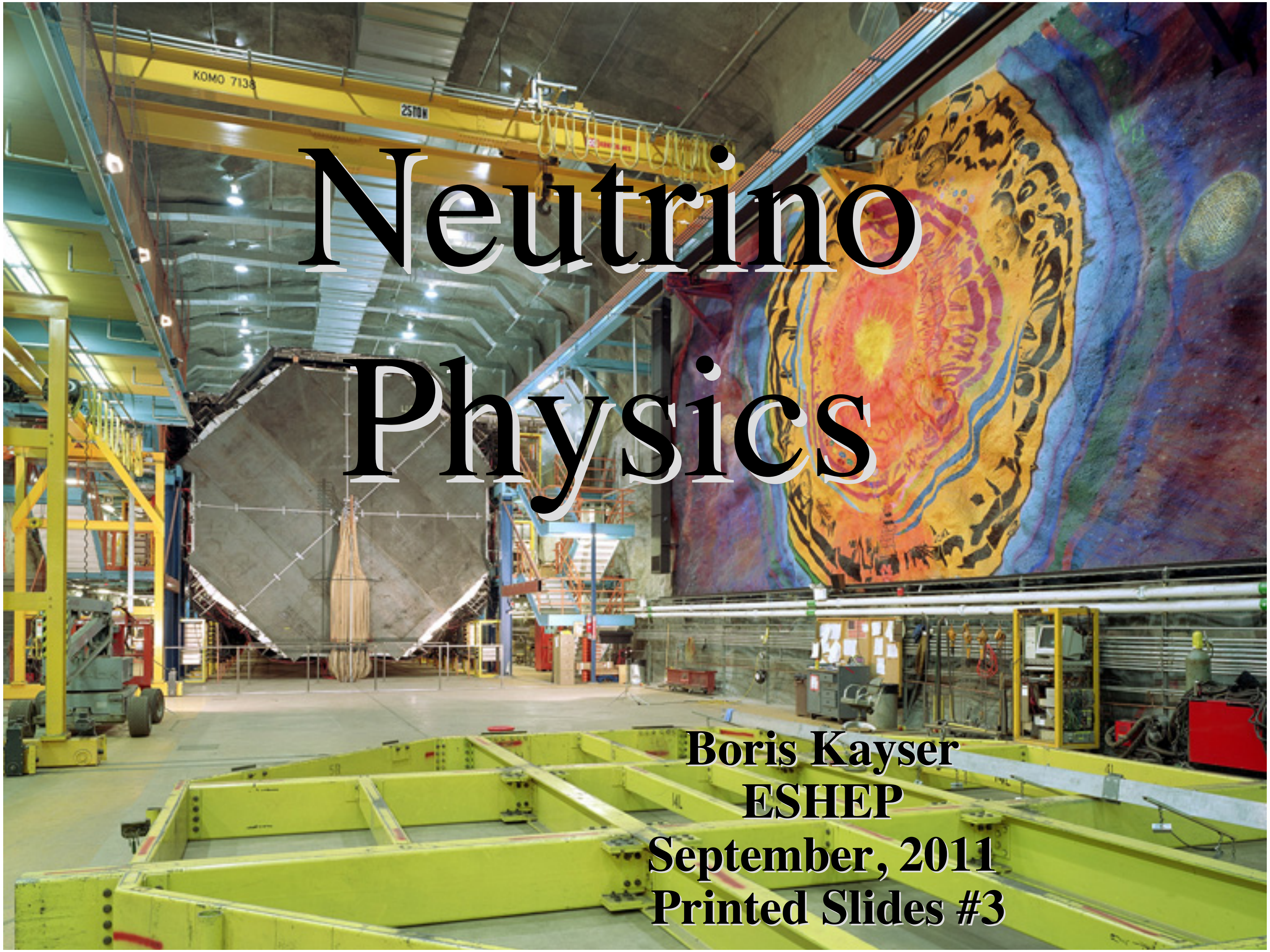


Neutrino Physics

Boris Kayser
ESHEP
September, 2011
Printed Slides #3

We Must Be Alert To **Surprises**!

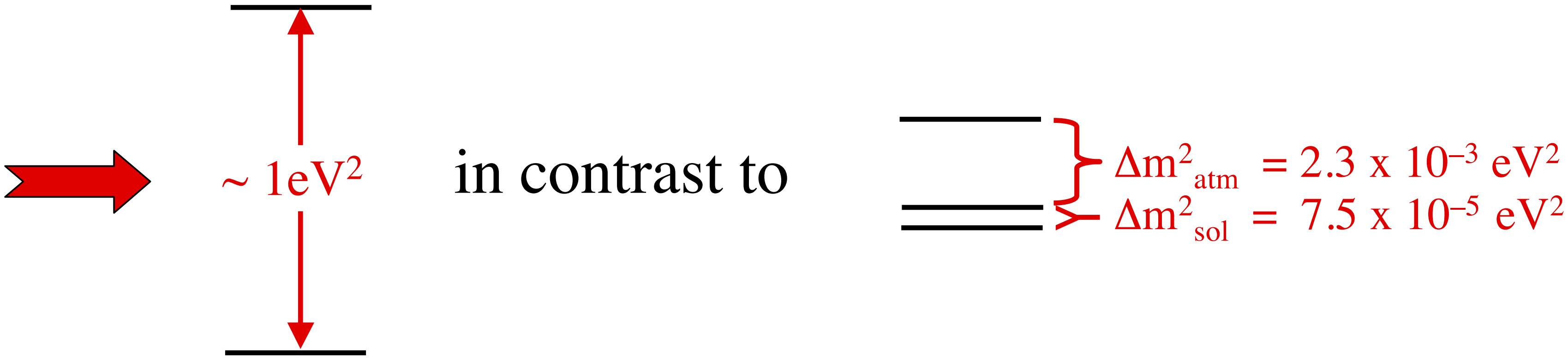
Are There *More* Than 3 Mass Eigenstates?

Are There Sterile Neutrinos?

The Hint From LSND

Rapid $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ neutrino oscillation reported by the L(iquid) S(cintillator) N(eutrino) D(etector) —

$$P\left(\overline{\nu_\mu} \rightarrow \overline{\nu_e}\right) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$



~ 1eV^2

in contrast to

$\Delta m^2_{atm} = 2.3 \text{ x } 10^{-3} \text{ eV}^2$

$\Delta m^2_{sol} = 7.5 \text{ x } 10^{-5} \text{ eV}^2$

At least **4** mass eigenstates.

Are There Sterile Neutrinos?

At least **4** mass eigenstates ⇒ At least **4** flavors.

Measured $\Gamma(Z \rightarrow \nu\bar{\nu})$ ⇒ only **3** different flavor neutrinos made of light mass eigenstates couple to the Z.

If there are > 3 light mass eigenstates, as hinted by LSND, then the extra flavors do not couple to the Z.

In the Standard Model, flavor neutrinos that do not couple to the Z do not couple to the W either.

Such neutrinos, with no SM interactions, are called ***sterile*** neutrinos.

LSND hints at the existence of sterile neutrinos.

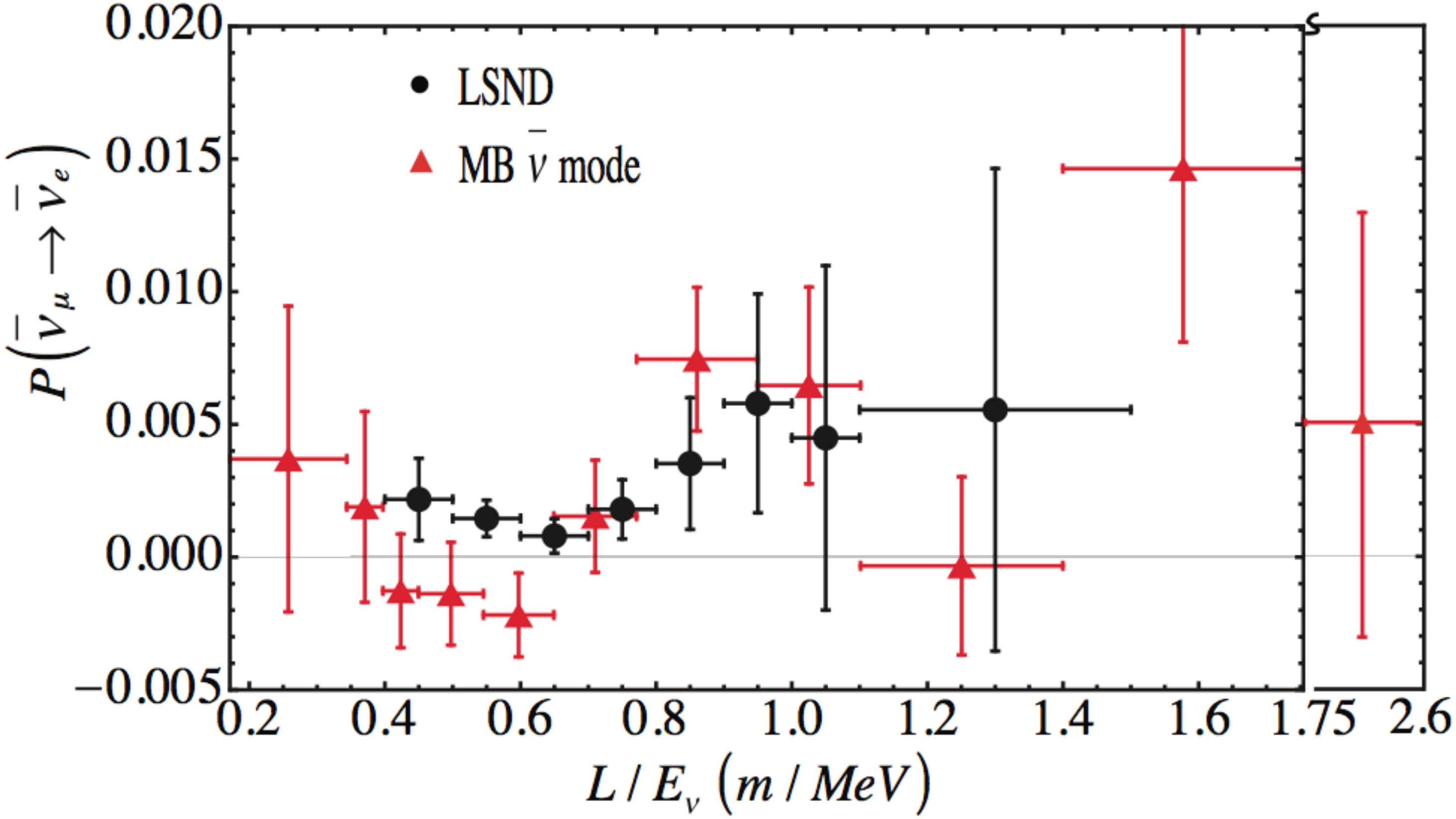
Is the LSND Signal Genuine Neutrino Oscillation?

The MiniBooNE experiment is
trying to confirm or refute LSND.

In MiniBooNE, both L and E are ~ 17 times
larger than they were in LSND,
and L/E is comparable.

MiniBooNE has recently reported
its $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results.

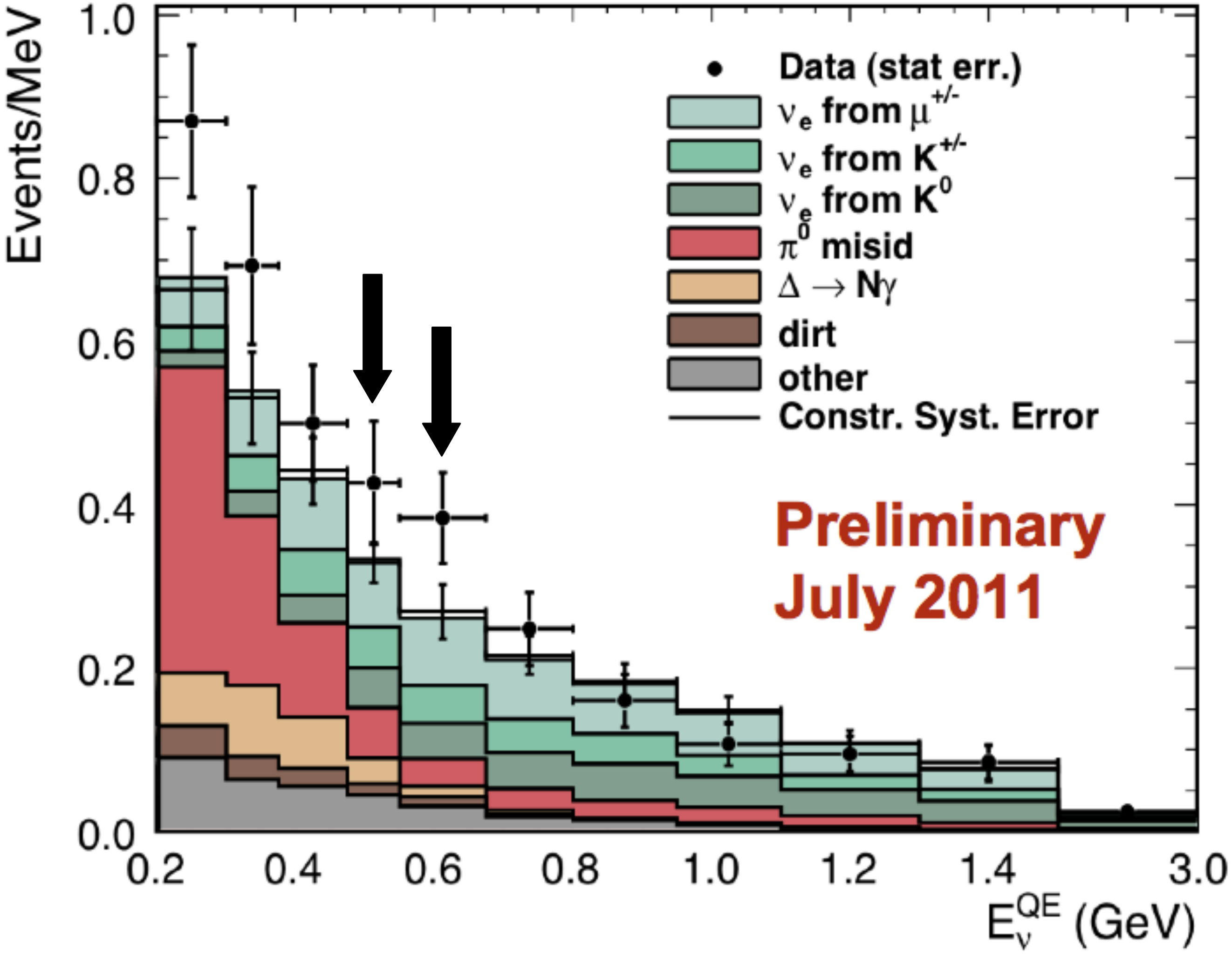
Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data



(Phys.Rev.Lett.105:181801, 2010)

Latest from MiniBooNE (July, 2011 at PANIC):
Significance of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signal reduced.

MiniBooNE



E. Zimmerman and M. Shaevitz at PANIC 2011

The Reactor $\overline{\nu}_e$ Flux Surprise

The prediction for the un-oscillated $\overline{\nu}_e$ flux from reactors has increased by about 3%.

(Mueller et al.)

Measurements of the $\overline{\nu}_e$ flux at (10 – 100)m from reactor cores now show a ~ 6% disappearance.

(Mention et al.)

Disappearance at L(m)/E(MeV) ~ 1 suggests oscillation with $\Delta m^2 \sim 1$ eV^2, like LSND and MiniBooNE.

Fits to all data with 2 extra neutrinos are improved.

(Kopp et al.)

Clearly, more information is needed.

While awaiting further news —

We will assume there are
only 3 neutrino mass eigenstates,
and no sterile neutrinos.

What Is the

Mass Ordering?

The Mass Spectrum:  or  ?

Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

However, ***Majorana masses***, with no quark analogues, could turn  into  .

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the ***matter effect*** on accelerator neutrinos.

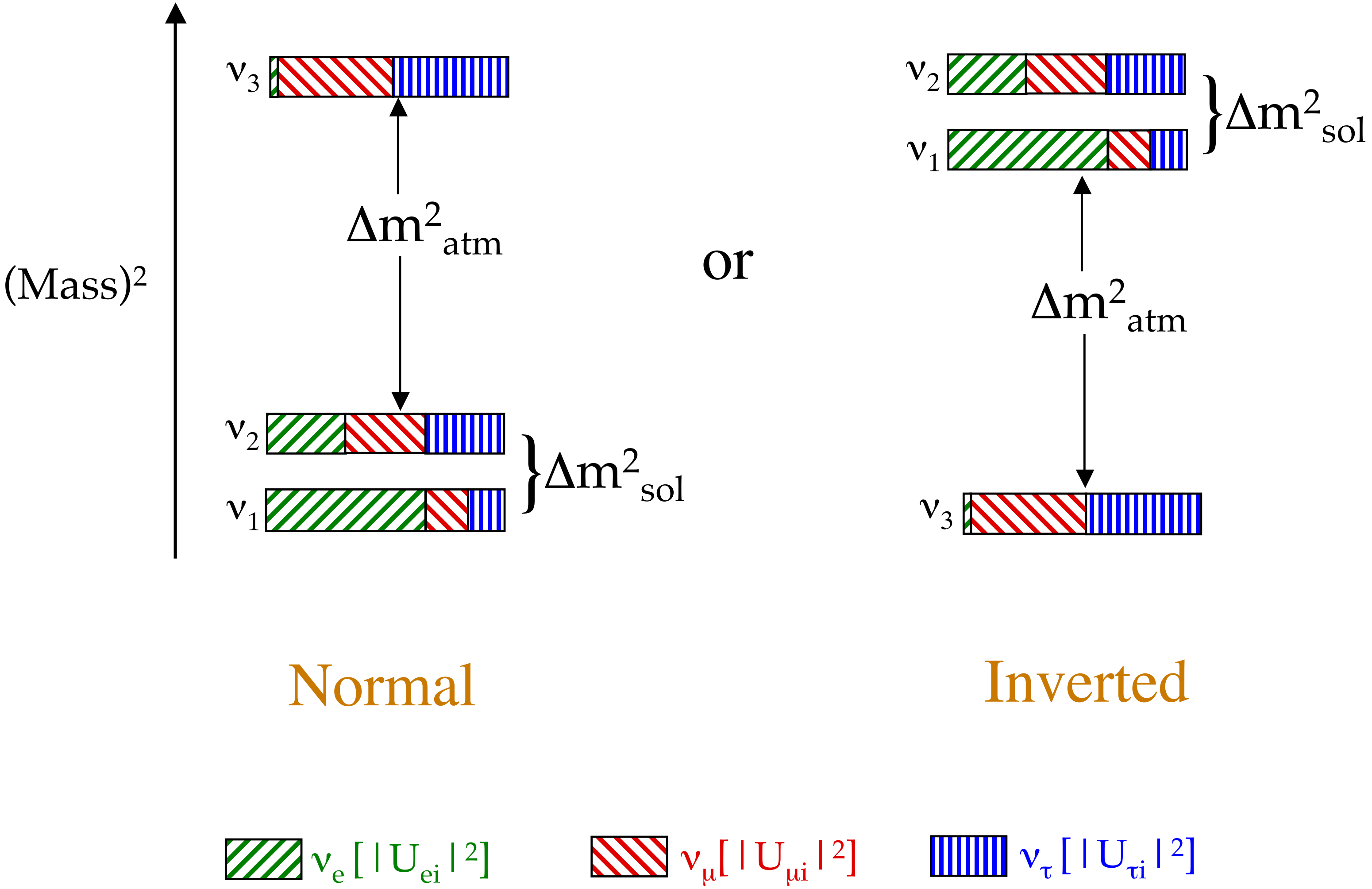
Recall that the matter effect ***raises*** the effective mass of ν_e, but ***lowers*** that of $\bar{\nu}_e$. Thus, it affects ν and $\bar{\nu}$ oscillation ***differently***, leading to:

$$\frac{P(\nu_\mu \rightarrow \nu_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

Note fake ~~CP~~

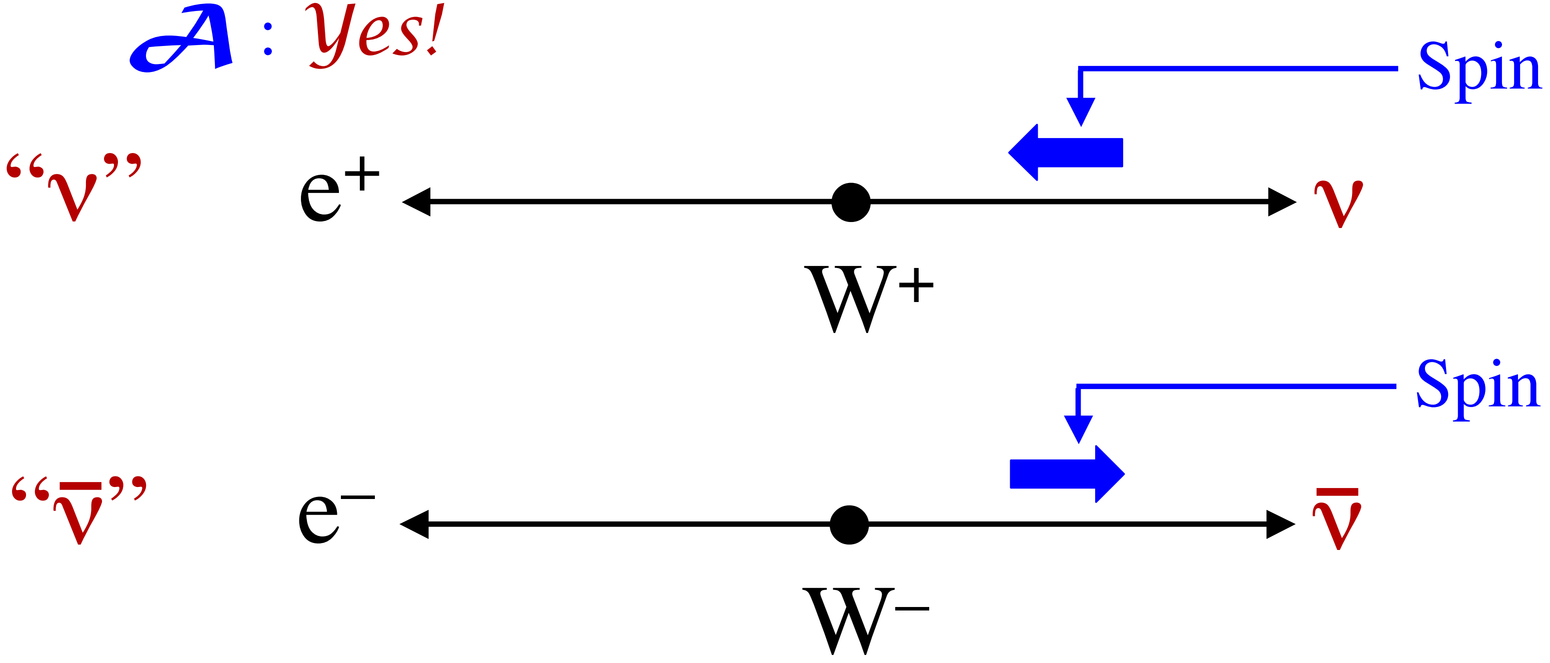
Note dependence on the mass ordering

The matter effect depends on whether the spectrum is Normal or Inverted.



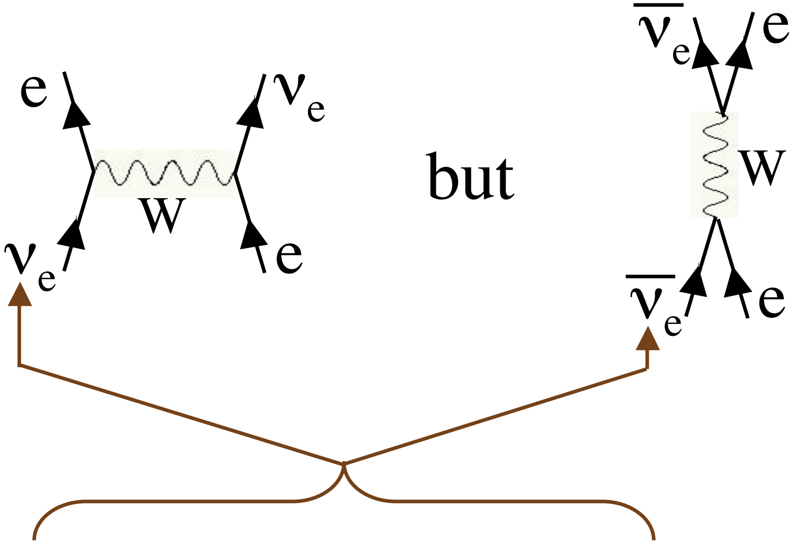
***Q** : Does matter still affect ν and $\bar{\nu}$ differently when $\bar{\nu} = \nu$?*

***A** : Yes!*



The weak interactions violate ***parity***. Neutrino – matter interactions depend on the neutrino ***polarization***.

Recall that in matter —



Oppositely polarized

The polarization alone is sufficient to determine which diagram will act.

The effective mass of "ν_e" is raised, while that of "$\overline{\nu_e}$" is lowered .

Is CP Violated?

Do Neutrino Interactions Violate CP?

Are we descended from heavy neutrinos?

The Challenge —
A Cosmic Broken Symmetry

The universe contains baryons,
but essentially no antibaryons.

$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10} \quad ; \quad \frac{n_{\bar{B}}}{n_B} \sim 0 \, (< 10^{-6})$$

Standard cosmology: Any initial
baryon – antibaryon asymmetry
would have been erased.

How did $n_{\bar{B}} = n_B$ → $n_{\bar{B}} << n_B$?

Sakharov: $n_{\overline{B}} = n_B \quad \Rightarrow \quad n_{\overline{B}} << n_B$ requires $\cancel{CP}$.

The $\cancel{CP}$ in the quark mixing matrix, seen in B and K decays, leads to much too small a $B-\overline{B}$ asymmetry.

If ***quark*** $\cancel{CP}$ cannot generate the observed $B-\overline{B}$ asymmetry, can some scenario involving ***leptons*** do it?

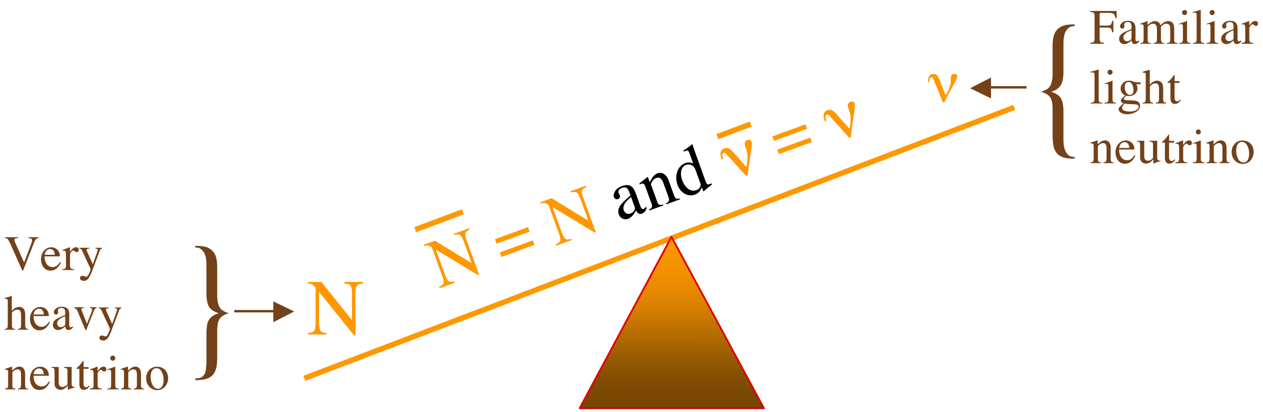
The candidate scenario: *Leptogenesis*.

(Fukugita, Yanagida)

Leptogenesis – A Two-Step Process

Leptogenesis is an outgrowth of the most popular theory of why neutrinos are so light —

The See-Saw Mechanism



Very heavy neutrino } → N

$\bar{N} = N$ and $\bar{\nu} = \nu$

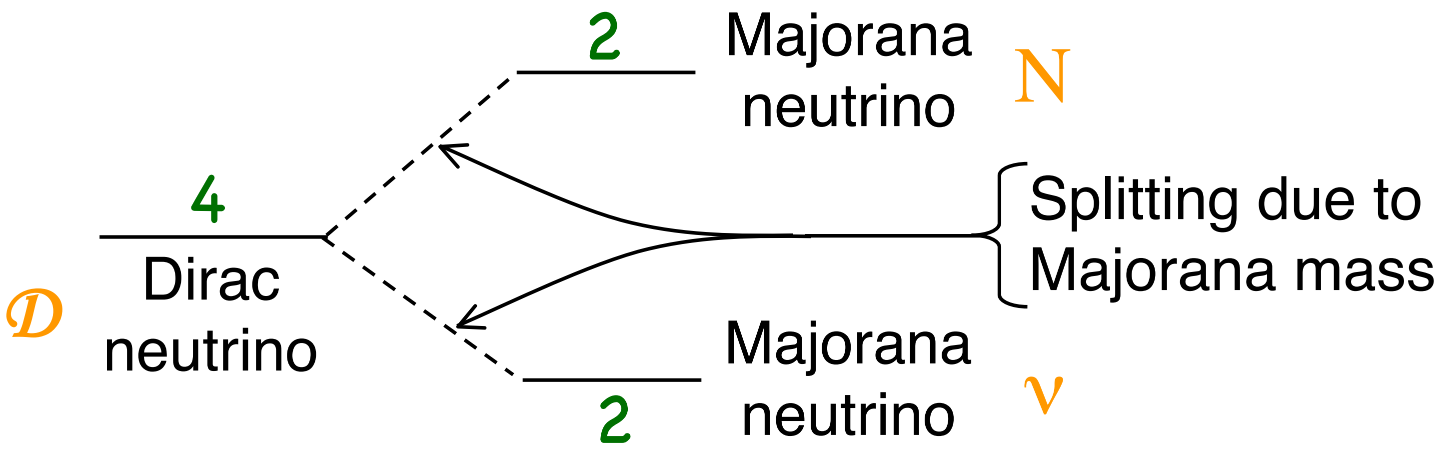
ν ← { Familiar light neutrino

$$m_\nu \propto \frac{1}{m_N}$$

Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski

What Happens In the See-Saw

A ***BIG*** Majorana mass term splits a Dirac neutrino into two ***widely-spaced*** Majorana neutrinos.



$m_\nu m_N \approx m_{\mathcal{D}}^2$ ***The See-Saw Relation***

If $m_{\mathcal{D}}$ *is a typical fermion mass,* m_N *will be very large.*

In standard leptogenesis, to account for the
observed cosmic baryon – antibaryon asymmetry,
and to explain the tiny light neutrino masses,
we must have —

$$m_N \sim 10^{(9\text{–}10)}\ \text{GeV} \quad .$$

Thus, the heavy neutrinos N represent New Physics far beyond the range of the Standard Model and the LHC.

But these heavy neutrinos would have been made
in the ***hot*** Big Bang.

In a straightforward see-saw model, there are 3 heavy neutrinos N_i, to match the 3 light lepton families (ν_α, ℓ_α).

The heavy neutrinos are coupled to the rest of the world only through the "Yukawa" interaction —

$$\mathcal{L}_{\text{new}} = \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} y_{\alpha i} \left[\overline{\nu_{L\alpha}}\, \overline{H^0} - \overline{\ell_{L\alpha}}\, H^- \right] N_{Ri} + h.c.$$

RH component

Yukawa coupling matrix

SM Higgs doublet

This "new" interaction simply gives leptons the same Yukawa interaction as the quarks have in the SM.

Each N_i couples to ν_α and ℓ_α with equal strength because of SM weak isospin invariance.

The Yukawa interaction —

$$\mathcal{L}_{\text{new}} = \sum_{\substack{\alpha=e,\mu,\tau\\ i=1,2,3}} y_{\alpha i}\left[\overline{\nu_{L\alpha}}\,\overline{H^0} - \overline{\ell_{L\alpha}}H^-\right]N_{Ri} + h.c.$$

causes the decays —

$$N \to \ell^\mp + H^\pm \quad \text{and} \quad N \to \overset{(-)}{\nu} + \overset{(-)}{H^0}$$

SM Higgs particle

~~CP~~ phases in the matrix y will lead to —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \overline{\nu} + \overline{H^0}\right)$$

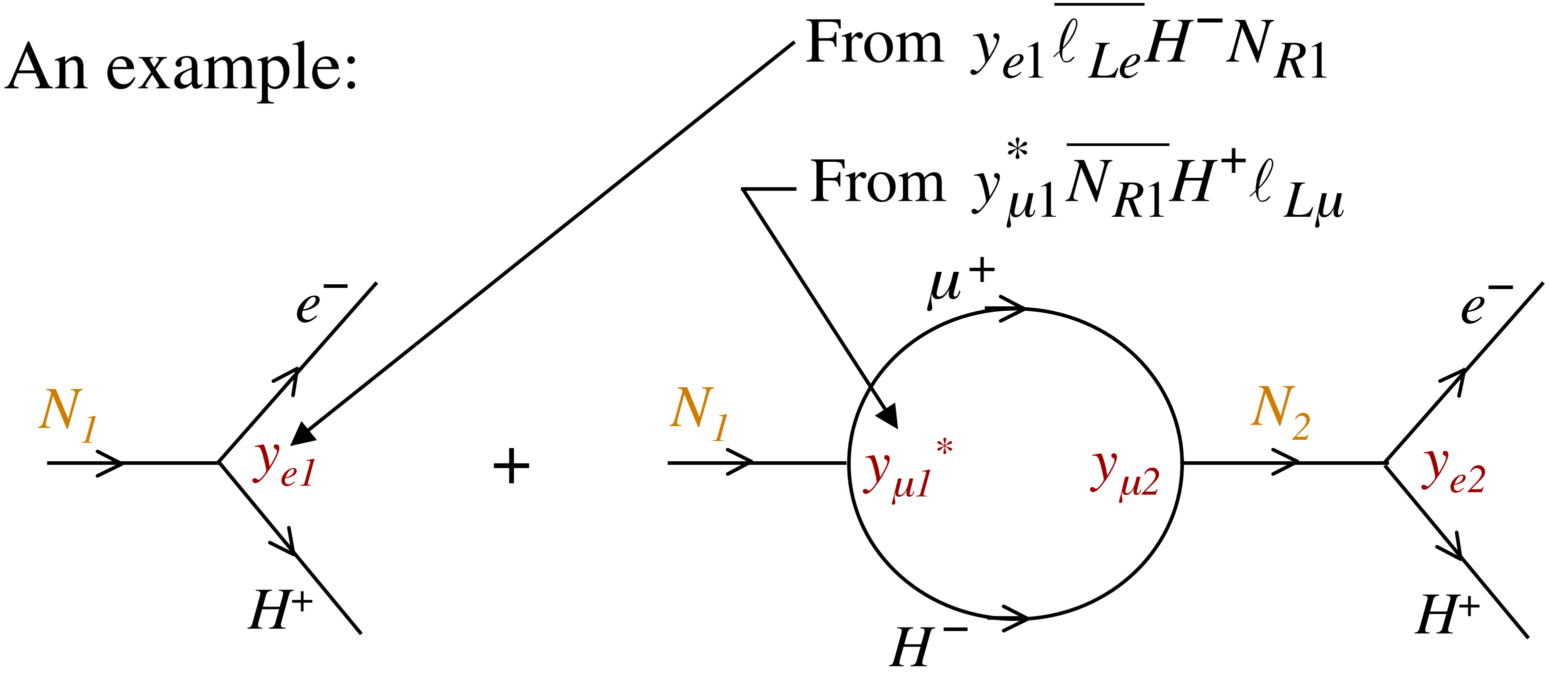
How Do Such ~~CP~~ Inequalities Come About?

~~CP~~ always comes from *phases*.

Phases never matter except in *interferences* between coherent amplitudes.

∴ These decays must involve interfering amplitudes.

An example:



From $y_{e1}\overline{\ell_{Le}}H^- N_{R1}$

From $y_{\mu 1}^*\overline{N_{R1}}H^+\ell_{L\mu}$

Tree

Loop

$$\Gamma\left(N_1 \to e^- + H^+\right) = \left|y_{e1}K_{\text{Tree}} + y_{\mu 1}^* y_{\mu 2} y_{e2} K_{\text{Loop}}\right|^2$$

Kinematical factors

$$\Gamma\left(N_1 \rightarrow e^- + H^+\right) = \left|y_{e1}K_{\text{Tree}} + y^*_{\mu 1}y_{\mu 2}y_{e2}K_{\text{Loop}}\right|^2$$

When we go to the CP-mirror-image decay, $N_1 \rightarrow e^+ + H^-$, all the coupling constants get complex conjugated, but the kinematical factors do not change.

$$\Gamma\left(N_1 \rightarrow e^+ + H^-\right) = \left|y^*_{e1}K_{\text{Tree}} + y_{\mu 1}y^*_{\mu 2}y^*_{e2}K_{\text{Loop}}\right|^2$$

Then —

$$\boxed{\begin{aligned}&\Gamma\left(N_1 \rightarrow e^- + H^+\right) - \Gamma\left(N_1 \rightarrow e^+ + H^-\right)\\ &= 4\,\text{Im}\left(y^*_{e1}y^*_{\mu 1}y_{e2}y_{\mu 2}\right)\text{Im}\left(K_{\text{Tree}}K^*_{\text{Loop}}\right)\end{aligned}}$$

The $\cancel{CP}$ inequalities —

$$\Gamma\left(N \rightarrow \ell^{-} + H^{+}\right) \neq \Gamma\left(N \rightarrow \ell^{+} + H^{-}\right)$$

and

$$\Gamma\left(N \rightarrow \nu + H^{0}\right) \neq \Gamma\left(N \rightarrow \bar{\nu} + \overline{H^{0}}\right)$$

will produce a universe with unequal numbers of leptons (ℓ^{-} and ν) and antileptons (ℓ^{+} and $\bar{\nu}$).

In this universe the lepton number L, defined by $L\left(\ell^{-}\right) = L(\nu) = -L\left(\ell^{+}\right) = -L(\bar{\nu}) = 1$, is not zero.

This is Leptogenesis — Step 1

Leptogenesis — Step 2

The Standard-Model ***Sphaleron*** process,
which does not conserve Baryon Number B,
or Lepton Number L, but does conserve $B - L$, acts.

$$B_i = 0$$
$$L_i \neq 0$$

Sphaleron
Process

$$B_f \cong -\frac{1}{3} L_i$$
$$L_f \cong \frac{2}{3} L_i \cong -2B_f$$

Initial state
from N decays

Final state

There is now a nonzero Baryon Number**.**

There are baryons, but ~ no antibaryons.

Reasonable parameters give the observed n_B / n_γ **.**

Leptogenesis and ~~CP~~
In Light ν Oscillation

In a convenient basis, the coupling matrix
y is the only source of CP violation among the leptons.

The see-saw relation, in complete detail, is —

Heavy *N* mass eigenvalues

$$M_\nu = -v^2 U^T \left(y^* M_N^{-1} y^\dagger \right) U$$

Light *ν* mass eigenvalues

Leptonic mixing matrix

The Higgs vev, a real number

Through ***U***, the phases in ***y*** lead to $\cancel{CP}$ in light neutrino oscillation.

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) =$$

e, μ, or τ

Distance

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

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

Neutrino (Mass)^2 splitting

Energy

The observation of CP violation in neutrino oscillation would make it more plausible that ***leptogenesis*** *occurred in the early universe.*

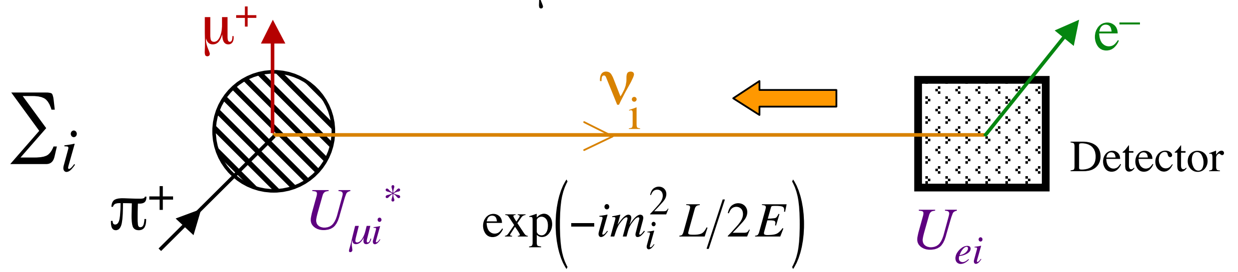
Seeking CP violation in neutrino oscillation is now a worldwide goal.

The search will use long-baseline accelerator neutrino beams to study $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, or their inverses.

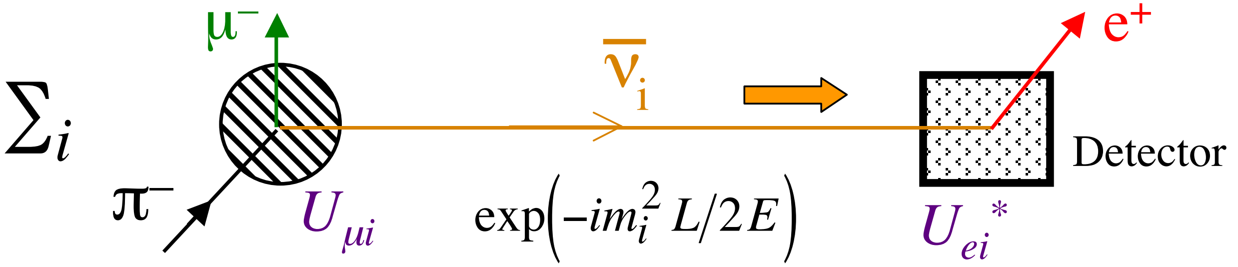
Q : *Can CP violation still lead to* $\mathcal{P}(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \neq \mathcal{P}(\nu_\mu \rightarrow \nu_e)$ *when* $\overline{\nu} = \nu$?

A : *Certainly!*

Compare $\nu_\mu \rightarrow \nu_e$



with "$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$"



Accelerator $\overset{(-)}{\nu}$ Oscillation Probabilities

With $\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31}$, $\Delta \equiv \dfrac{\Delta m^2_{31} L}{4E}$, and $x \equiv \dfrac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$ —

$m^2(\text{—}) - m^2(\text{═})$

$$P\left[\nu_\mu \to \nu_e\right] \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4 \;;$$

Atmospheric

CP-odd interference

$$T_1 = \sin^2\theta_{23} \frac{\sin^2\left[(1-x)\Delta\right]}{(1-x)^2} \,, \quad T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)} \,,$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)} \,, \quad T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

CP-even interference

Solar

$$P\left[\bar{\nu}_\mu \to \bar{\nu}_e\right] = P\left[\nu_\mu \to \nu_e\right] \text{ with } \delta \to -\delta \text{ and } x \to -x.$$

(Cervera *et al*., Freund, Akhmedov *et al*.)

What Facility Is Needed?

$$P\left(\nu_\mu \to \nu_e\right) \sim \sin^2 2\theta_{13}$$

A conventional accelerator neutrino beam from π and K decay is mostly ν_μ, but has a ~1% ν_e contamination.

Studying $\nu_\mu \to \nu_e$ with a conventional beam would be difficult if $\sin^2 2\theta_{13} < 0.01$.

More Powerful Facilities

β Beam:	β^+ emitting nuclei in a storage ring produce a flavor-pure ν_e beam. Look for $\nu_e \to \nu_\mu$.
ν Factory:	The decays $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$ of muons in a storage ring, plus a magnetized detector with μ^+/μ^- discrimination, yields an effectively flavor-pure ν_e beam. Look for $\nu_e \to \nu_\mu$.

$\sin^2 2\theta_{13}$	Use
$> 10^{-(2\text{-}3)}$	Conventional “Superbeam”
$< 10^{-(2\text{-}3)}$	β Beam or ν Factory

T2K & MINOS results, and global fits, suggest that $\sin^2 2\theta_{13}$ may well be greater than 10^{-2}.

Then we can start studying CP violation and the mass ordering with a conventional Superbeam, and then use a β Beam or ν Factory for precision studies.

Can the Heavy Neutrinos *N* of the *See-Saw* and *Leptogenesis* Be Within Range of the LHC?

Yes, in alternative models of the see-saw and leptogenesis, they can be.

Alternative models with this feature include —

Nearly degenerate heavy neutrinos. (Many authors)

Two additional spinless-particle doublets,
besides the Higgs doublet. (B.K. & Segre)

It is certainly interesting to look for (“sterile”) heavy neutrinos at the LHC.

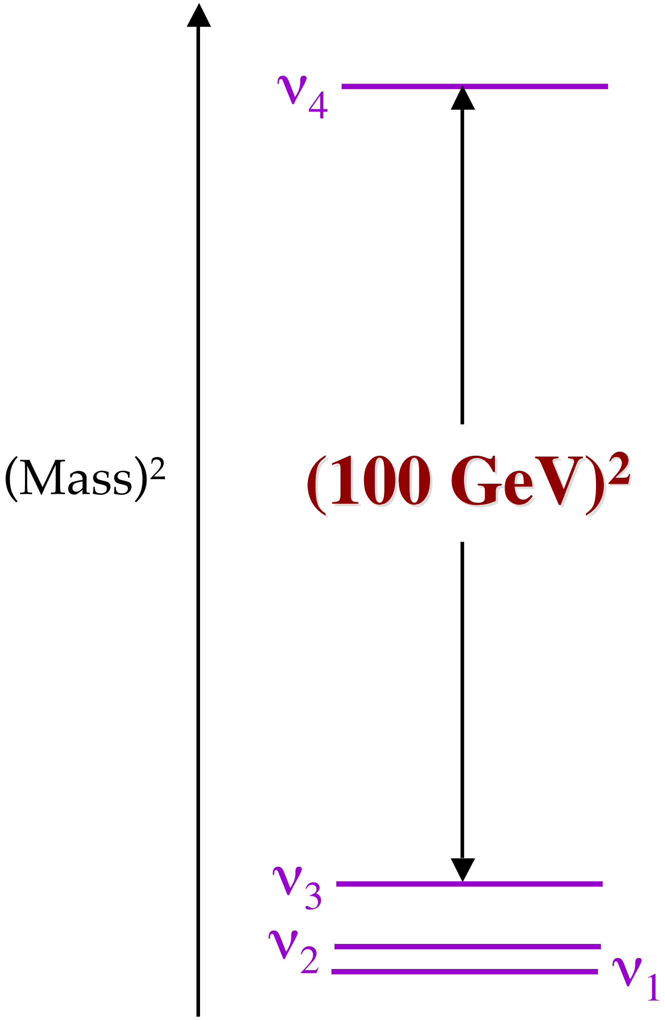
Is There a Fourth Generation?

With 4 generations, there are 4 charged-lepton mass eigenstates, and 4 neutrino mass eigenstates.

The mixing matrix U is 4 × 4, and unitarity reads —

$$\sum_{i=1}^{\boxed{4}} U_{\alpha i}^{*} U_{\beta i} = \delta_{\alpha\beta}$$

The $(\text{Mass})^2$ Spectrum??

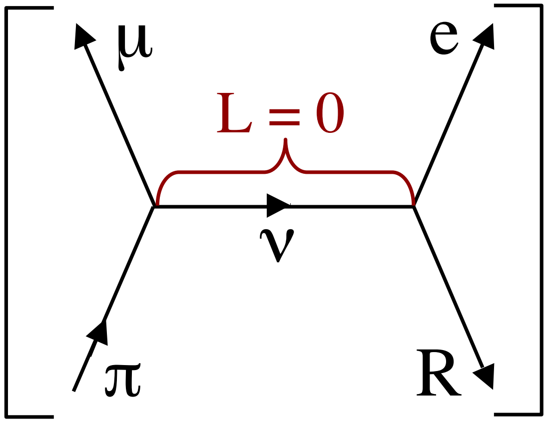


One Consequence:
Instantaneous Flavor Change

$$\text{Unitarity: } \sum_{i=1}^{\boxed{4}} U^*_{\mu i} U_{ei} = 0$$

But the heavy mass eigenstate ν_4 cannot be emitted in pion decay. Thus —

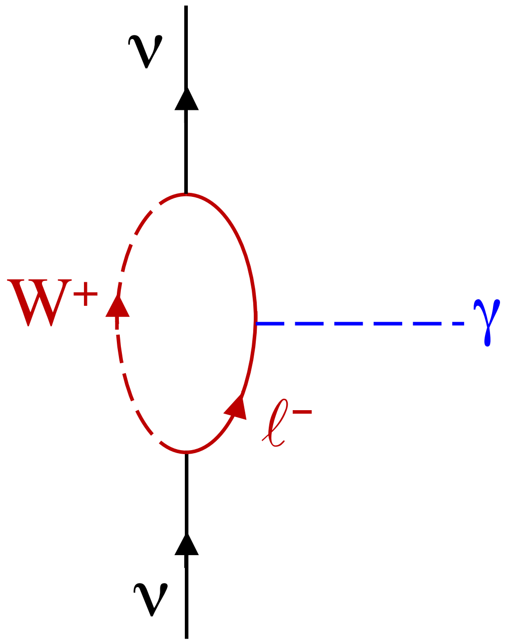
Amp



$$\propto \sum_{i=1}^{\boxed{3}} U^*_{\mu i} U_{ei} \neq 0$$

What Are the Neutrino Dipole Moments?

In the Standard Model, loop diagrams like —



produce, for a *Dirac* neutrino of mass m_ν,
a magnetic dipole moment —

$$\mu_\nu = 3 \text{ x } 10^{-19} (m_\nu/1\text{eV}) \, \mu_B$$

(Marciano, Sanda; Lee, Shrock; Fujikawa, Shrock)

A *Majorana* neutrino cannot have a magnetic or electric dipole moment:

$$\vec{\mu}\left[\ \underset{e^+}{\Uparrow}\ \right] = -\,\vec{\mu}\left[\ \underset{e^-}{\Uparrow}\ \right]$$

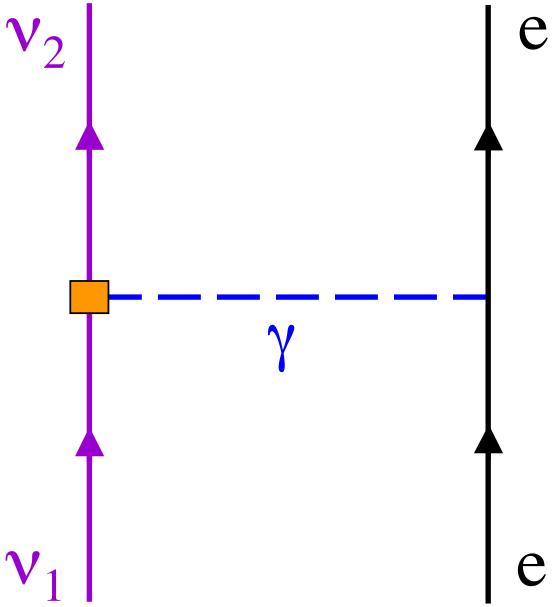
But for a Majorana neutrino,

$$\overline{\nu}_i = \nu_i$$

Therefore,

$$\vec{\mu}\,[\overline{\nu}_i] = \vec{\mu}\,[\nu_i] = 0$$

Both *Dirac* and *Majorana* neutrinos can have ***transition*** dipole moments, leading to —



One can look for the dipole moments this way.

To be visible, they would have to *vastly* exceed Standard Model predictions.

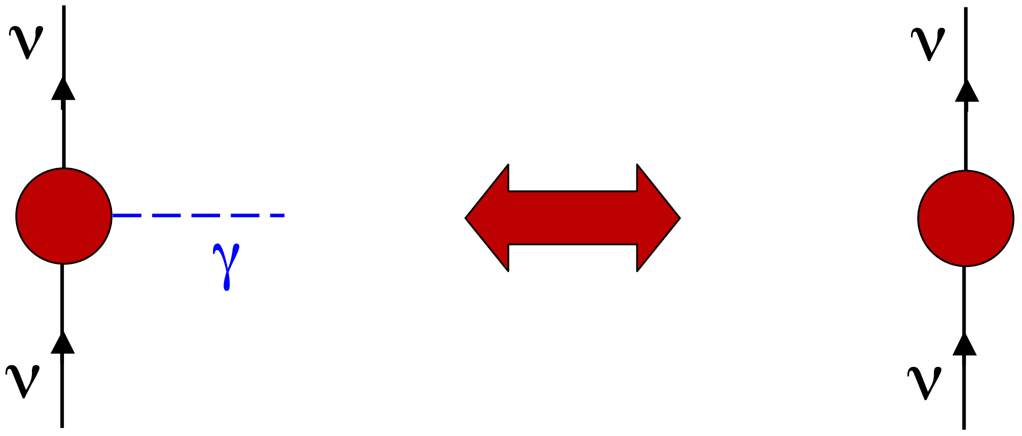
Present Bounds On Dipole Moments

$$\text{Upper bound} = \begin{cases} 1.3 \text{ x } 10^{-11}\, \mu_B & \text{; Wong et al. (Reactor)} \\ 5.4 \text{ x } 10^{-11}\, \mu_B & \text{; Borexino (Solar)} \\ 3 \text{ x } 10^{-12}\, \mu_B & \text{; Raffelt (Stellar E loss)} \end{cases}$$

New Physics can produce larger dipole moments than the $\sim 10^{-20} \mu_B$ SM ones.

But the dipole moments cannot be arbitrarily large.

The Dipole Moment – Mass Connection



Dipole Moment

Mass Term

$$\mu_\nu \sim \frac{eX}{\Lambda}$$

← Scale of New Physics

$$m_\nu \sim X\Lambda$$

$$\Rightarrow \quad m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

(Bell *et al.*)

Any dipole moment leads to a contribution to the neutrino mass that grows with the scale Λ of the new physics behind the dipole moment.

The dipole moment must not be so large as to lead to a violation of the upper bound on neutrino masses.

The constraint —

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\text{TeV}}\right)^2 \text{eV}$$

can be evaded by some new physics.

But the evasion can only go so far.

In the *Majorana* case, a *symmetry* suppresses the contribution of the dipole moment to the neutrino mass. So a bigger dipole moment is permissible. One finds —

For *Dirac* neutrinos, $\boldsymbol{\mu < 10^{-15}\,\mu_B}$ for $\Lambda > 1$ TeV

For *Majorana* neutrinos, $\boldsymbol{\mu <}$ ***Present Bound***

$\left(\begin{matrix}\text{Bell, Cirigliano, Davidson, Gorbahn, Gorchtein,}\\ \text{Ramsey-Musolf, Santamaria, Vogel, Wise, Wang}\end{matrix}\right)$

An observed μ below the present bound but well above 10^{-15} μ_B would imply that neutrinos are Majorana particles.

A dipole moment that large requires L-violating new physics $\lesssim$ 1000 TeV.

Neutrinoless double beta decay at the planned level of sensitivity only requires this new physics at ~ 10^{15} GeV, near the Grand Unification scale.

Searching for $0\nu\beta\beta$ is the more conservative way to probe whether $\bar{\nu} = \nu$.

But there may be surprises!

Good luck!