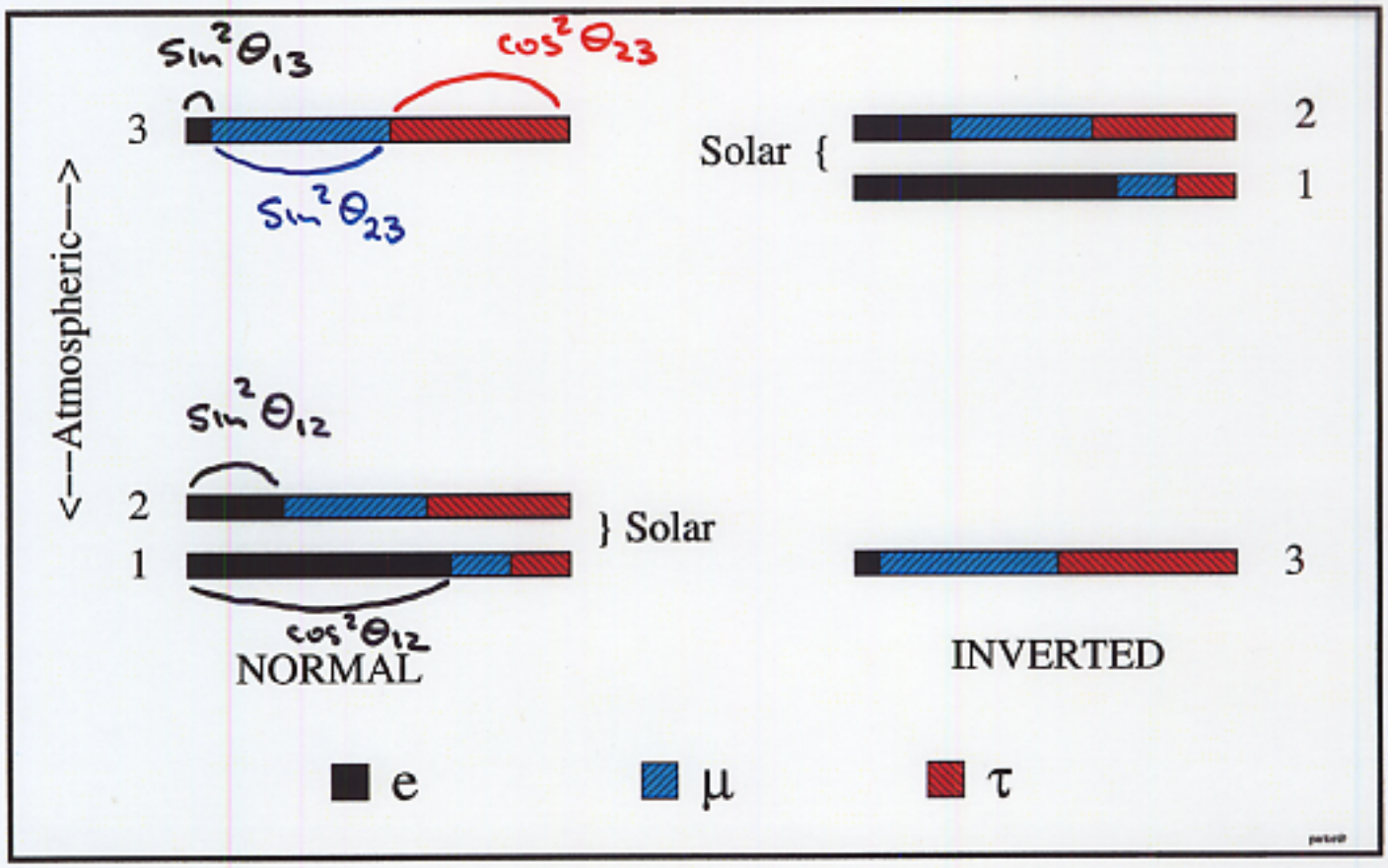
Stephen Parke

→ Current Status:

→ Questions:

→ Opportunities:

Sans LSND

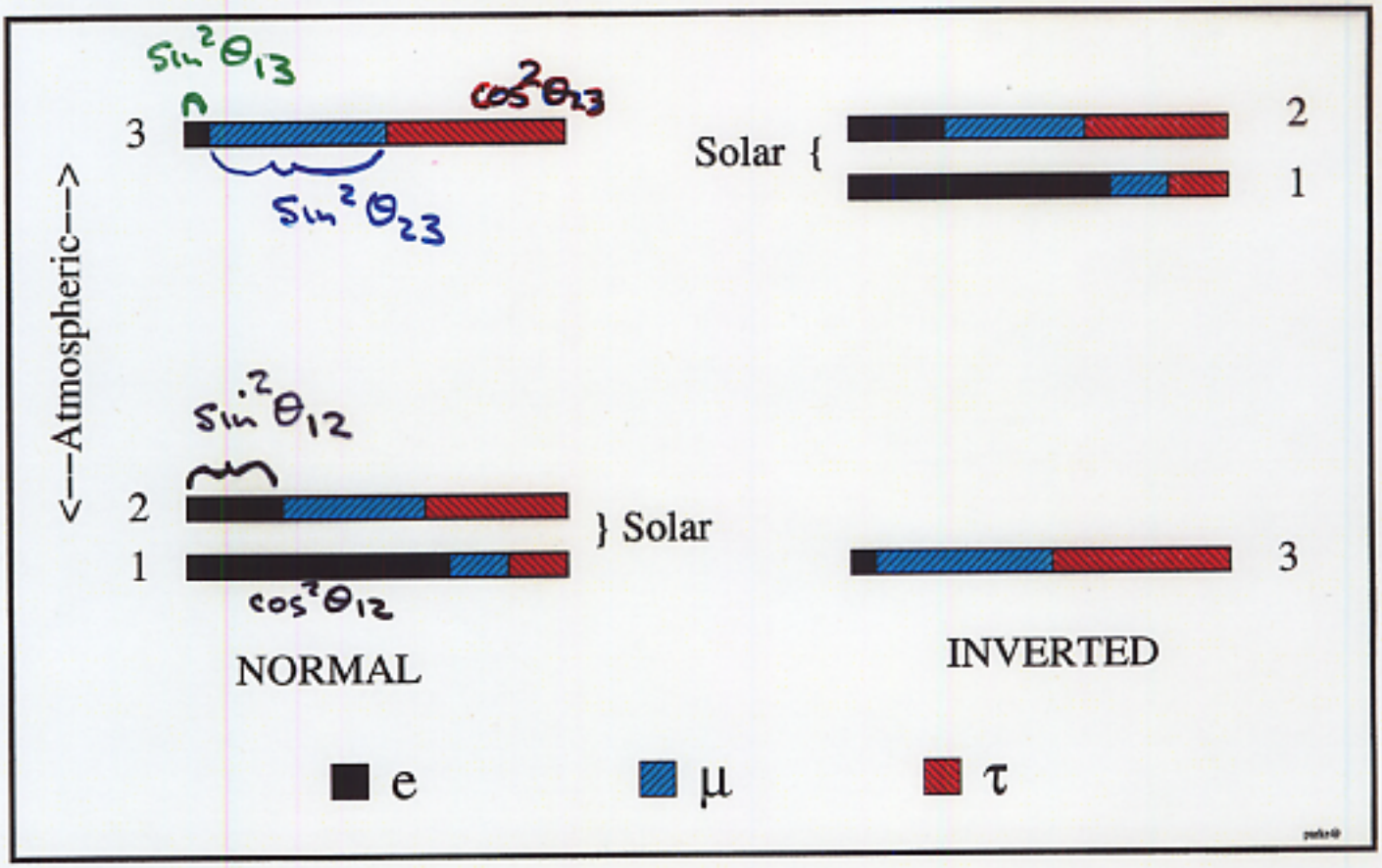


δm^2_{atm} ; δm^2_{solar}

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

$\sin^2\theta_{13}$ and phase δ_{CP}

Sams LSND



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

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

$$0.23 < \sin^2\theta_{12} < 0.35$$ ($\frac{1}{2}$ excluded at 5.4σ)

ATMOSPHERIC: (SK, K2K, ...)

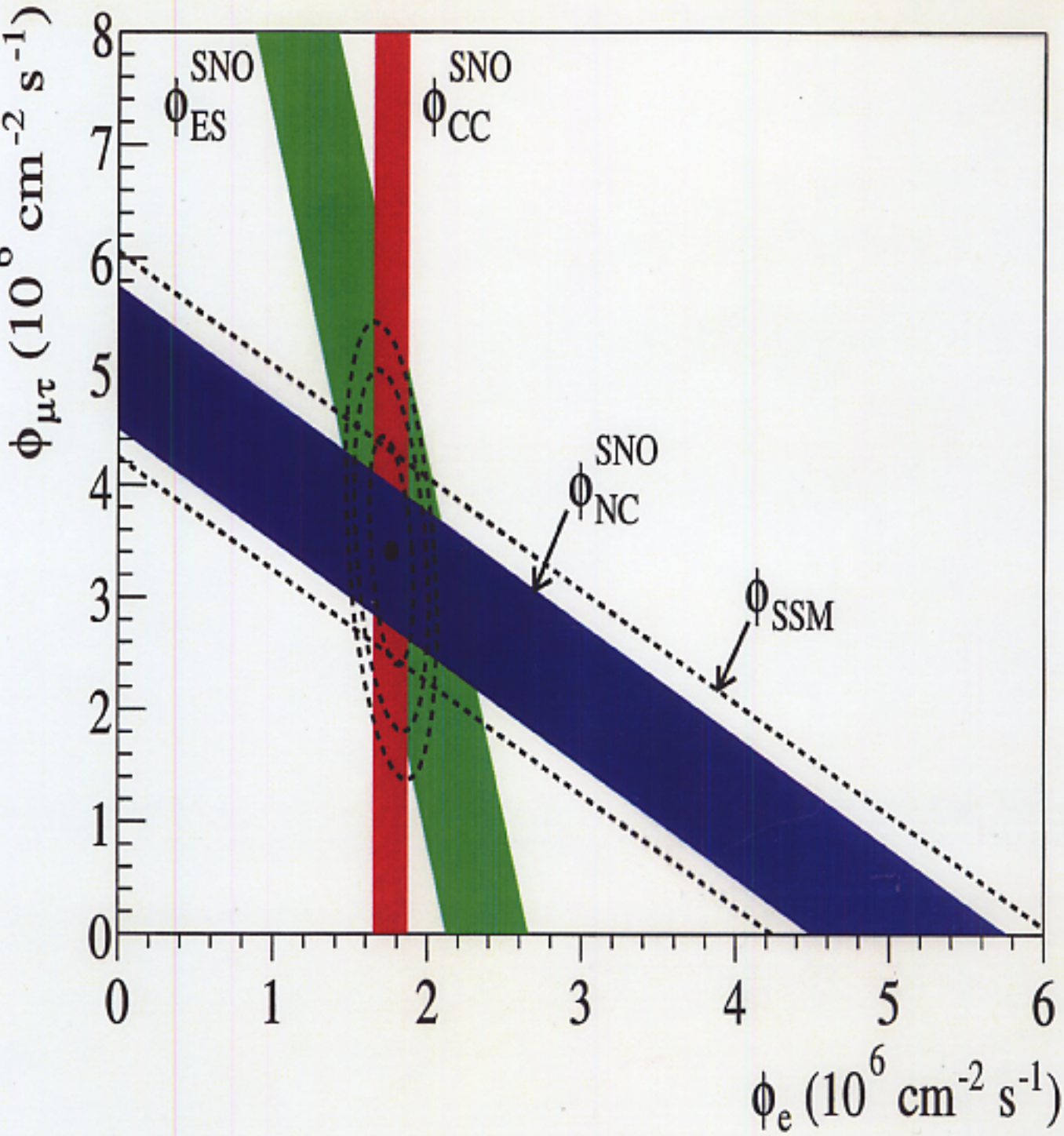
$$|\delta m^2_{atm}| = 1.5 - 3.5 \times 10^{-3}\,eV^2$$

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

CHOOZ: (+SK)

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

— SNO —


SNO
ϕ_{ES}
SNO
ϕ_{CC}
SNO
ϕ_{NC}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8

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

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

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

Reactor: Vacuum

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

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

$$= 0.58$$

KAMLAND = 0.61 ✓

Diamond in the rough ???

LSND:

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

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

$\sin^2 2\theta \sim 10^{-2 \pm 0.5}$

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)

QUESTIONS:

— Number of light Neutrinos:

3 active + ? sterile

— Mass Spectrum:

normal, inverted, degenerate
(mass scale)

— Mixings:

Is $\theta_{23} = \pi/4$?

How small is θ_{13} ?

Complex ? δ $\left\{ \begin{array}{l} \text{CP violation} \\ \text{leptogensis} \end{array} \right\}$

— Majorana / Dirac

Is lepton number conserved?

$\beta\beta$ decay — extra phases:

Number of light Neutrinos?

Are there any light sterile neutrinos?

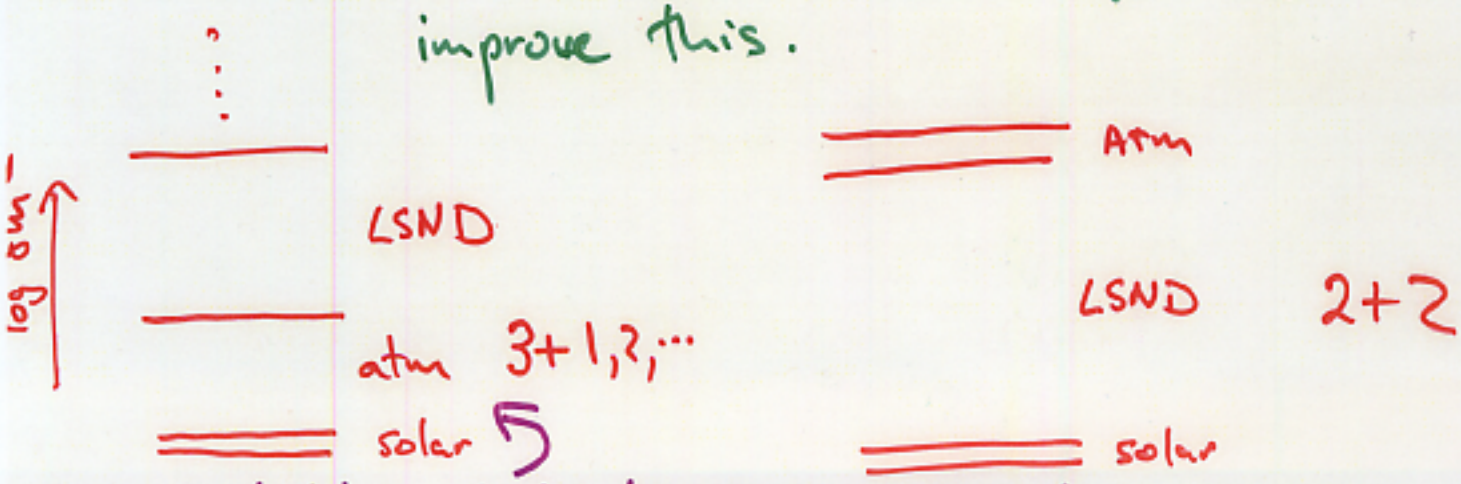
δm^2_{atm} scale:

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

MINOS (NC/CC ratio)

δm^2_{solar} scale:

SNO { < 50% coming from theoretical uncertainty in ^8B flux. D/N asymmetry may improve this.



Highly constraint by ν_μ and ν_e disappearance measurements

Mini-BOONE:

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 (FINESSE)

or a FAR Detector (BOONE)

or BOTH ???

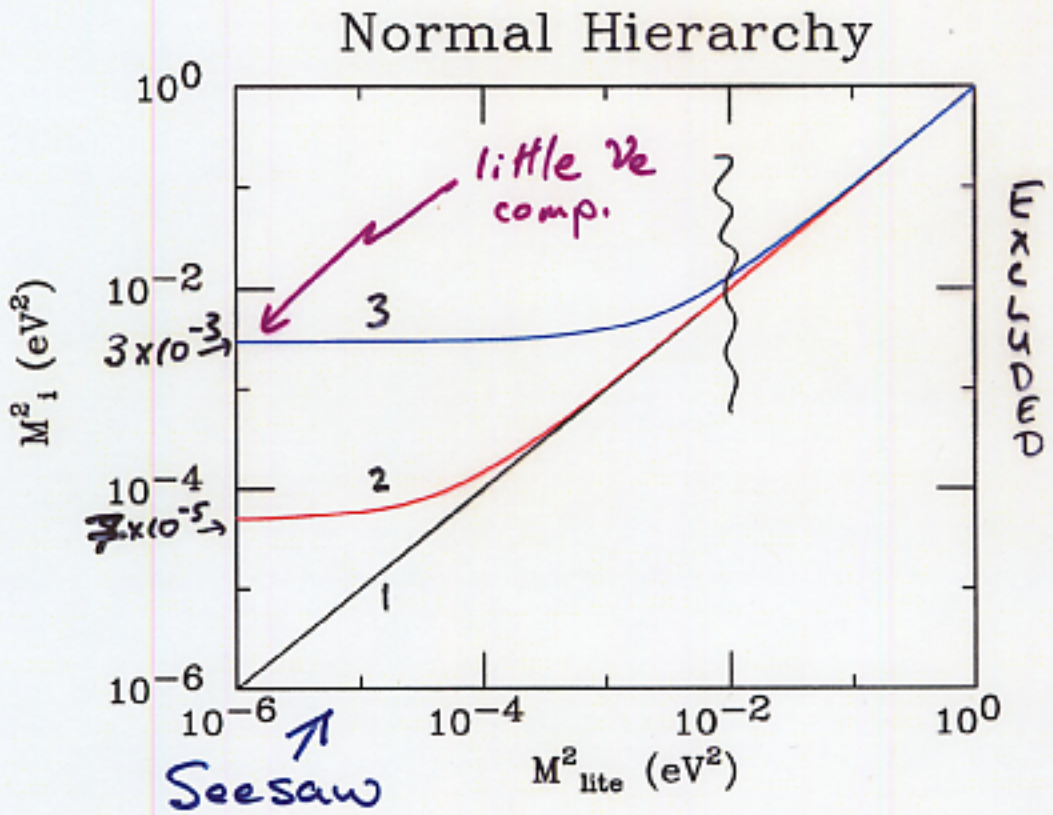
What about CP violation? $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$

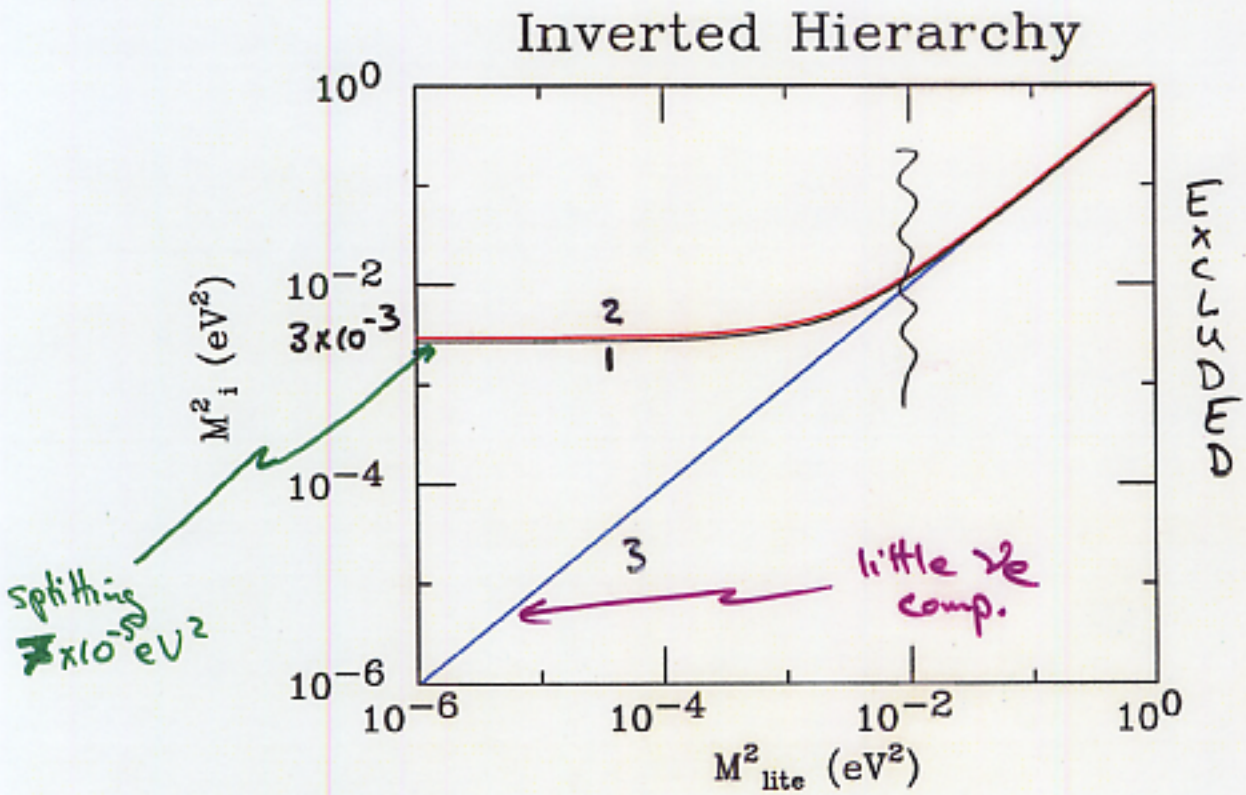
How ~~about~~ is ν_τ involved?

Can FERMILAB response in a timely fashion?

– cern — japan — Brookhaven

MASS SPECTRUM! n = 3





Beacom + Bell

✦ Absolute Mass Scale:

- Tritium Beta decay

$$\langle m_e^2 \rangle = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$

KATRIN will probe down to 0.3eV

— degenerate case —

- Cosmology:

wmap ~ 1eV

See Frieman talk in a few weeks

- $\not{\nu}$ $\beta\beta$ decay

$$\langle m_{\beta\beta} \rangle = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3 \right|$$

but Majorana phases are important.

MIXINGS:

θ_{23} , θ_{13} , δ ,

$\text{sign}\,\delta m^2_{31}$

MIXINGS:

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

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

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

JParc + NuMI-Off-Axis will make a $\sim 1\%$ measurement of $\sin^2 2\theta_{23}$!

Suppose $\sin^2 2\theta_{23} = 0.96 \; (0.99)$

then $\sin^2\theta_{23} = 0.40 \; (0.45)$

OR

$\sin^2\theta_{23} = 0.60 \; (0.55)$

Sign of Symmetry Breaking ???

θ_{13} ?

		δm^2_{atm}
Chooz limit:	$\sin^2\theta_{13} < 0.03$	$3\times10^{-3}\,eV^2$
	< 0.05	$2\times10^{-3}\,eV^2$

- Direct Measurement from Reactors:

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\,\sin^2\frac{\Delta m^2_{13} L}{4E}$$

$L \sim 1 - 2$ km

with systematic uncertainty about 1%

$$\Rightarrow \sin^2\theta_{13} \sim 0.003 \qquad (\sin^2 2\theta_{13} \sim 0.01)$$

No complications from θ_{23}, sign δm^2_{31}, δ

BUT HOW LOW CAN YOU GO?? HOW FAST??

— LHC, SDSS, Auger, CDMS, ...

◆ Long Baseline:

JPARC, NuMI-Off-Axis ....

$$\nu_\mu \to \nu_e$$

$$P_{\nu_\mu \to \nu_e} \sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)$$

$$= 2\sin^2\theta_{23} \qquad \left(= \tfrac{1}{2}\sin^2 2\theta_{13}\right)$$

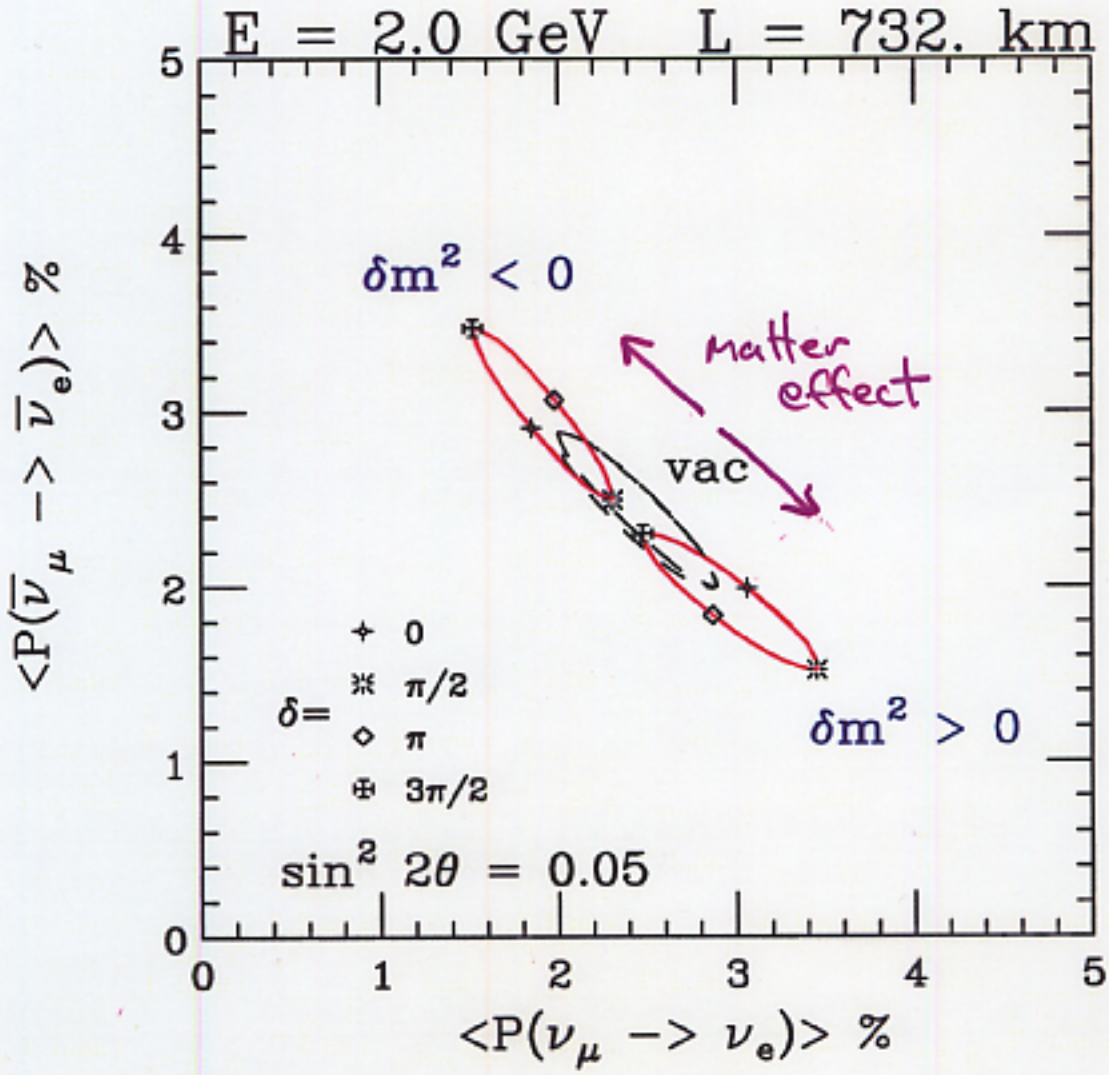
BUT in detail depends also

δ and sign δm^2_{13}.

(and θ_{23})

This <u>Weakness</u> is also its <u>Strength</u>:

$\sin^2\theta_{13} = 0.0125$



actual variables measured are

$$\left.\begin{array}{l} \sin\theta_{23}\sin\theta_{13} \\ \cos\theta_{23}\sin\delta \\ \cos\theta_{23}\cos\delta \end{array}\right\}$$

minimum of 3 measurements

and $\text{sign}\ \delta m^2_{13}$

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

$\sin^2\theta_{23} = \frac{1\mp\epsilon}{2}$ and $\cos^2\theta_{23} = \frac{1\pm\epsilon}{2}$

two choices for θ_{23}.)

LONG BASELINE PHYSICS

Can measure a number of important parameters:

	NuMI
θ_{13}	$\sin^2\theta_{13} > 0.003$
sign ΔM^2_{31}	Yes - matter effect
δ, CP violation	✓ $\nu + \bar{\nu}$
$\sin^2\theta_{23} \lesssim \frac{1}{2}$	with θ_{13} from reactors

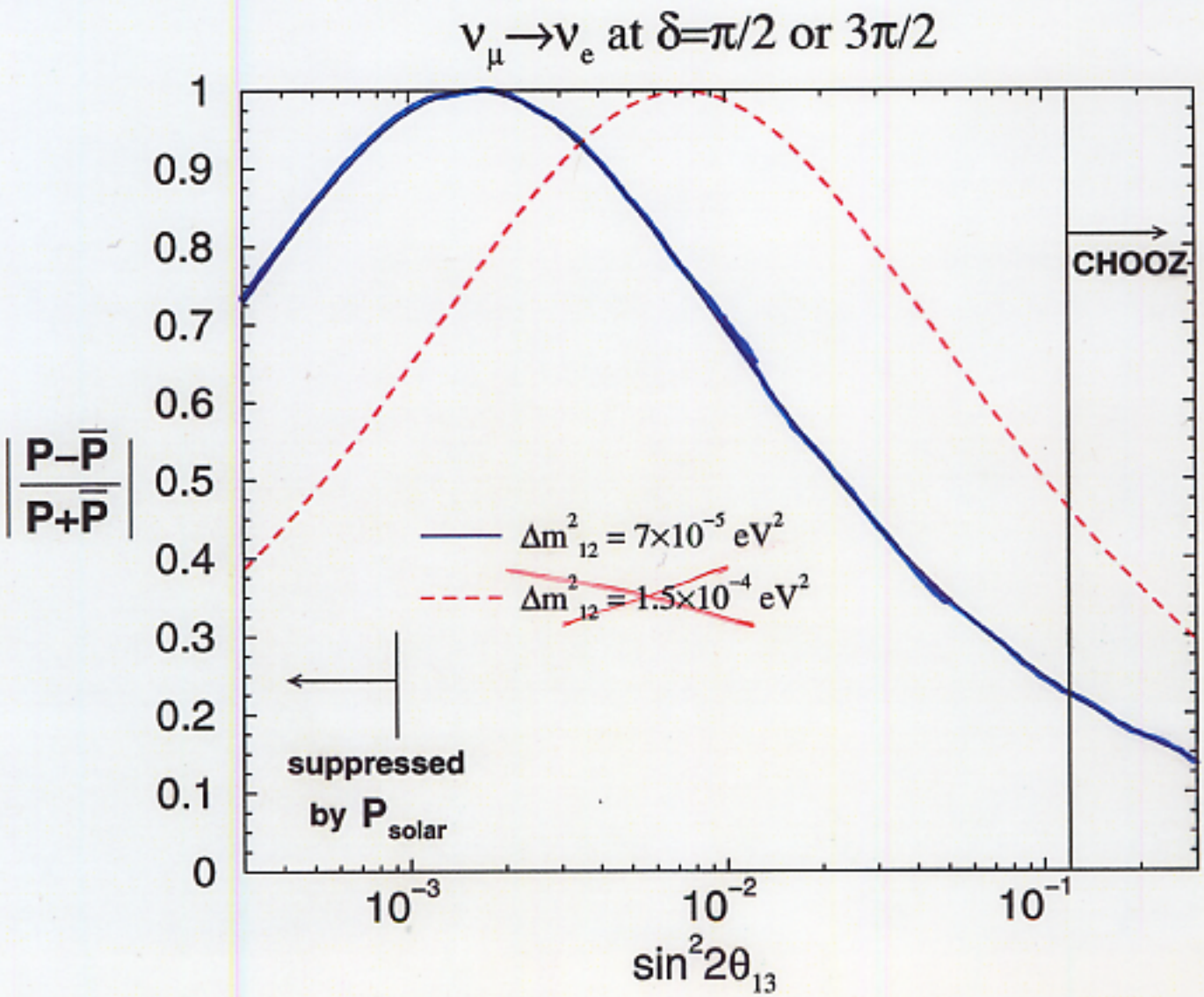
Can be extended to very small θ_{13} with muon-storage-ring (ν factory $\nu_e \to \nu_\mu$)

Asymmetry:

At first Osc. Max. in vacuum

$$|P-\bar{P}| \sim \sin\theta_{13}$$

$$|P+\bar{P}| \sim 2\sin^2\theta_{13} + P_\odot$$

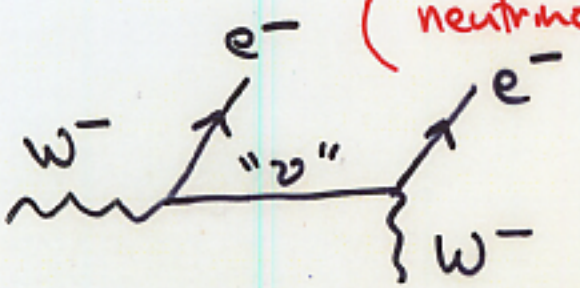


Majorana / Dirac

Majorana	Dirac
2 comp.	4 components
minimal	unnatural

If Majorana then lepton number is NOT conserved as the mass couples ν_L to ν_R

(neutrino) (anti-neutrino)



BUT suppressed by $\left(\frac{m_\nu}{E}\right)^2$ tiny

$\beta\beta$ decay

$$\langle m_{\beta\beta} \rangle = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3 \right|$$

since $\sin^2\theta_{12} < \frac{1}{2}$ non-zero for inverted hierarchy:

Fermilab Opportunities:

◀ Non-Oscillation Physics

- low Q^2 neutrino cross sections etc
  (near detectors in ν beamlines:
  - FINESSE in mini-BOONE beamline
  - MINERvA in NuMI beamline)

(besides the physics these are excellent training grounds for young physicists
– think E665 model)

- $\nu_\mu - e$ scattering – Super NuTEV
  $\sin^2\theta_W$ at low Q^2
  "free" of low Q^2 QCD effects.
  assumes NuTeV anomaly survives!

◆ 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

◆ θ_{13} : MINOS will improve on CHOOZ.

- Reactor Experiment (dissappearance)
  direct measurement of θ_{13}
  probes $\sin^2\theta_{13} \to 0.003$ (no θ_{23}, δ or sign δm^2 dependence)

- long baseline $\nu_\mu \to \nu_e$: NuMI-Off-Axis

– richer physics program (cf JHF→SK)

θ_{13}, θ_{23}, δ and sign δm^2_{31}

CP violation (leptogenesis) matter effect

– $\bar{\nu}$ earlier than (JHF→SK)?

– matter effect can be used to determine sign δm^2_{31} – UNIQUE to NuMI

- if θ_{13} is very small we will need a ν-factory or some other novel ν-beam.

- PROTONS:

#EVENTS $\propto$ P.O.T * DETECTOR MASS

trade off

P.O.T $\uparrow$ and DET. MASS $\uparrow$

<u>COHERENT</u> approach to upgrading the proton source to provide maximum benefit to as many experiments as possible.

— lesson from Japanese —

We need

" experiments

NOT

Studies "