Fermilab
April 3, 2003

—THE NEUTRINOS—

What Have We Learned?

What Would We Like to Find Out?

Boris Kayser

The Scene

The last 5 years have brought compelling evidence that neutrinos change flavor.

Not through flavor-changing interactions with matter, but through—

neutrino masses and mixing.

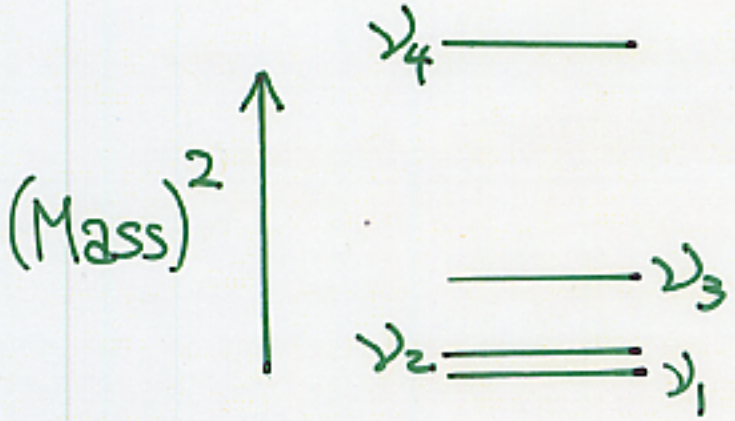
The discovery of ν mass and mixing opens a whole ν world to explore.

We would like to explore this world because—

- Its physics is beautiful
- It is a window on what lies beyond the Standard Model
- It has potentially major implications for astrophysics and cosmology

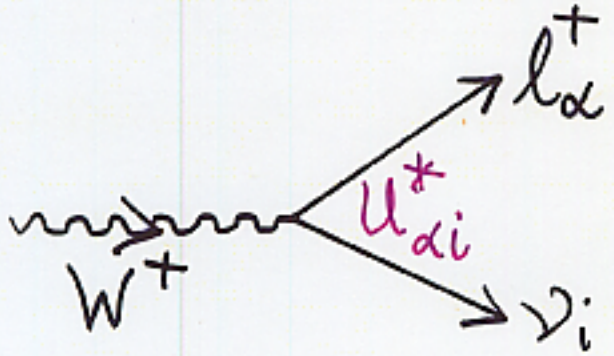
To Learn

1) The neutrino mass spectrum.



$$\text{Mass}(\nu_i) \equiv m_i$$

2) The leptonic mixing matrix U.



$(l_e \equiv e,\ l_\mu \equiv \mu,\ l_\tau \equiv \tau)$

The neutrino state produced together with the charged lepton mass eigenstate l_α is the superposition

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle .$$

Neutrino of flavor α

Unitary

In a detector —

Only a ν_e can make an e

" ν_μ " " μ

" ν_τ " " τ

But suppose the mass eigenstates ν_i have differing masses m_i.

Then, when $\pi^+ \to W^+ \to \mu^+ + \nu_\mu$, the superposition ν_μ will evolve, in time, into a different superposition, containing, e.g., a ν_τ component.

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

Neutrino Oscillation

Inverting $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$,

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

Flavor-α fraction of $\nu_i = |\langle\nu_\alpha|\nu_i\rangle|^2 = |U_{\alpha i}|^2$.

C.11 If there are, say, four mass eigenstates then one linear combination of them,

$$|\nu_s\rangle = \sum_i U^*_{si} |\nu_i\rangle ,$$

has no charged-lepton partner.

$\therefore$ ν_s 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.

More than 3 neutrinos $\Longrightarrow$
A new kind of neutrino.

Neutrino Oscillation in Vacuum

With L = distance a neutrino travels, and E = neutrino energy,

the amplitude for the vacuum oscillation $\nu_\alpha \to \nu_\beta$ is —

$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i \underbrace{U_{\alpha i}^*}_{\nu_\alpha \text{ is } \nu_i} \underbrace{e^{-i m_i^2 \frac{L}{2E}}}_{\nu_i \text{ propagates}} \underbrace{U_{\beta i}}_{\nu_i \text{ is } \nu_\beta} .$$

The oscillation probability

$$P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2$$

depends only on the —

splittings $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$.

The "Two" Neutrino Case

- Only 2 ν_i couple significantly to the initial ℓ_α

or

- The experiment thinks $\overset{-}{=}$ is $\overset{-}{-}$

because its L/E is too small for it to see the small splitting.

Then—

$$P(\nu_\alpha \to \nu_\alpha) \cong 1 - \sin^2 2\theta \, \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

The mixing angle

The sole (mass)^2 splitting

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}

$$\phi_{\nu_\mu, \nu_\tau} = \left(3.45 \begin{smallmatrix} +0.65 \\ -0.62 \end{smallmatrix}\right) \times 10^6 / \mathrm{cm}^2\,\mathrm{sec}$$

(5.5σ from zero)

†Also measured by Super Kamiokande (SK)

The favored explanation of this $\nu_e \longrightarrow [\nu_\mu$ 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 favored mass splitting and mixing are —

$$2.3\times10^{-5} \lesssim \Delta m^2_{\odot} \lesssim 9.3\times10^{-5}\,eV^2$$

Value determined by density of electrons in the sun.

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 $\xRightarrow{\text{CPT}}$

KamLAND, ~200 km from reactor $\bar{\nu}_e$ sources, should see substatial disappearance of $\bar{\nu}_e$ flux.

Other candidate explanations of solar ν flavor change $\Rightarrow$

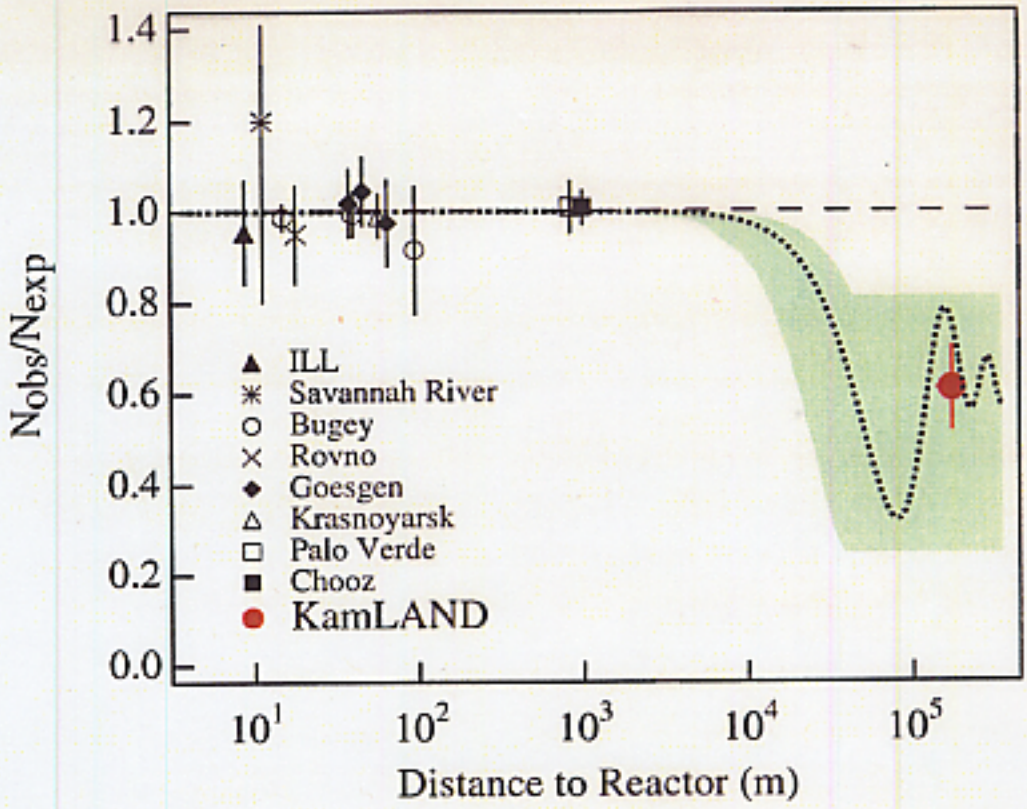
KamLAND should see no disappearance of $\bar{\nu}_e$ flux.

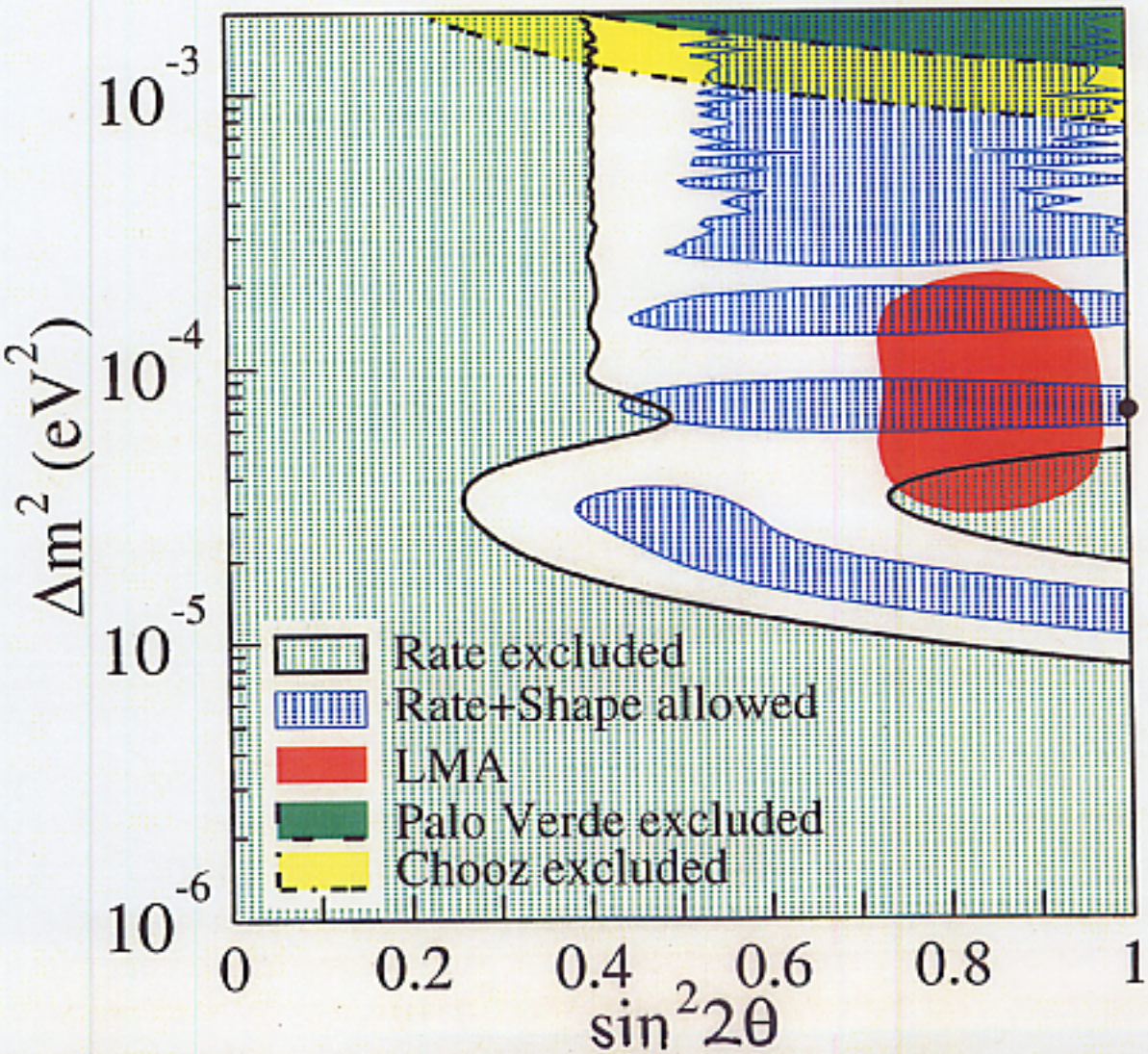
KamLAND actually does see —

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

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

Is this disappearance due to flavor change?


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

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]

$\Delta m^2_\odot$ and $\sin^2 2\theta_\odot$ in the range of any other solar candidate are ruled out by KamLAND:

$\Delta m^2_\odot$ would be too small for KamLAND to see disappearance.

$\not{CP}$

The question of whether neutrino oscillation violates CP is particularly intriguing.

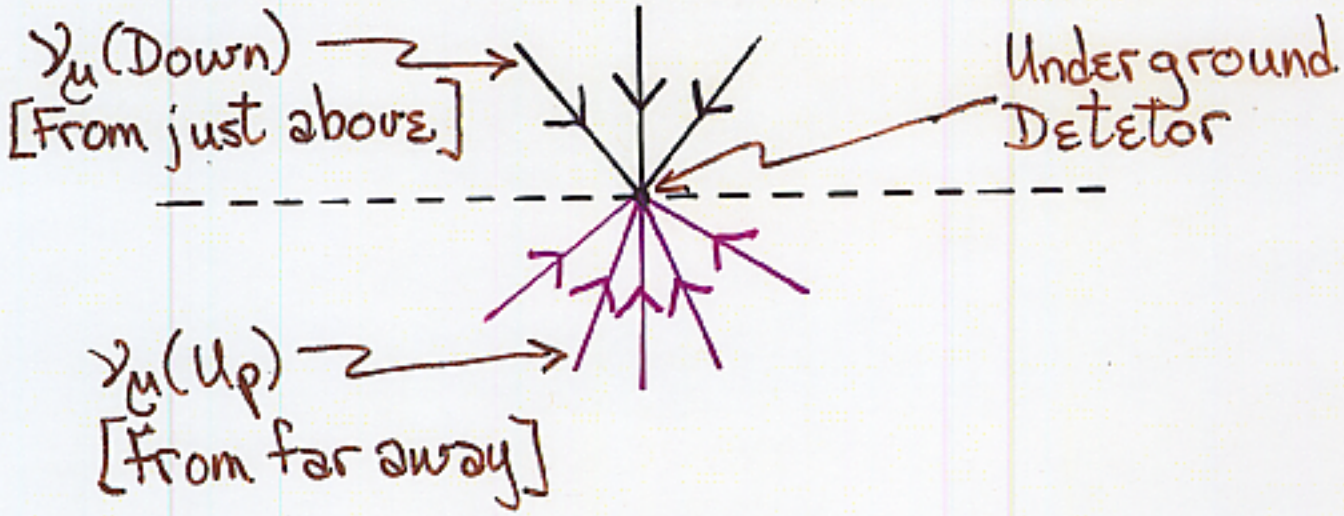
Is there not only quark-sector $\not{CP}$ but also leptonic $\not{CP}$?

Assuming only 3 neutrinos, LMA-MSW is the only solar candidate whose $\Delta m^2_\odot$ and $\theta_\odot$ are both large enough to make $\not{CP}$ observable in terrestrial ν oscillation.

We are very lucky: Nature has chosen LMA-MSW.

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 —

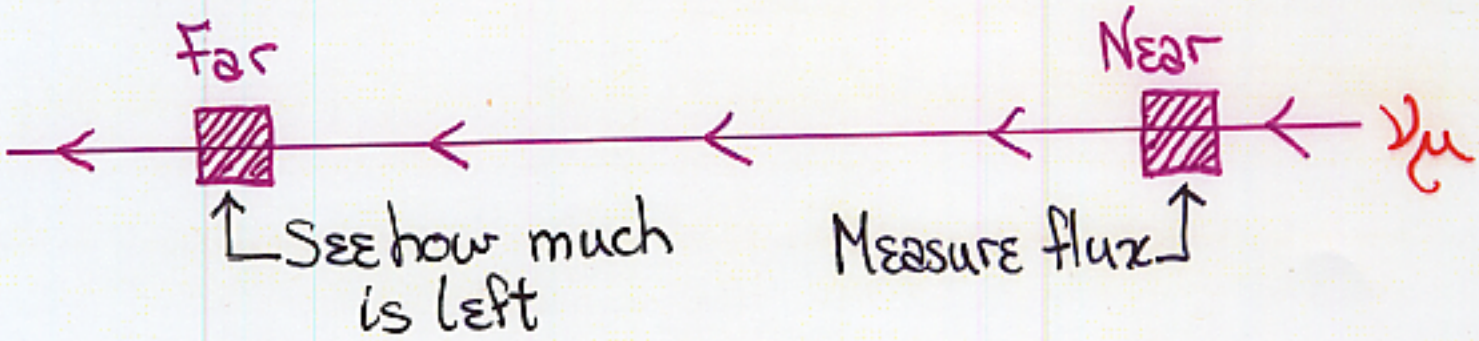
$$\sin^2 2\theta_{atm} > 0.92$$

(Super-K 90% CL)

Compatible values from MACRO, Soudan.

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 $\nu_\mu \to \nu_\tau$, and confirm undulation.

R.M.

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

Reports a signal for $\bar{\nu}_e$ in beam made by –

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

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

A joint analysis of LSND and the null KARMEN experiment $\Longrightarrow$

$$0.2 \lesssim \Delta m^2_{LSND} \lesssim 1\,eV^2 \;\&\; .003 \lesssim \sin^2 2\theta_{LSND} \lesssim .03$$

–or–

$$\Delta m^2_{LSND} \simeq 7\,eV^2 \;\&\; \sin^2 2\theta_{LSND} \simeq .004$$

(Church et al.)

Value $\sim 1\,eV^2$ determined by

$$(L/E)_{LSND} \sim (30\,m/30\,MeV) = 1\,km/GeV$$

Sterile Neutrinos?

Nature contains 3 charged leptons:

$$e, \mu, \tau.$$

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

$$\nu_1, \nu_2, \nu_3, \nu_4.$$

The reason:

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

Only 3 neutrinos $\Longrightarrow$

$$\sum \Delta m^2 = (m_3^2 - m_2^2) + (m_2^2 - m_1^2) + (m_1^2 - m_3^2) = 0.$$

The experimentally required splittings do not satisfy this constraint.

If all splittings are genuine, there are ≥ 4 ν_i.

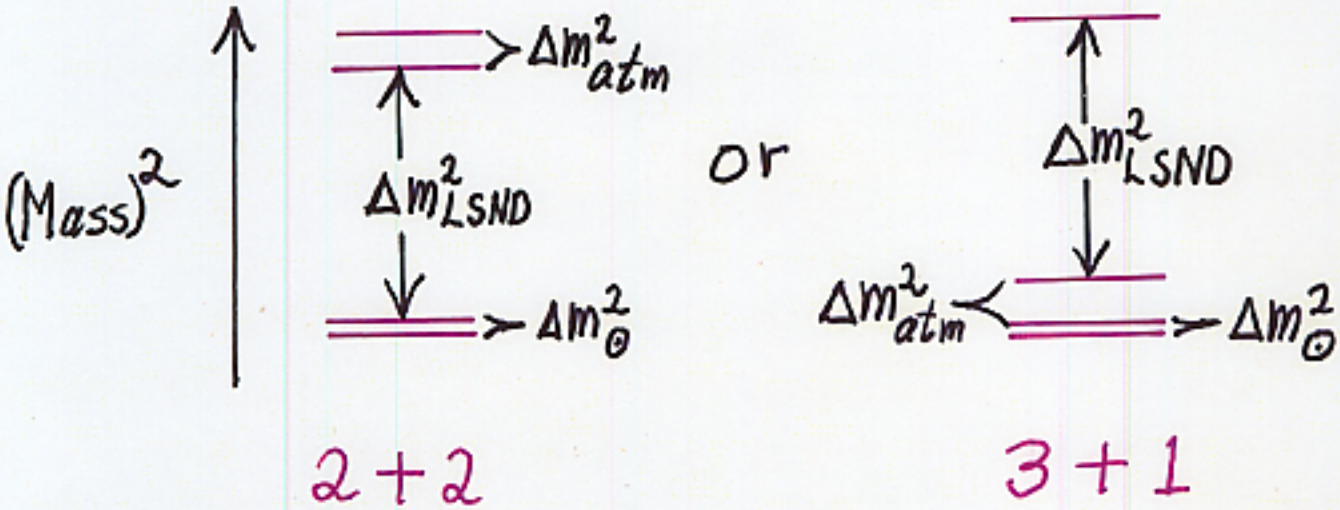
Confirmation of LSND $\Longrightarrow$ Existence of sterile neutrinos.

MiniBooNE is testing LSND.

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)

The LSND question must be settled experimentally

The Cosmological Upper Bound

WMAP + 2dFGRS + Other Data $\Rightarrow$

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

(95% CL
Spergel et al.)

This very interesting upper bound depends on cosmological assumptions.

Example: If the Primordial Power Spectrum does not have the usually-assumed shape, one finds —

$$\sum_i m_i \lesssim 1.2\ \text{eV}.$$

(95% CL
Abazajian et al.)

Example: $\dfrac{\text{Number}(\nu)}{\text{Volume}} = \dfrac{\text{Number}(\bar{\nu})}{\text{Volume}}$

Every candidate 4-neutrino spectrum is at least somewhat challenged by the bound $\sum_i m_i < 0.71$ eV.

Confirmation of LSND and establishment of a 4-neutrino spectrum, plus some tightening of the cosmological bound would imply—

New Cosmology.

Surprise!

With B ≡ Big and s ≡ small,

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

but

$$\mathcal{U}_{(\text{leptons})} = \begin{bmatrix} B & B & s \\ B & B & B \\ B & B & B \end{bmatrix}.$$

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

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 —

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

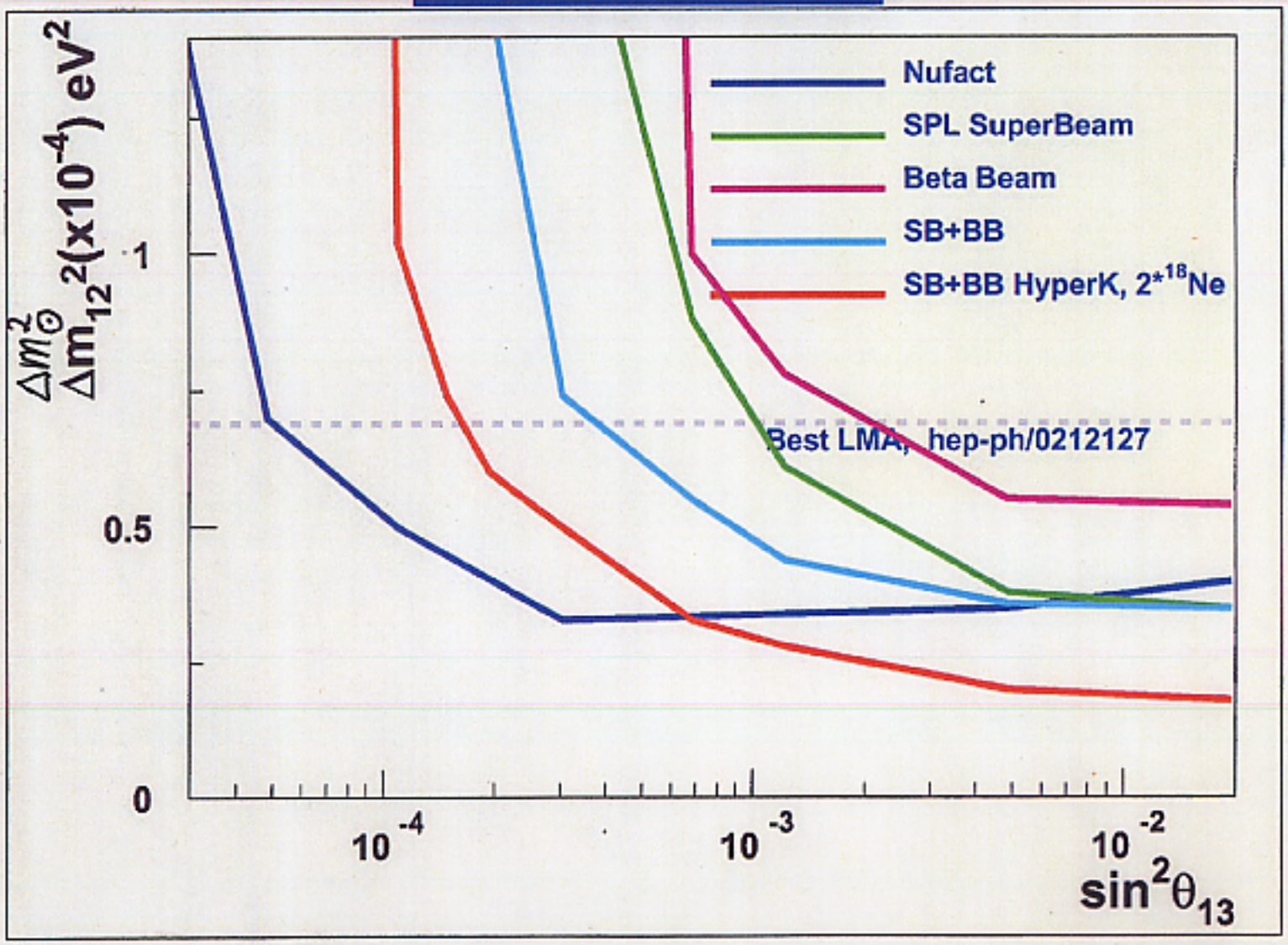
$$\times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij}$$

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

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

Final CP sensitivity.



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 –

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

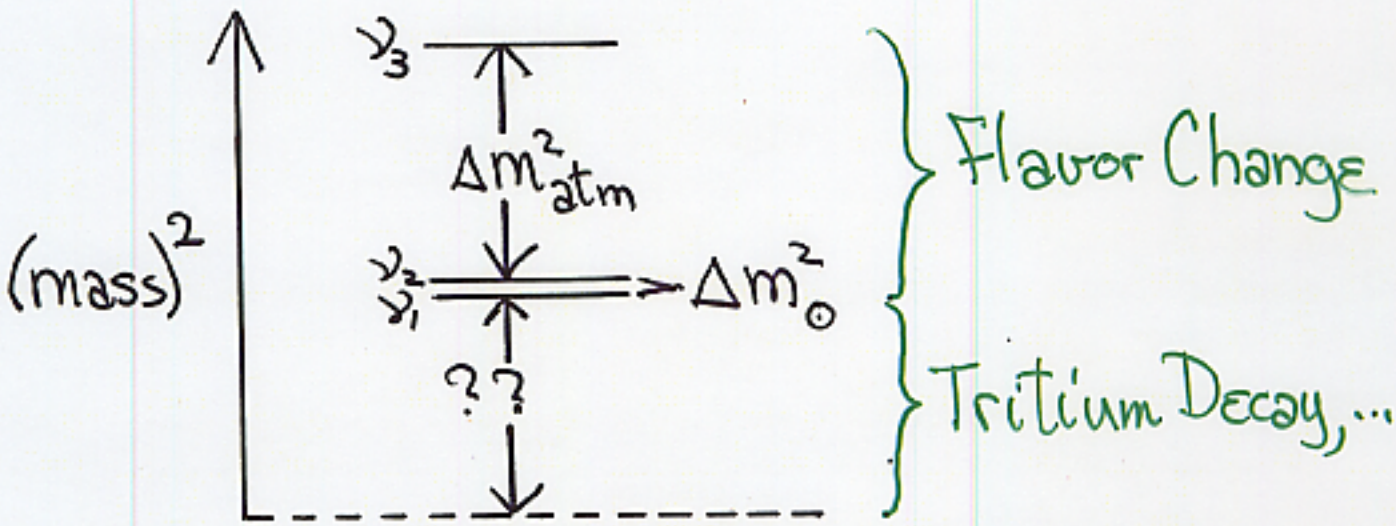
$\alpha_{1,2}$ are known as Majorana phases.

They have no quark analogue.

The Future—Questions That Need Answers

* How many neutrino species are there? Do sterile neutrinos exist?

* What are the masses of the mass eigenstates ν_i?



Is the spectral pattern $\equiv$ or $\equiv$?

After WMAP, if 3 neutrinos,

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

$\sqrt{\Delta m^2_{atm}}$ Cosmology

* Is each mass eigenstate —

- A Majorana particle $(\bar{\nu}_i = \nu_i)$

or

- A Dirac particle $(\bar{\nu}_i \neq \nu_i)$?

The theoretical prejudice: $\bar{\nu}_i = \nu_i$.

This will be true if nature contains Majorana mass terms, e.g. $M\overline{\nu_R^c}\,\nu_R$.

S(tandard) M(odel): $m_\nu = 0$.

Why not add a Dirac mass term, $m\bar{\nu}_L \nu_R$?

This requires ν_R. Then no SM principle prevents the occurrence of $M\overline{\nu_R^c}\,\nu_R$.

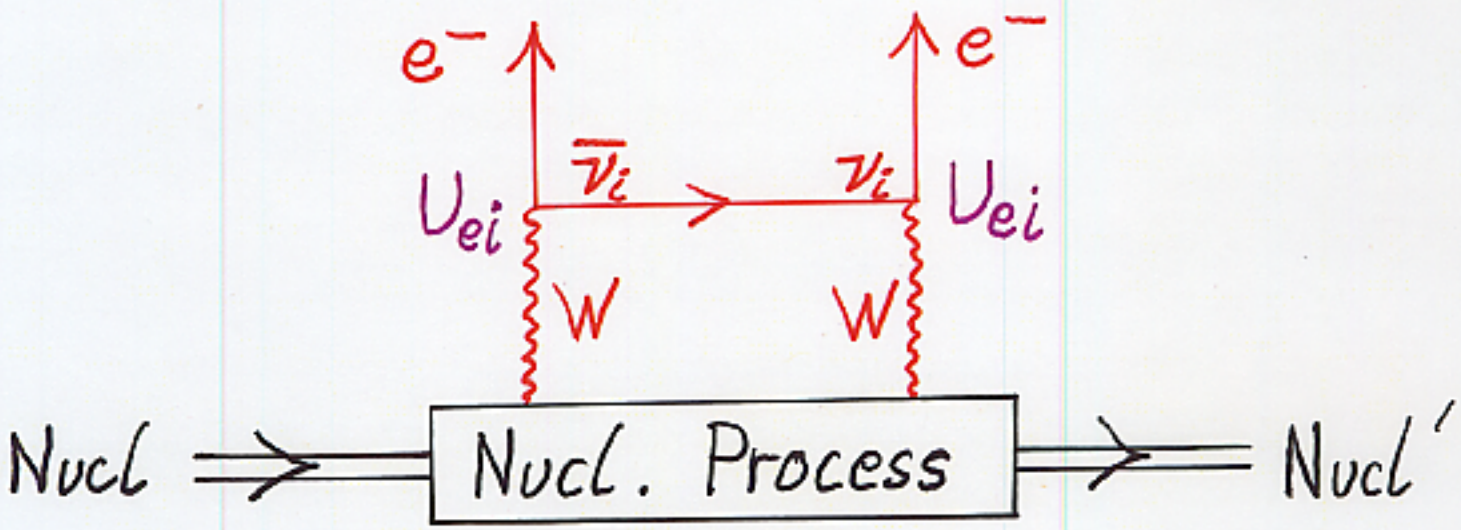
How can we confirm that $\bar{\nu}_i = \nu_i$?

Assuming CPT invariance —

$0\nu\beta\beta\ [\mathrm{Nucl} \to \mathrm{Nucl}' + 2e^-] \Rightarrow \bar{\nu}_i = \nu_i$.

(Schechter + Valle)

The dominant mechanism is expected to be —



$\bar{\nu}_i$ is emitted $[RH + \mathcal{O}(\frac{m_i}{E})LH]$

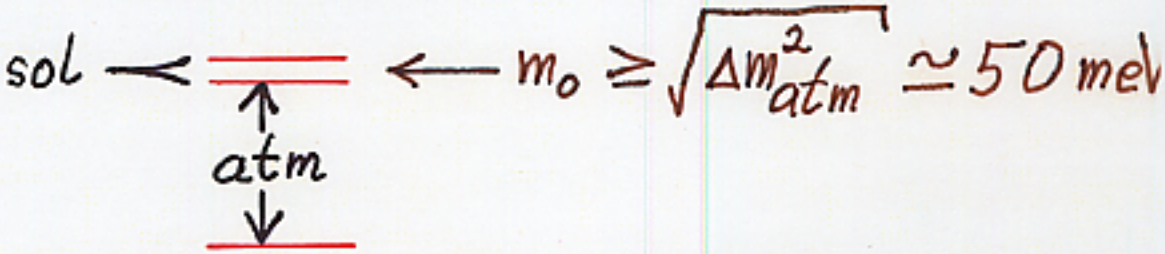
$\therefore$ Amp$[\nu_i$ contribution$] \propto m_i$

$$\mathrm{Amp}\,[0\nu\beta\beta] \propto \left|\sum_i m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$

$m_{\beta\beta}$ is a measure of the ν mass scale.

Desirable sensitivity: $m_{\beta\beta} \lesssim 50$ meV.

If the spectrum looks like —



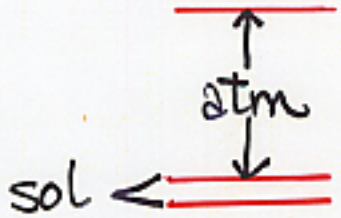
then —

$$m_{\beta\beta} \cong m_0 \sqrt{1 - \sin^2 2\theta_\odot \sin^2\left(\frac{\alpha_2 - \alpha_1}{2}\right)}$$

$$\geq m_0 \cos 2\theta_\odot .$$

$\cos 2\theta_\odot \gtrsim 0.2$ @ 90% CL.

If the spectrum looks like —



then

$$0 < m_{\beta\beta} < \text{Present Bound } [(0.3-1.0)\ \text{eV}] .$$

(Petcov et al.)

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

  $$\begin{matrix} - \\ = \end{matrix} \quad \text{or like} \quad \begin{matrix} = \\ - \end{matrix} \quad ?$$

  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,

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

Diagonalizes ℓ mass matrix

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,

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

How $\overset{-}{=}$ vs. $\overset{=}{-}$ 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.]

In earth matter of ~ constant density,

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

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

[3ν spectrum]

If $\underline{\underline{\quad}}$, $\overset{(-)}{\Delta m^2_M} \overset{<}{(>)} \Delta m^2_{atm}$.

If $\underline{\underline{\quad}}$, $\overset{(-)}{\Delta m^2_M} \overset{>}{(<)} \Delta m^2_{atm}$.

One can easily show that—

$$\overset{(-)}{\Delta m^2_M} \sin 2\overset{(-)}{\theta}_M = \Delta m^2_{atm} \sin 2\theta_{13}.$$

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

F.15

To determine—

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

- Pass neutrinos through matter
- Beat the unknown sign S against the known Sign [$\underbrace{\text{Extra Energy of } \nu_e \text{ in Matter}}_{\text{From } \nu_e e \to \nu_e e}$]

Coherent forward

in matter

— raises ν_e energy.

— lowers $\bar{\nu}_e$ energy.

How May We Seek $\not{CP}$ in Oscillation?

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

If there are $\geq 4\nu$, the $\not{CP}$ pattern may be very rich.

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

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

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

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

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

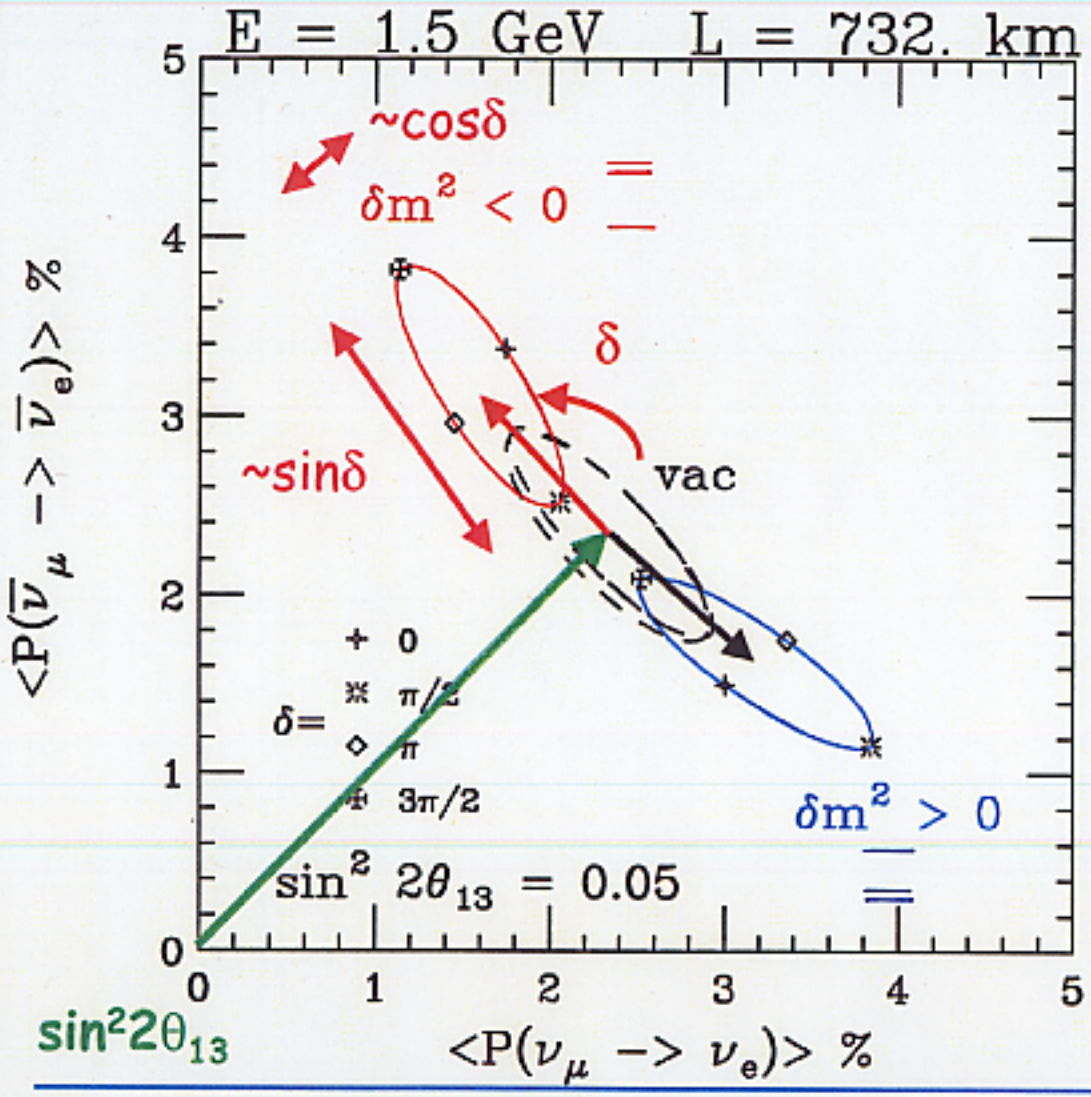
Individual oscillation probabilities depend on the ~~CP~~ phase δ, on CP-conserving variables like θ_{13}, and on matter effects.

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

Anatomy of Bi-probability ellipses

Minakata and Nunokawa, hep-ph/0108085



Observables are:

- $\underline{P}$
- $\bar{P}$

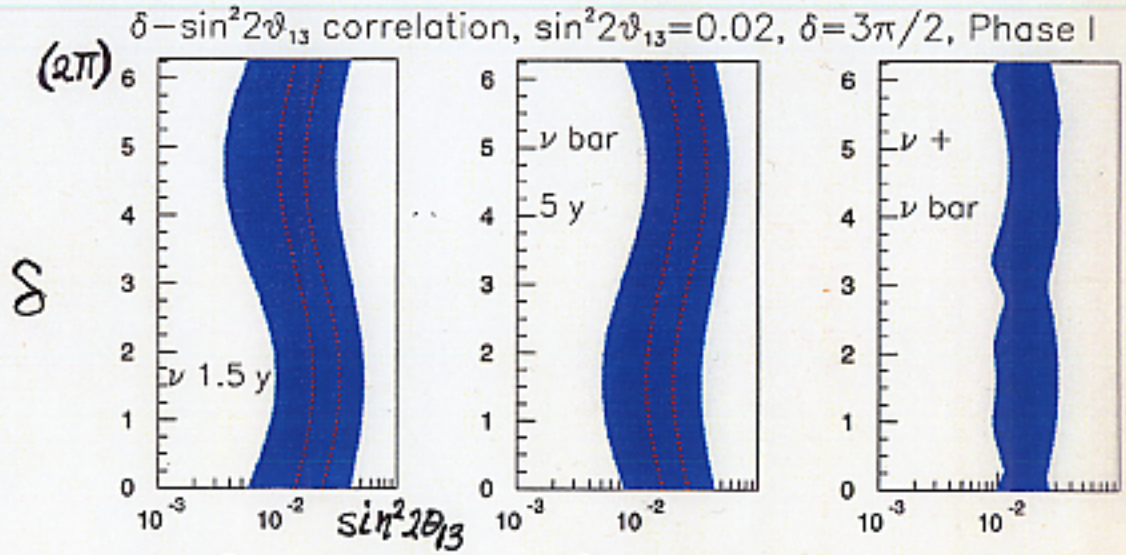
Interpretation in terms of $\sin^2 2\theta_{13}$, δ and sign of Δm^2_{23} depends on the value of these parameters and on the conditions of the experiment: L and E

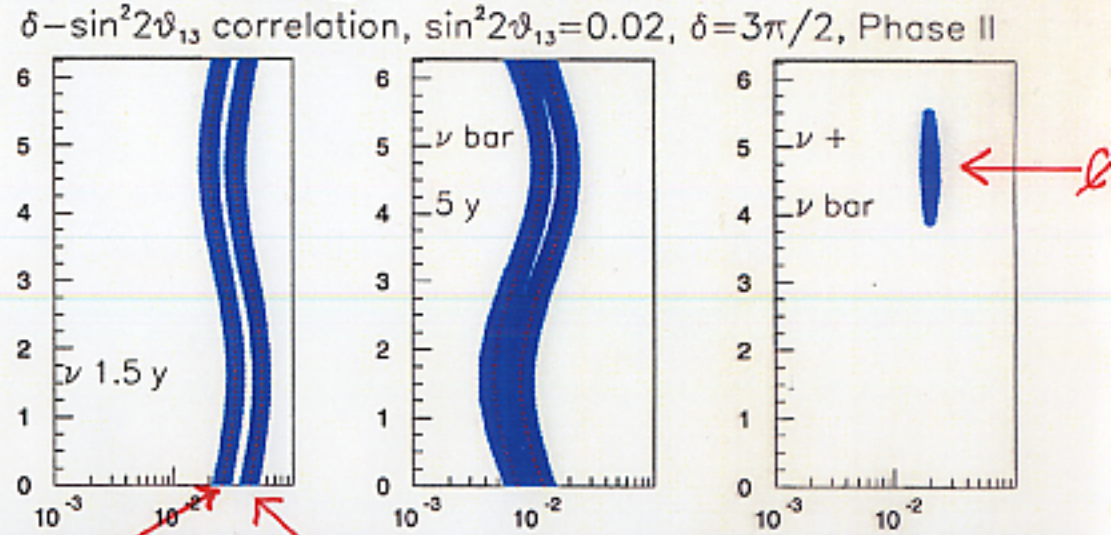
NuMI Off-axis Sensitivity for Phases I and II

Phase I

20 kton Detector

4×10^{20} p/yr





We take the Phase II to have 25 times higher POT x Detector mass

Neutrino energy and detector distance remain the same

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

$$\Gamma[N \to \ell^+ + \text{Higgs}^-] \underset{\uparrow \not{CP}}{>} \Gamma[N \to \ell^- + \text{Higgs}^+].$$

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 $\not{CP}$ in ν Oscillation Related To $\not{CP}$ in Leptogenesis?

The relation is model-dependent.

However —

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

(Davidson, Pascoli, Petcov, Rodejohann, Yanagida)

Conclusion

We have learned that neutrinos have masses.

But we do not know—

- How many ν species there are
- How much the neutrinos weigh
- Whether $\bar{\nu} = \nu$

We have discovered that two mixing angles are large.

But we do not know—

- The size of the crucial 3rd angle
- Whether ν oscillation violates CP
- Whether the spectral pattern is $\equiv$ or $\equiv$

The paths to answering many of these questions will involve accelerator neutrinos.

Fermilab could play a very important role.

The coming years should be very interesting indeed.

C.2

$$P(\nu_\alpha \to \nu_\beta) =$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

$$+ 2 \sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\Delta m^2_{ij} \frac{L}{2E}\right)$$

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta ; U) \underset{CPT}{=} P(\nu_\beta \to \nu_\alpha ; U)$$

$$\underset{\text{Above}}{=} P(\nu_\alpha \to \nu_\beta ; U^*)$$

$$P(\overleftrightarrow{\nu}_\alpha \to \overleftrightarrow{\nu}_\beta) =$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$\pm 2 \sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

$$P(\overline{\nu}_\alpha \to \overline{\nu}_\beta ; U) \underset{CPT}{=} P(\nu_\beta \to \nu_\alpha ; U)$$

$$\underset{\text{Above}}{=} P(\nu_\alpha \to \nu_\beta ; U^*)$$

Complex phases in U can lead to the ~~CP~~

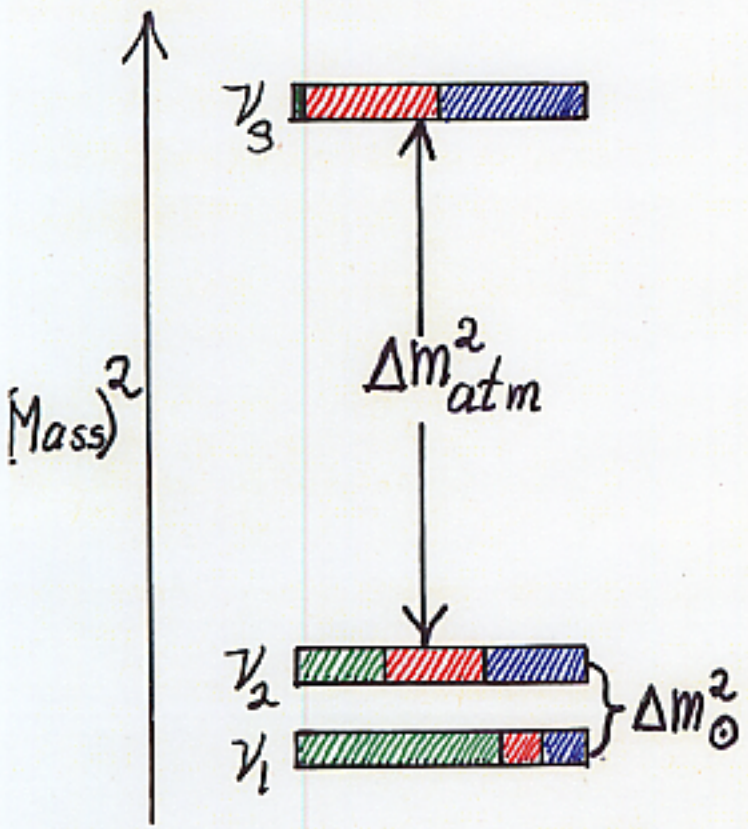
$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta).$$

WHAT DO THE OBSERVATIONS IMPLY?

If LSND is confirmed ...

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

Assuming LMA-MSW, the spectrum looks like —



$\nu_e\,[|U_{ei}|^2]$ $\nu_\mu\,[|U_{\mu i}|^2]$ $\nu_\tau\,[|U_{\tau i}|^2]$.

WHAT DO THE OBSERVATIONS IMPLY?

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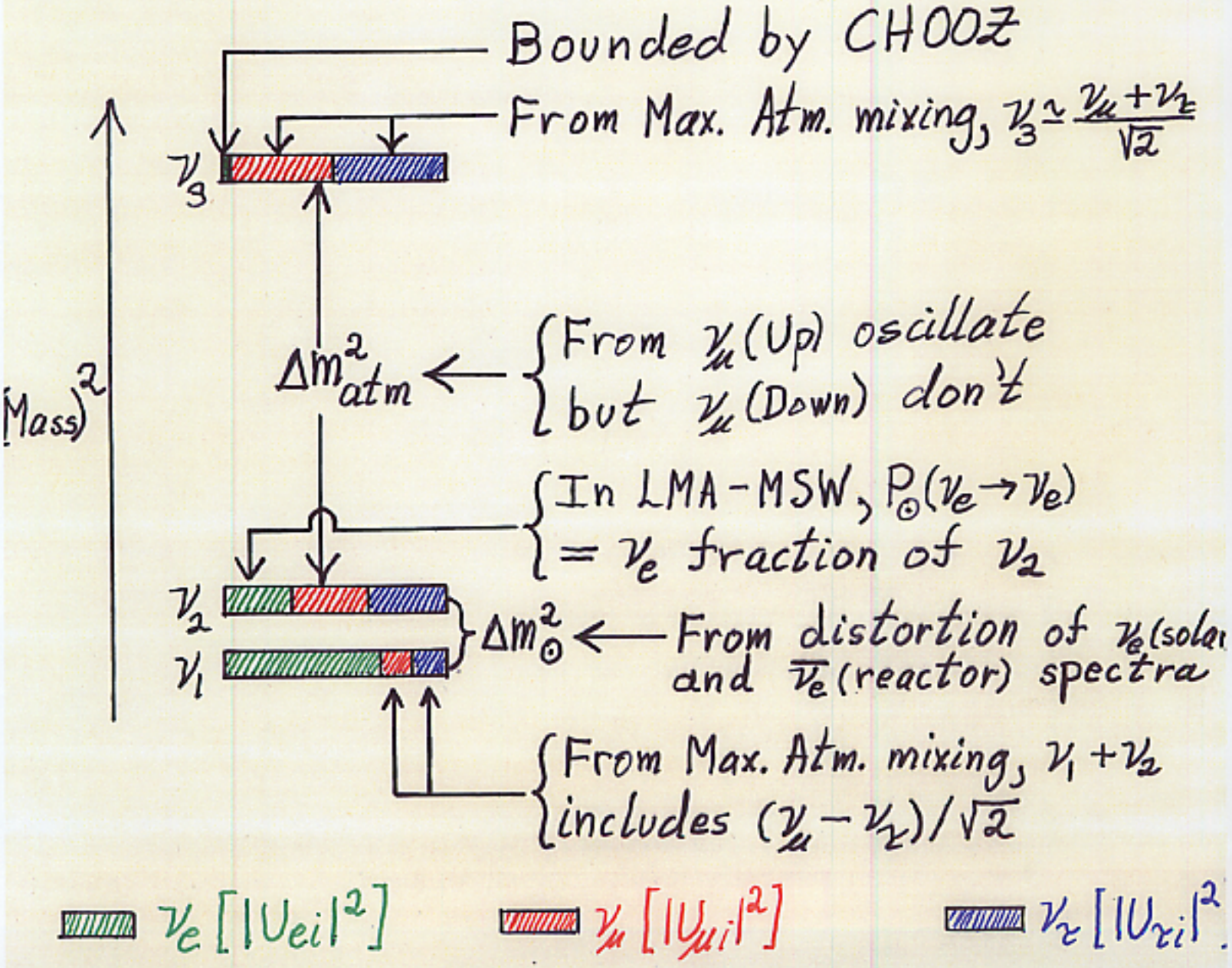
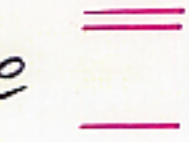
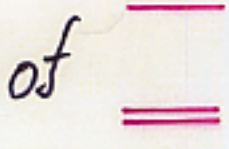


The spectrum could be  instead of 

[F.10]

Corresponding to the flavor content shown,

Close pair — Isolated

$$
U \approx \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array}
\begin{array}{c}
\begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{bmatrix}
c\, e^{i\frac{\alpha_1}{2}} & s\, e^{i\frac{\alpha_2}{2}} & s_{13}\, e^{-i\delta} \\
-\frac{s}{\sqrt{2}} e^{i\frac{\alpha_1}{2}} & \frac{c}{\sqrt{2}} e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \\
\frac{s}{\sqrt{2}} e^{i\frac{\alpha_1}{2}} & -\frac{c}{\sqrt{2}} e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\end{array}
$$

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

With LMA-MSW,

$0.24 \lesssim \sin^2\theta_\odot \lesssim 0.38$ (90% CL) (Lisi)

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

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