ν Fact ϕ3 Summer Institute

Neutrino Oscillation Physics
Lectures 5 & 6

Neutrino Oscillation: Evidence, Implications, and Open Questions

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Fermilab
May 29 & 30

Evidence for Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor ($L \sim 180$ km)	Very Strong
Atmospheric	Compelling
Accelerator ($L = 250$ km)	Interesting
Stopped μ^+ Decay (LSND, $L \approx 30$ m)	Unconfirmed

Solar Neutrinos

Nuclear reactions in the core of the sun make ν_e. Only ν_e.

Sudbury Neutrino Observatory (SNO) measures the high-E part of the $\nu_\odot$ flux arriving at earth 3 ways:

Reaction	Flux Measured
$\nu_\odot d \to \nu n p$ (NC)	$\phi_{\nu_e} + \phi_{\nu_\mu \nu_\tau}$
$^\dagger \nu_\odot e \to \nu e$ (ES)	$\phi_{\nu_e} + 0.15\, \phi_{\nu_\mu \nu_\tau}$
$\nu_\odot d \to e p p$ (CC)	ϕ_{ν_e}

$$\phi_{\nu_\mu \nu_\tau} = (3.45\ ^{+0.65}_{-0.62}) \times 10^6 / \text{cm}^2\ \text{sec}$$

(5.5σ from zero)

†Also measured by Super Kamiokande (SK)

The favored explanation of this $\nu_e \longrightarrow [\nu_\mu \text{ and/or } \nu_\tau]$ is the —

Large Mixing Angle —
Mikheyev Smirnov Wolfenstein
— Effect.

This effect involves flavor-preserving interactions between $\nu_\odot$ and solar material, and also neutrino mass and mixing.

No flavor change without mass and mixing, even in LMA-MSW.

The (vacuum) neutrino properties implied by LMA-MSW are —

$$2.3 \times 10^{-5} \lesssim \Delta m^2_{\odot} \lesssim 9.3 \times 10^{-5} \text{eV}^2$$

(Value determined by spectral distortion)

and —

$$0.66 \lesssim \sin^2 2\theta_{\odot} \lesssim 0.88 \, .$$

(SNO; 90% CL)

Reactor (Anti) Neutrinos

The (vacuum) neutrino properties implied by LMA-MSW $\Longrightarrow$

KamLAND, ~ 180 km from reactor $\bar{\nu}_e$ sources, should see substantial disappearance of $\bar{\nu}_e$ flux.

5.2

KamLAND actually does see —

$$\frac{\phi_{\bar{\nu}_e}}{\phi_{\bar{\nu}_e}\big|_{\text{No Loss}}} = 0.611 \pm 0.085\,(\text{stat}) \pm 0.041\,(\text{syst})$$

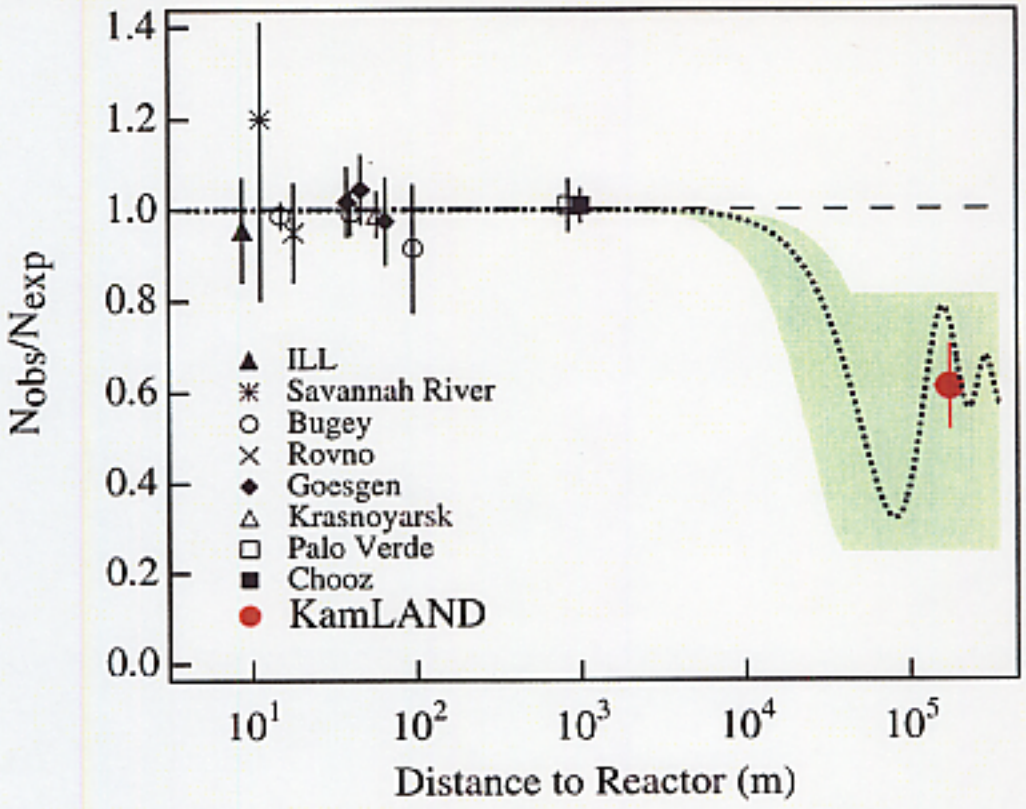
Reactor $\bar{\nu}_e$ disappear.

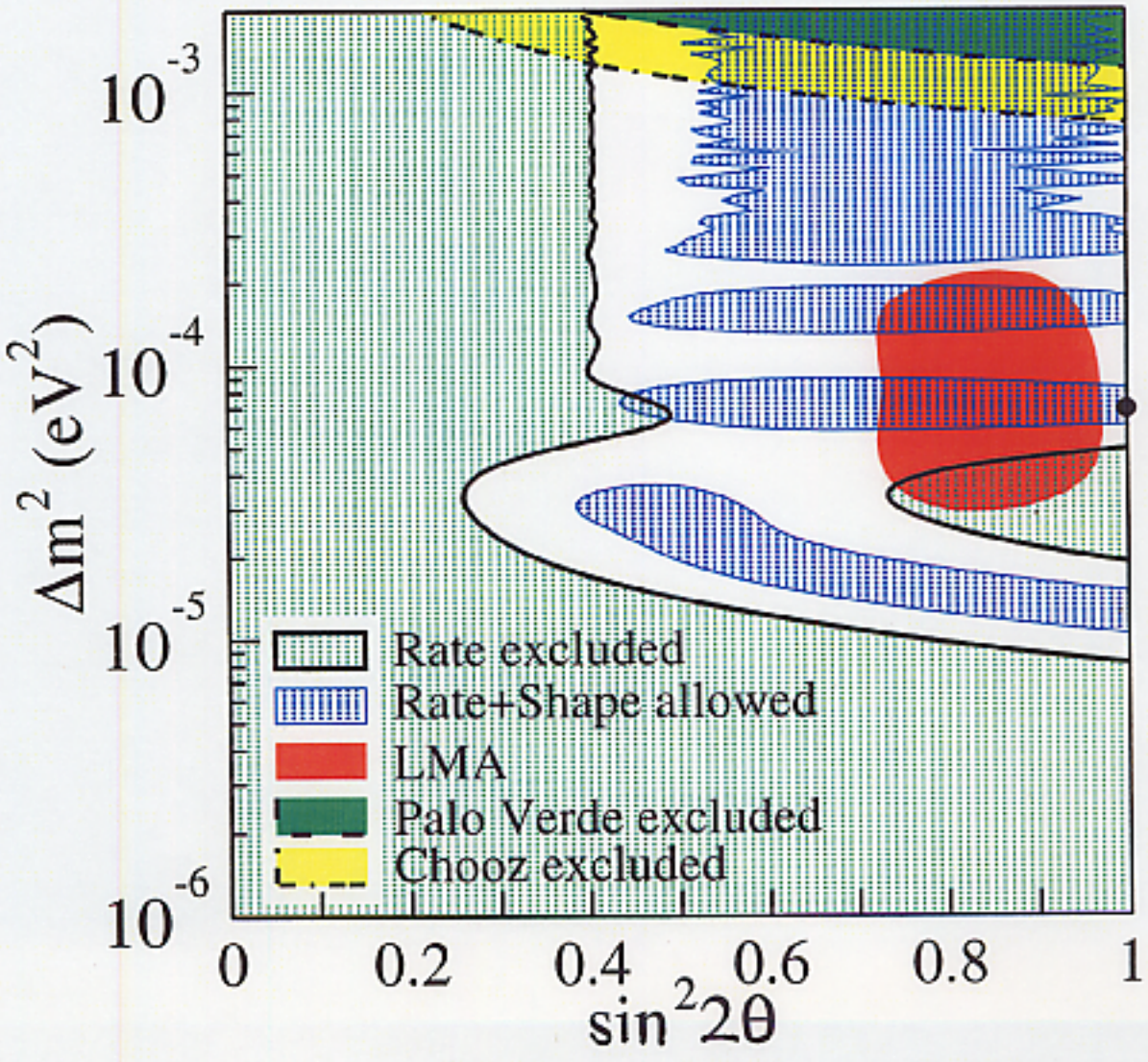
Is this disappearance due to

flavor change?

Many analyses: Flavor change, with $\Delta m^2_\odot$ and $\sin^2 2\theta_\odot$ in the LMA-MSW range, fits both the solar and reactor data.

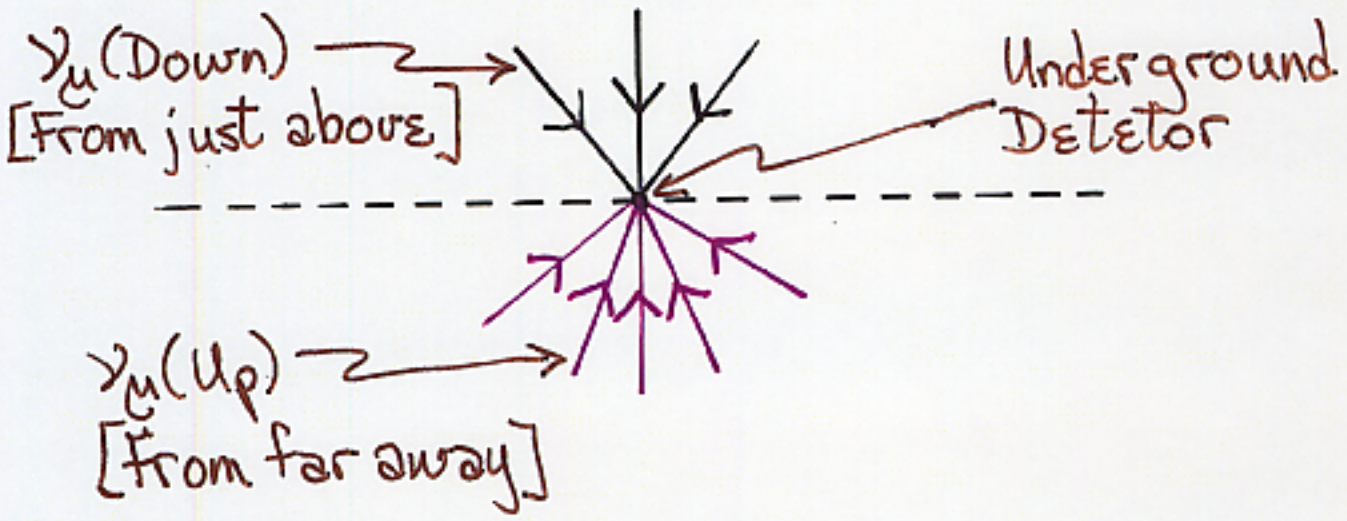
[Fig]


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)


10^-3
10^-4
10^-5
10^-6
Δm^2 (eV^2)
Rate excluded
Rate+Shape allowed
LMA
Palo Verde excluded
Chooz excluded
0
0.2
0.4
0.6
0.8
1
sin^2 2θ

Atmospheric Neutrinos

Compelling evidence for atmospheric ν_μ disappearance from ϕ_{ν_μ} vs. direction:



Isotropy of the $\gtrsim 2$ GeV cosmic rays + Gauss' Law + No ν_μ disappearance

$$\Longrightarrow \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1.$$

But Super Kamiokande finds for $E_\nu \gtrsim 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 0.54 \pm 0.04 .$$

Half of the upward-going, long-distance-traveling ν_μ are disappearing.

Voluminous atmospheric neutrino data are well described by —

$$\nu_\mu \longrightarrow \nu_\tau ,$$

with —

$$1.6 \times 10^{-3} < \Delta m^2_{atm} < 3.9 \times 10^{-3} \text{ eV}^2$$

(Value determined by diameter of earth)

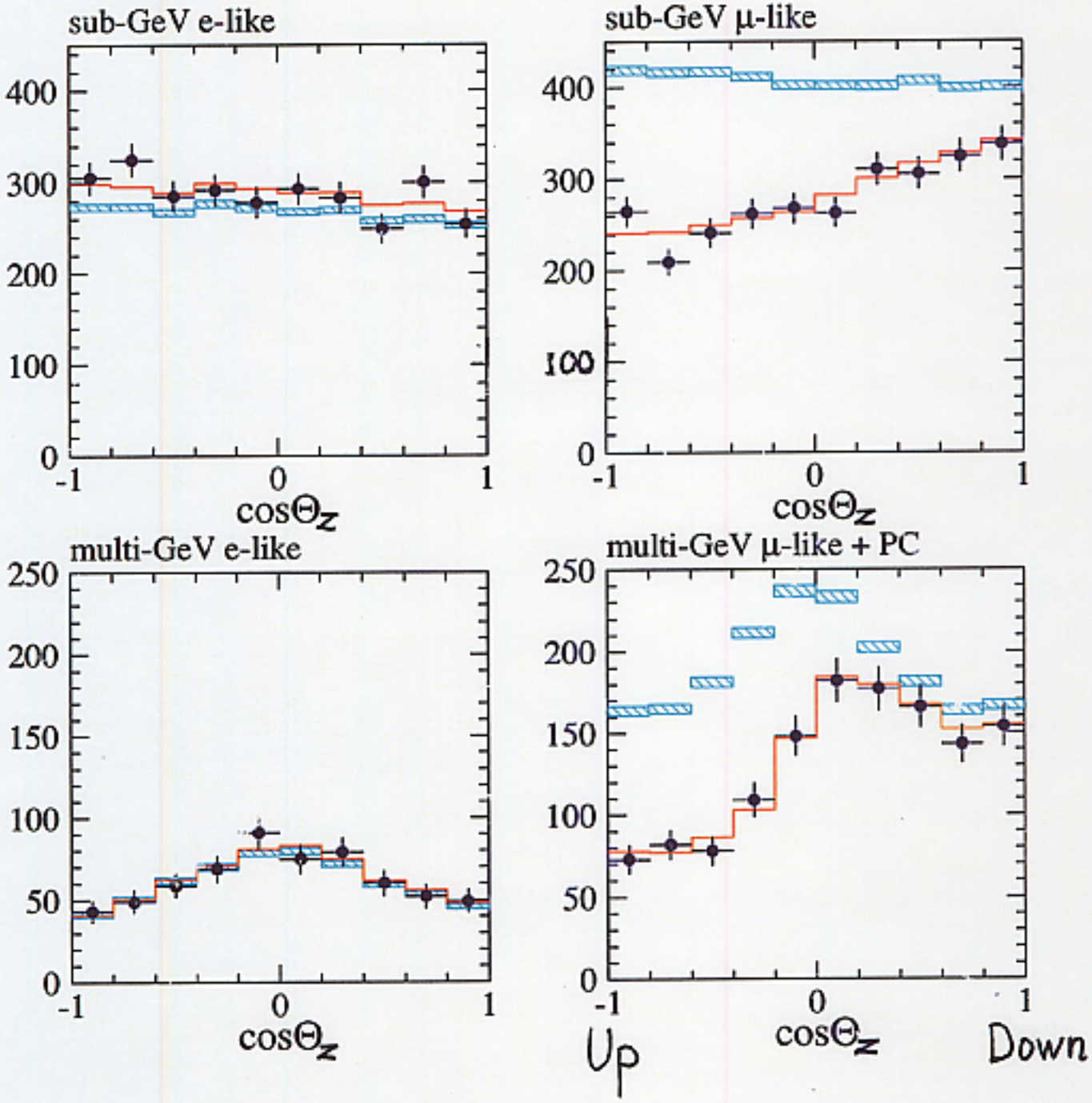
and —

$$\sin^2 2\theta_{atm} > 0.92$$

(Super-K 90% CL)

Compatible values from MACRO, Soudan.

Atmospheric Neutrinos in Super-K



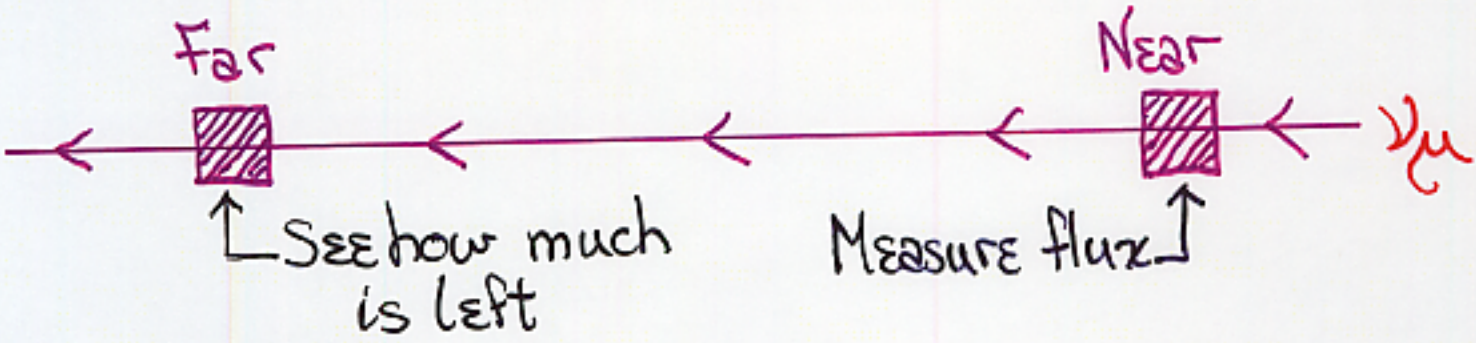
No oscillation

— Oscillation $\nu_\mu \to \nu_\tau$
$(2.5 \times 10^{-3}\,eV^2; 1.0)$

(Thanks to Mark Messier & Ed Kearns)

Long Base Line Accelerator Neutrinos

Do accelerator ν_μ disappear too?



K2K: 56 ν_μ events seen in far detector when 80 expected if no disappearance

Low ν_μ rate and E_{ν_μ} spectrum in far detector are best fit by —

$$\Delta m^2_{K2K} = 2.8 \times 10^{-3}\ eV^2, \quad \sin^2 2\theta_{K2K} = 1.0.$$

Atmospheric oscillations are best fit by —

$$\Delta m^2_{atm} = 2.5 \times 10^{-3}\ eV^2, \quad \sin^2 2\theta_{atm} = 1.0.$$

MINOS will have <u>much</u> more power.

Try to establish $\nu_\mu \rightarrow \nu_\tau$, and confirm undulation.

3.4 L(iquid) S(cintillator) N(eutrino) D(etector)

Reports an unconfirmed signal for $\bar{\nu}_e$ in a beam made by —

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu .$$

Hypothesis: $\bar{\nu}_\mu \to \bar{\nu}_e$.

This interpretation $\Rightarrow \Delta m^2_{LSND} \sim 1\ eV^2$.

D.O

Sterile Neutrinos ?

Nature contains 3 charged leptons:

e , μ , τ .

If LSND is confirmed, nature must contain at least 4 neutrinos:

ν_1 , ν_2 , ν_3 , ν_4 .

The reason :

Neutrinos	Required $\Delta m^2 (eV^2)$
Solar	$10^{-(4-5)}$
Atmospheric	$\sim 10^{-3}$
LSND	~ 1

Only 3 neutrinos $\Rightarrow$ $(\text{Mass})^2$ ↑ — / =

$\Rightarrow$ $\Delta m^2_{LSND} = \Delta m^2_{atm} + \Delta m^2_{\odot}$.

The experimentally required splittings do not satisfy this constraint.

Three linear combinations of $\nu_1 \ldots \nu_4$ are the active neutrinos ν_e, ν_μ, ν_τ.

The 4th linear combination, ν_s, has no charged-lepton partner. So it can't couple to the W.

$Z \to \nu\bar{\nu}$ decays yield only 3 distinct neutrino species. So ν_s doesn't couple to Z either.

Such a neutrino is called sterile.

Confirmation of LSND $\Rightarrow$

Existence of sterile neutrinos.

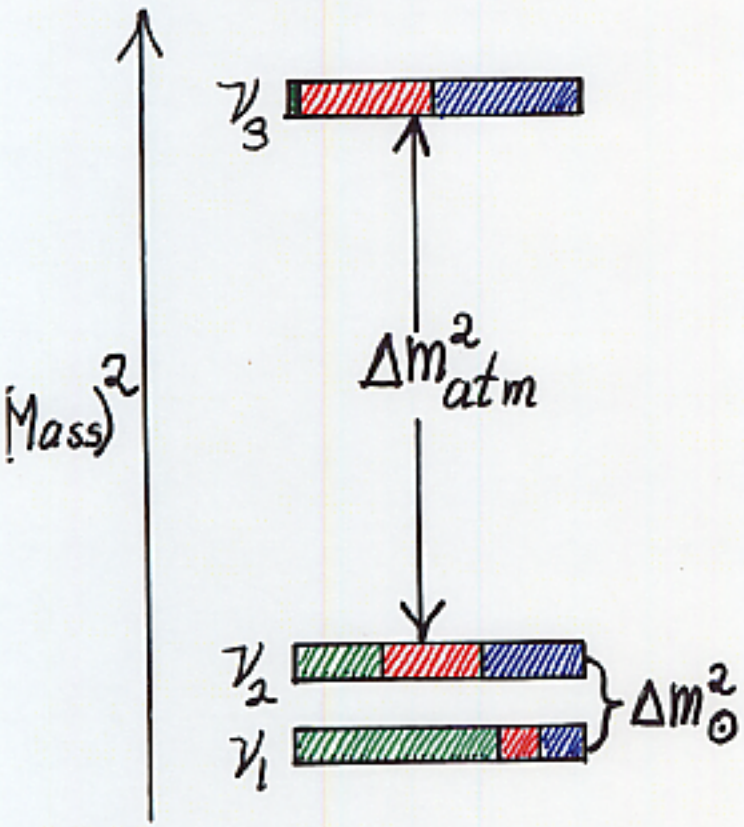
V.8

WHAT DO THE OBSERVATIONS IMPLY?

If LSND is confirmed ... [4V]

If LSND is not confirmed, nature may contain only 3 neutrinos.

Assuming LMA-MSW, the spectrum looks like —

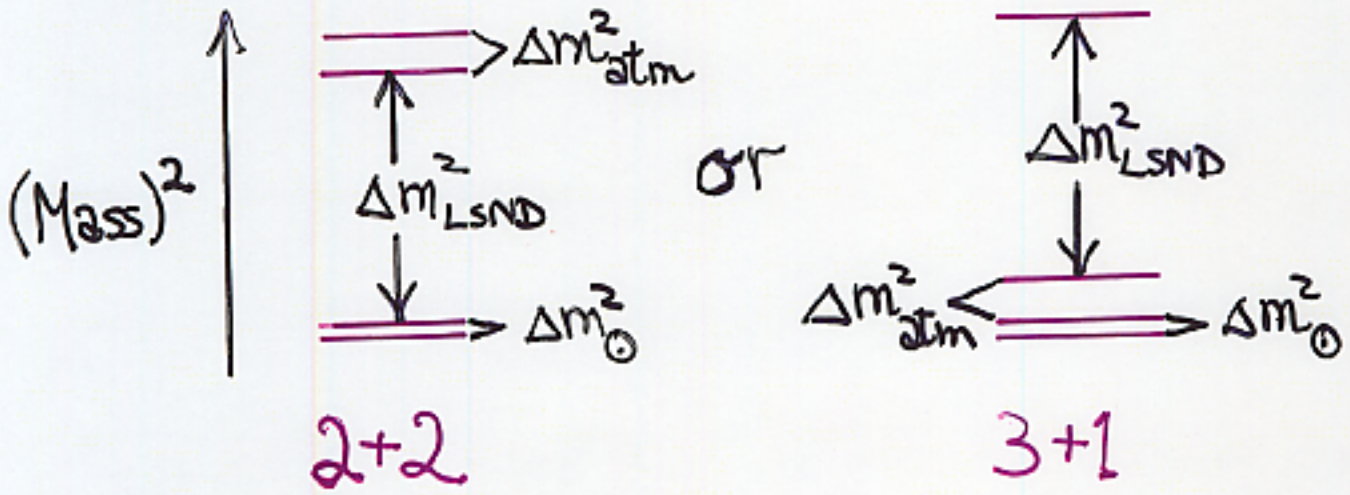


ν_e $[|U_{ei}|^2]$ ν_μ $[|U_{\mu i}|^2]$ ν_τ $[|U_{\tau i}|^2]$

If LSND is Confirmed

At least 4 mass eigenstates are required.

The spectrum looks like —



2+2 3+1

or "upside-down" version.

The 4-neutrino spectra do not produce great fits, but are not firmly excluded.

(Päs, Song, Weiler)

Five-neutrino spectra do much better.

(Sorel, Conrad, Shaevitz)

The LSND question must be settled experimentally

WHAT DO THE OBSERVATIONS IMPLY?

[4V]

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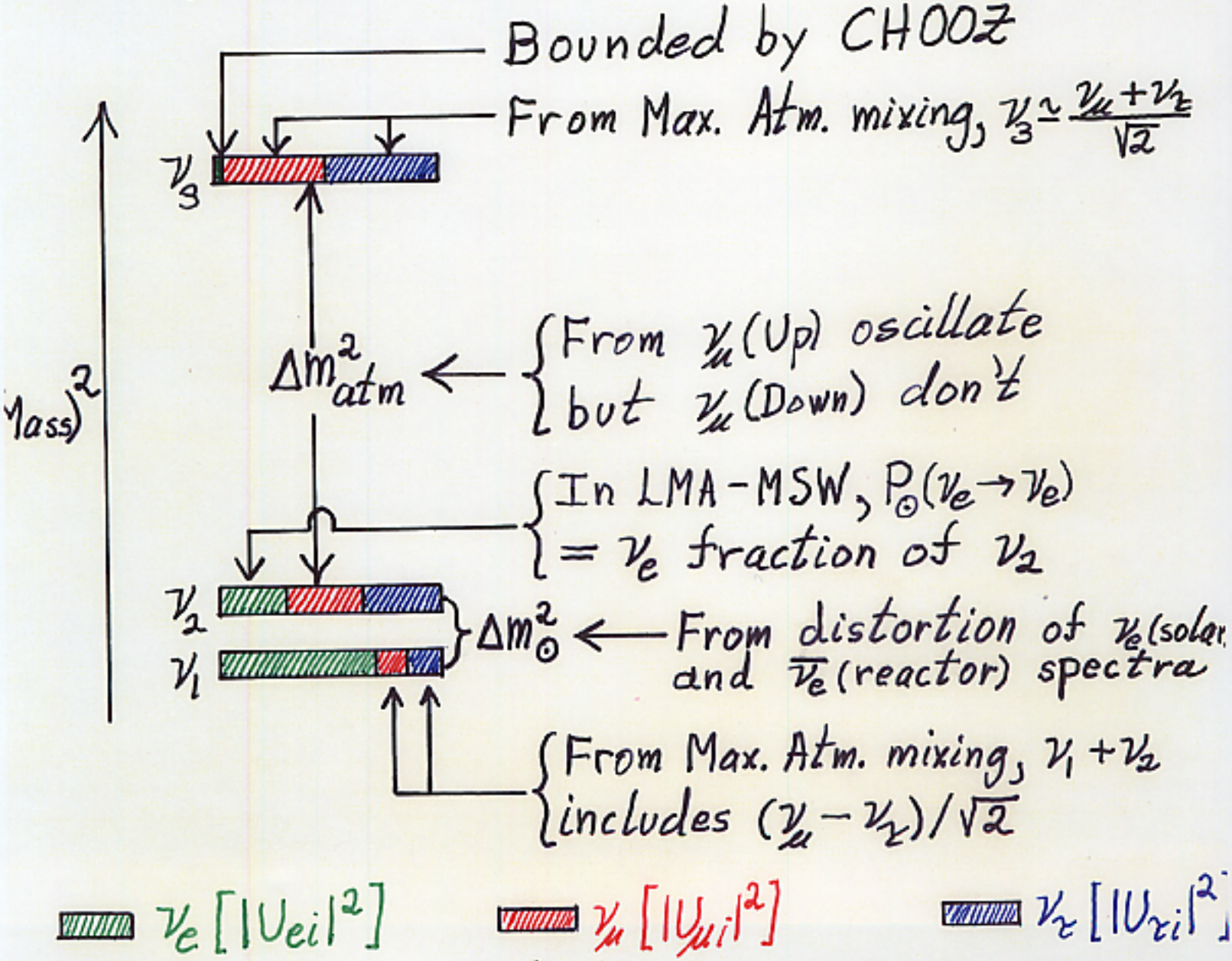


U.9]

The spectrum could be

instead of

B.8

A Cosmic Connection

WMAP + Other Cosmological Data

+ Cosmological Assumptions

$$\Rightarrow \sum_i m_i < 0.71 \text{ eV}.$$

m_i: Mass(ν_i)

(95% CL, Spergel et al.)

Tension between this bound and 4-neutrino spectra.

(Pierce & Murayama, Giunti, Strumia)

If there are only 3 neutrinos,

$$0.05\text{ eV} \lesssim \text{Mass}[\text{Heaviest } \nu_i] < 0.23\text{ eV}$$

$\sqrt{\Delta m^2_{atm}}$ — Cosmology

The Mixing Matrix

The flavor content picture shows the $|U_{\alpha i}|^2$, but not the signs or phases of the $U_{\alpha i}$.

For 3 neutrinos —

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}$$

$$\times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}\,, \quad s_{ij} \equiv \sin\theta_{ij} \qquad [27]$$

$$\theta_{12} \simeq \theta_{\odot} \simeq 34^\circ\,, \quad \theta_{23} \simeq \theta_{atm} \simeq 45^\circ$$

$$\theta_{13} \lesssim 10^\circ$$

The spectrum could be $\overline{\overline{}}$ instead of $\overline{}\,\overline{}$.

[F.10]

Corresponding to the flavor content shown,

Close pair (ν_1, ν_2) — Isolated (ν_3)

$$U \approx \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{bmatrix} c\,e^{i\frac{\alpha_1}{2}} & s\,e^{i\frac{\alpha_2}{2}} & s_{13}\,e^{-i\delta} \\ -\frac{s}{\sqrt{2}}\,e^{i\frac{\alpha_1}{2}} & \frac{c}{\sqrt{2}}\,e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}}\,e^{i\frac{\alpha_1}{2}} & -\frac{c}{\sqrt{2}}\,e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

$c \equiv \cos\theta_\odot$, $s \equiv \sin\theta_\odot$, $s_{13} \equiv \sin\theta_{13}$

With LMA1-MSW,

$0.25 \lesssim \sin^2\theta_\odot \lesssim 0.40$ (90% CL) (Fogli et al.)

From bounds on reactor $\overline{\nu}_e$ oscillation,

$\sin^2\theta_{13} \lesssim 0.03$ (90% CL) (CHOOZ, Palo Verde)

Surprise!

With B ≡ Big and s ≡ small ,

$$V_{(quarks)} = \begin{bmatrix} 1 & s & s \\ s & 1 & s \\ s & s & 1 \end{bmatrix} ,$$

but

$$U_{(leptons)} = \begin{bmatrix} B & B & s \\ B & B & B \\ B & B & B \end{bmatrix} .$$

Does this mean that leptonic mixing has a different origin than quark mixing does ??

δ leads to ~~CP~~ in oscillation:

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta).$$

ALL effects of δ are $\propto s_{13}$.

High priority:

Show $\theta_{13} \neq 0$.

Measure θ_{13}. [Fig]

α_1, α_2, and δ lead to ~~CP~~ in —

$$Nucl \to Nucl' + 2e^- \quad (0\nu\beta\beta).$$

$\alpha_{1,2}$ are known as Majorana phases.

They have no quark analogue.

What Is There To Know?

What physics is responsible for neutrino masses and mixing?

What is the scale of neutrino mass?

Are neutrinos Majorana particles ($\bar{\nu} = \nu$)?

Do neutrino interactions violate CP?

Is leptonic ~~CP~~ responsible for the baryon asymmetry in the universe?

How many neutrino species are there?

What is the neutrino mass spectral pattern?

What is the leptonic mixing matrix?

F.13

Major Questions for Future Accelerator ν Experiments

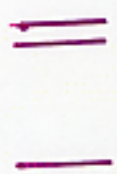
* How big is θ_{13} ?

* Does neutrino oscillation violate CP?

  If there are only 3 neutrinos,

  $$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \propto \sin\theta_{13}.$$

* If there are only 3 neutrinos, is the spectral pattern like

  or like  ?

  Answering this depends on θ_{13}.

* Is atmospheric ν mixing truly maximal?

  Is a symmetry, like CP in $K^0 \leftrightarrow \bar{K}^0$, involved?

How big do we expect θ_{13} to be ??

A prejudice

In gauge theory,

$$U = X_\ell X_\nu = \begin{bmatrix} B & B & \theta_{13} \\ B & B & B \\ B & B & B \end{bmatrix} ; \; B \equiv \text{Big}$$

X_ℓ: Diagonalizes ℓ mass matrix

X_ν: Diagonalizes ν mass matrix

Except for $U_{e3} \sim \theta_{13}$,

$$\text{all } U_{\alpha i} = \sum_j (X_\ell)_{\alpha j} (X_\nu)_{ji} \text{ are Big}$$

It would take a special cancellation (caused by a symmetry ??) for U_{e3} to be very much smaller than all other $U_{\alpha i}$.

How θ_{13} May Be Measured

$\sin^2\theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3. ν_3 is at one end of Δm^2_{atm}.

$\therefore$ We need an experiment with L/E sensitive to Δm^2_{atm}, and involving ν_e.

In a Long Base Line (LBL) experiment, neglecting matter effects,

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \cong P(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu) \cong \frac{1}{2}\sin^2 2\theta_{13}\,\sin^2\left(\Delta m^2_{atm}\frac{L}{4E}\right)$$

[R]

How $\overline{=}$ vs. $=$ May Be Determined

We determined that $m(K_L) > m(K_S)$ by —

- Passing kaons through matter (Regenerator)
- Beating the unknown Sign $[m(K_L) - m(K_S)]$ against the known Sign [Regeneration Amp.]

[2] θ_{13} with Reactor $\bar{\nu}_e$

For $\Delta m^2_{atm} \frac{L}{4E} \sim 1$ $\left[\frac{L}{E} \sim \frac{1\ km}{1\ MeV}\right]$,

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left(\Delta m^2_{atm} \frac{L}{4E}\right).$$

Look for a very small disappearance of $\bar{\nu}_e$ flux. [Present bound: $\sin^2 2\theta_{13} < 0.1$]

Systematics?

To determine—

$$\text{Sign}[m^2(\text{—}) - m^2(=)] \equiv S,$$

- Pass neutrinos through matter
- Beat the unknown sign S against the known Sign [Extra Energy of ν_e in Matter]

From $\nu_e e \to \nu_e e$

Coherent forward

in matter

— raises ν_e energy.

— lowers $\overline{\nu_e}$ energy.

In earth matter of ~ constant density,

$$P(\overrightarrow{\nu}_\mu \to \overrightarrow{\nu}_e) \cong P(\overrightarrow{\nu}_e \to \overrightarrow{\nu}_\mu) \cong \frac{1}{2} \sin^2 2\overleftarrow{\theta}_M \sin^2\left(\overrightarrow{\Delta m^2_M} \frac{L}{4E}\right)$$

Same formula as in vacuum, but with θ_{13} and Δm^2_{atm} replaced by their effective values in matter.

[3ν spectrum]

If $\overrightarrow{\Delta m^2_M} \lessgtr \Delta m^2_{atm}$.

If $\overleftarrow{\Delta m^2_M} \gtrless \Delta m^2_{atm}$.

One can easily show that —

$$\overrightarrow{\Delta m^2_M} \sin 2\overleftarrow{\theta}_M = \Delta m^2_{atm} \sin 2\theta_{13}.$$

If the (mass)^2 gap shrinks, the mixing grows.

How May We Seek ~~CP~~ in Oscillation?

Compare ν and $\bar{\nu}$ oscillation.

If there are $\geq 4\nu$, the ~~CP~~ pattern may be very rich.

If there are only 3ν, <u>in principle</u> the pattern is very simple —

20)

Let $P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \equiv \Delta_{\not CP}(\alpha\beta)$.

If there are only 3 neutrinos,

$$\Delta_{\not CP}(e\mu) = \Delta_{\not CP}(\mu\tau) = \Delta_{\not CP}(\tau e)$$

$$= 16\, J\, k_{12}\, k_{23}\, k_{31}\,,$$

where

$$J \equiv Im(U_{e1}^*\, U_{e3}\, U_{\mu 1}\, U_{\mu 3}^*) \cong \frac{1}{4} \sin 2\theta_0 \sin\theta_{13} \sin\delta,$$

and

$$k_{ij} \equiv \sin\left(\Delta m_{ij}^2 \frac{L}{4E}\right).$$

In experiments being considered, perhaps

$$\Delta_{\not CP} \sim 1\%.$$

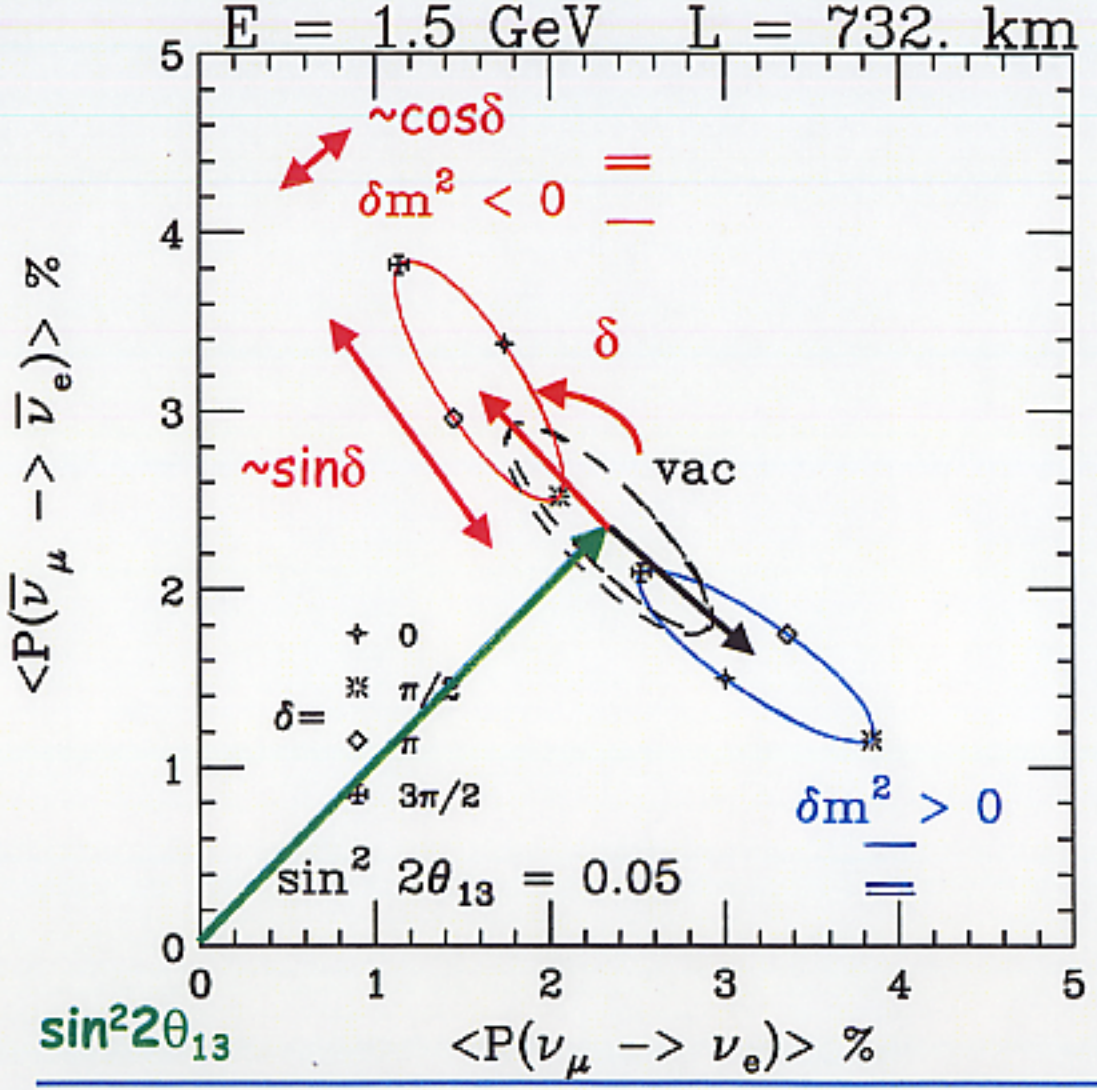
In Practice

Individual oscillation probabilities depend on the ~~CP~~ phase δ, on CP-conserving variables like θ_{13}, and on matter effects.

Complementary measurements will be needed to disentangle the parameters.

Barenboim, Barger, de Gouvea, Geer, Gomez-Cadenas, Harris, Huber, Lindner, Marfatia, Minakata, Nunokawa, Para, Parke, Szleper, Velasco, Whisnant, Winter, Gavela, Mena, Raja

Anatomy of Bi-probability ellipses



Minakata and Nunokawa, hep-ph/0108085

Observables are:

- P
- $\bar{P}$

Interpretation in terms of $\sin^2 2\theta_{13}$, δ and sign of Δm^2_{23} depends on the value of these parameters and on the conditions of the experiment: L and E

Why Is $\not{CP}$ in ν Oscillation So Interesting?

Demonstrating that $\not{CP}$ in oscillation is nonzero would establish that $\not{CP}$ is not a peculiarity of quarks.

Leptonic $\not{CP}$ might have been the $\not{CP}$ that made baryogenesis possible.

In the See-Saw mechanism, the light neutrinos have very heavy neutral lepton partners N, with

$$m_N \sim \frac{m_{top}^2}{m_\nu} \sim 10^{15}\ \text{GeV}.$$

Each N is a Majorana particle ($\bar{N}=N$).

Perhaps in the early universe there was

$$\Gamma[N \to \ell^+ + \text{Higgs}^-] > \Gamma[N \to \ell^- + \text{Higgs}^+].$$

↑ ~~CP~~

Leptogenesis

Standard Model (B−L) − conserving, but B- and L-violating, processes would then have converted some of this antilepton excess into a baryon excess.

(Fukugita & Yanagida)

How Is ~~CP~~ in ν Oscillation Related To ~~CP~~ in Leptogenesis?

The relation is model-dependent.

However —

It is not likely that we have one without the other.

(Davidson, Pascoli, Petcov, Rodejohann, Yanagida)