

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

NEUTRINO PHYSICS

Lectures IV & V

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Batavia, IL
U.S.A.**

References:

Past ICTP Summer School Lectures:

- Lisi — 2001 (ICTP web)
Akhmedov — 1999 hep-ph/0001264
Pakvasa — 1997 hep-ph/9804426

+ references therein

Recent Reviews

- Pakvasa + Valle hep-ph/0301601
Gonzalez \Leftarrow Garcia + Nir hep-ph/0202058

MSW + Solar ν 's

Smirnov — hep-ph/0305106

Parker — SLAC Summer School 1986

Fermilab - Conf - 86-131-T
available on SPIRES

click Fermilab-Library-Server:

⚡
little known

Problem:

2

Kamiland:

Expected: 87 ± 6

Observed: 54

Prob $< 0.05\%$

$$\frac{\text{Diff:}}{\sqrt{\text{Exp}}} = \frac{87 - 54}{\sqrt{87}} = 3.5 = \frac{33}{9.3}$$

K2K:

Expected: 80 ± 6

Observed: 56

Prob: $\sim 1.3\%$

$$\frac{\text{Diff:}}{\sqrt{\text{Exp}}} = \frac{80 - 56}{\sqrt{80}} = \frac{24}{8.9} = 2.7$$

Redo with Poisson ?

Statistics

Problem:

3

For 3 flavors:

SHOW

$$2 \sum_{i>j} \text{Im}(U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}) \sin 2\Delta_{ij}$$

$$= \pm \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \\ \sin \Delta_{21} \sin \Delta_{32} \sin \Delta_{31}$$

where $\Delta_{ij} = \frac{\delta m_{ij}^2 L}{4E}$

SAME for all $\alpha \neq \beta$ (if $\alpha \neq \beta$)

- or + for $\mu \rightarrow e, \tau \rightarrow \mu, e \rightarrow \tau$
+ or - for $e \rightarrow \mu, \mu \rightarrow \tau, \tau \rightarrow e$

Hint: $\Delta_{31} - \Delta_{32} - \Delta_{21} \equiv 0$

θ_{13} and Beyond

4

Reactors: $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance
ala Chooz (KamLAND etc)

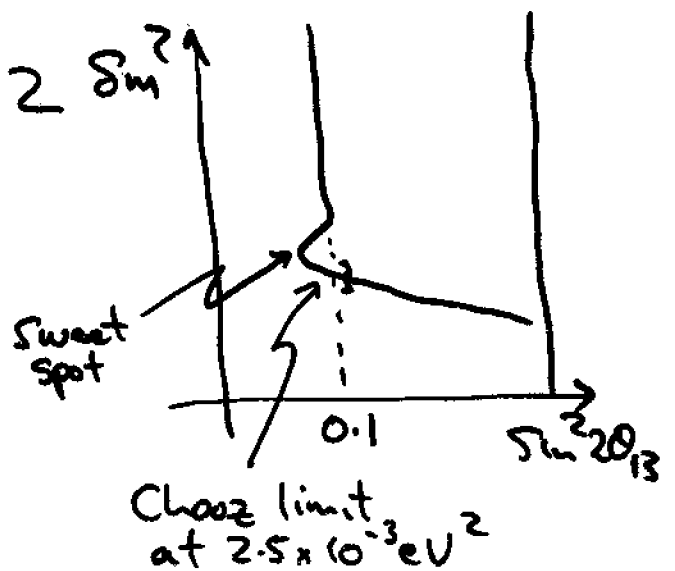
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31}$$
$$\Delta_{31} = \frac{\delta m_{31}^2 L}{4E}$$

Currently from Chooz

$$\sin^2 2\theta_{13} < 0.05 \text{ at any } \delta m_{31}^2$$

at $2.5 \times 10^{-3} \text{ eV}^2$: $\sin^2 2\theta_{13} < 0.01$
SK δm_{mat}^2

Could get a factor of 2 δm^2
by working at a better
distance



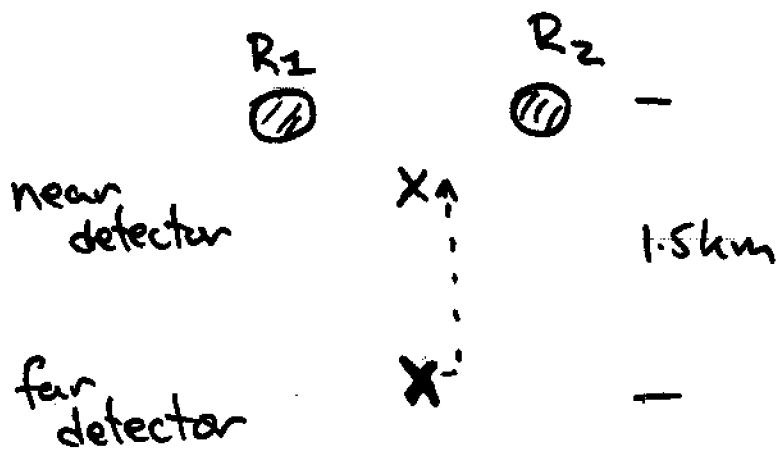
Oscillation Peak (or dip in disappearance) ⁵
occurs at

$$L = \frac{4\pi E}{2.8 \text{ km}^2_{\text{atm}}} = \frac{\pi E}{2(1.27) 8 \text{ km}^2_{\text{atm}}} = \frac{\pi 3 \times 10^{-3}}{2.54 \times 2.5 \times 10^{-3}} \text{ km}$$

$$\approx 1.5 \text{ km}$$

Also reduce systematic errors

→ 1%



Differential Total Flux measurement

maybe able to get to $\sin^2 2\theta_{13} \sim 0.01$ Shape
Lindner et al
'03

- to do better than Chooz, relatively easy
- to get to 0.01 HARD, DIFFERENT, ...

$$P_{\nu_e \rightarrow \nu_e} = \left| U_{e3} U_{e3}^* e^{-im_3 L/2E} + U_{e2} U_{e2}^* e^{-im_2 L/2E} + U_{e1} U_{e1}^* e^{-im_1 L/2E} \right|^2 \quad 6$$

$$U_{e1} U_{e1}^* = 1 - U_{e2} U_{e2}^* - U_{e3} U_{e3}^* \quad \text{unitarity}$$

$$P_{\nu_e \rightarrow \nu_e} = \left| 1 - 2i s_{13}^2 e^{-i\Delta_{31}} \sin \Delta_{31} - 2i c_{13}^2 s_{12}^2 e^{-i\Delta_{21}} \sin \Delta_{21} \right|^2$$

Square

$$= 1 - \sin^2 2\theta_{13} \left(\sin^2 \Delta_{31} + 2 s_{12}^2 \sin \Delta_{31} \cos \Delta_{32} \sin \Delta_{21} + s_{12}^4 \sin^2 \Delta_{21} \right) - c_{13}^2 \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

wiggles

At distances, intermediate between (30km) Chooz and KamLAND, there are wiggles which, for $\sin^2 2\theta_{13}$ not too small, could be used to determine $\delta m_{21}^2, \theta_{12}$ (atm). see Petcov et al June 2003



clinton



Old UCI Page

The President's View

Announcement *(excerpted from remarks at the MIT commencement, June 6, 1998)*

Paper
(submitted to
Phys.Rev.Lett)

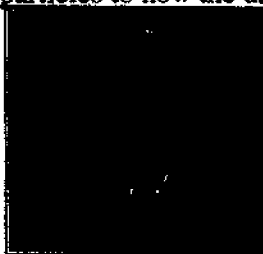
Clinton on
Neutrinos

FAQ

Glossary

Links

[W]e must help you to ensure that America continues to lead the revolution in science and technology. Growth is a prerequisite for opportunity, and scientific research is a basic prerequisite for growth. Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.



This discovery was made, in Japan, yes, but it had the support of the investment of the U.S. Department of Energy. This discovery calls into question the decision made in Washington a couple of years ago to disband the Super-conducting Supercollider, and it reaffirms the importance of the work now being done at the Fermi National Acceleration Facility in Illinois.

President Clinton addresses the graduating class at MIT

The larger issue is that these kinds of findings have implications that are not limited to the laboratory. They affect the whole of society -- not only our economy, but our very view of life, our understanding of our relations with others, and our place in time.



The full text is of the President's address is also available.

θ_{13} and

CP

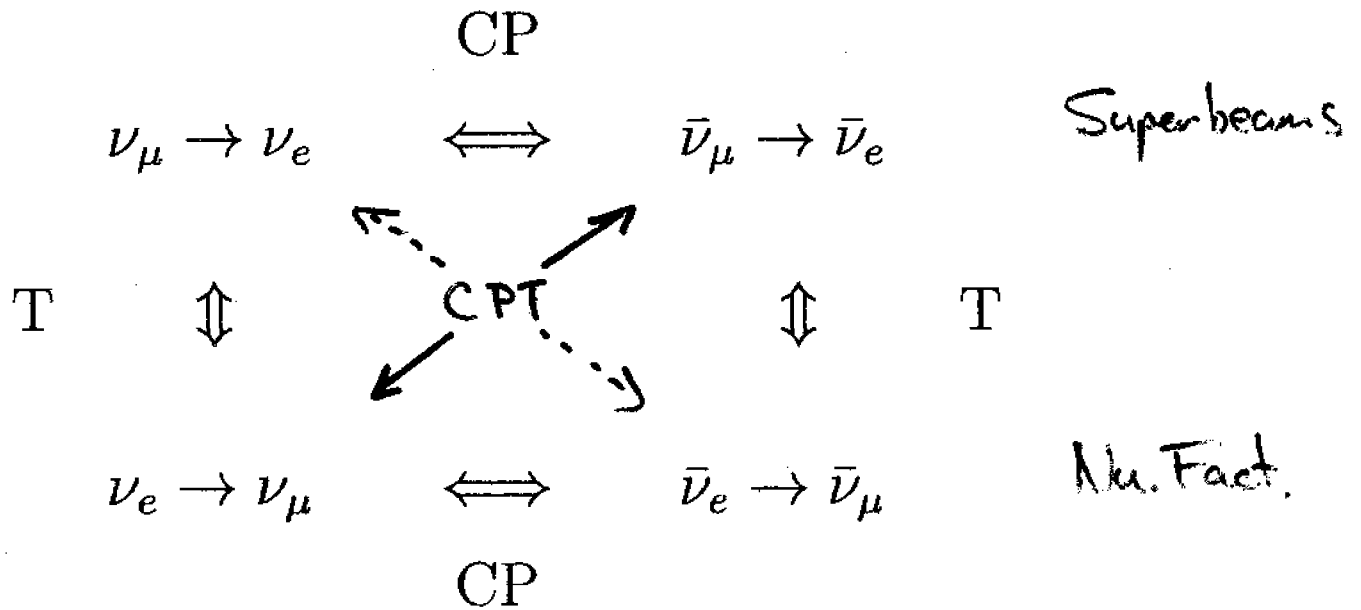
Violation:

Fermion

Mass

8

Leptonic CP and T Violation in Oscillations



IN GENERAL (in vacuum):

CP Violation:

$$\alpha \neq \beta \quad P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

T Violation:

$$\alpha \neq \beta \quad P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\nu_\beta \rightarrow \nu_\alpha)$$

and

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$$

CPT Violation:

$$\text{any } \alpha, \beta \quad P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$$

$$\underline{\underline{P_{\mu \rightarrow \nu e}}}$$

$$P_{\mu \rightarrow e} = \left| U_{e3} U_{\mu 3}^* e^{-im_3^2/2L} \right.$$

$$+ U_{e2} U_{\mu 2}^* e^{-im_2^2/2L}$$

$$\left. + U_{e1} U_{\mu 1}^* e^{-im_1^2/2L} \right|$$

multiple by $e^{+im_1^2/2L}$

$$\text{then } U_{e1} U_{\mu 1}^* = -U_{e3} U_{\mu 3}^* - U_{e2} U_{\mu 2}^* \quad \Delta_{ij} = \frac{\delta m_{ij}^2 L}{4E}$$

$$= \left| 2U_{e3} U_{\mu 3}^* e^{-i\Delta_{31}} \sin \Delta_{31} \right.$$

$$\left. + 2U_{e2} U_{\mu 2}^* e^{-i\Delta_{21}} \sin \Delta_{21} \right|^2$$

multiple by $e^{+i\Delta_{32}}$

$$= \left| e^{-i\Delta_{32}} 2U_{e3} U_{\mu 3}^* \sin \Delta_{31} \right.$$

$$\left. + 2U_{e2} U_{\mu 2}^* \sin \Delta_{21} \right|^2$$

$$2U_{e3}U_{\mu 3}^* = 2S_{13}C_{13} \cdot S_{23}e^{-i\delta} \quad ||$$

$$2U_{e2}U_{\mu 2}^* \approx 2C_{13}S_{12}(C_{23}C_{12} - S_{13}S_{12}S_{23}e^{-i\delta})$$

$$P_{\mu \rightarrow e} = \left| e^{-i(\Delta_{32} + \delta)} \sqrt{P_{\text{atm}}} + \sqrt{P_0} \right|^2$$

with

$$P_{\text{atm}} = \left(S_{23} \sin^2 2\theta_{13} \sin \Delta_{31} \right)^2$$

$$P_0 = \left(C_{13} C_{23} \sin 2\theta_{12} \sin \Delta_{21} \right)^2$$

Oscillation Max: $\Delta_{31} \approx \Delta_{32} = \frac{\pi}{2}$

Max: CP Violations: $\delta = \frac{\pi}{2}$

$$P_{\mu \rightarrow e} = \left| \sqrt{P_{\text{atm}}} \pm \sqrt{P_0} \right|^2$$

(+ ν) (- $\bar{\nu}$)

Asym:
$$\frac{P - \bar{P}}{P + \bar{P}} = \frac{2\sqrt{P_{\text{atm}}}\sqrt{P_0}}{(P_{\text{atm}} + P_0)}$$

$P(\nu_\mu \rightarrow \nu_e)$

Why Everybody is Excited!

• Maximum Allowed Asymmetry ($\delta = \frac{\pi}{2}$ or $\frac{3\pi}{2}$) for $\nu_\mu \rightarrow \nu_e$ at first Oscillation Maximum in vac:

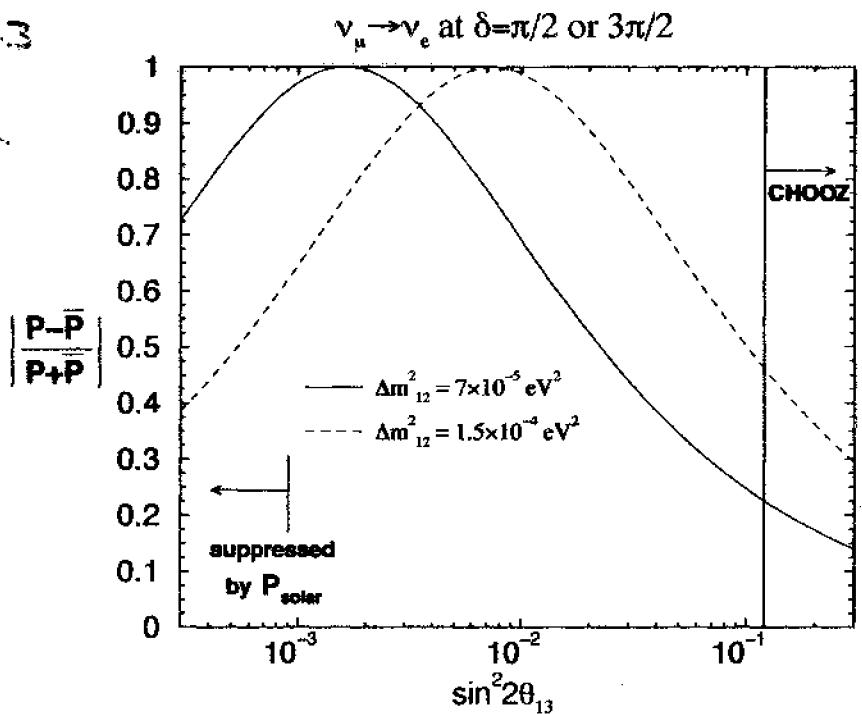
• $P, \bar{P} = |a_{\mu \rightarrow e}^{atm} + a_{\mu \rightarrow e}^\odot|^2 \approx (\sin \theta_{23} \sin 2\theta_{13} \pm \sqrt{P_\odot})^2$

• $|P - \bar{P}| \approx 4\sqrt{P_\odot} \sin \theta_{23} \sin 2\theta_{13}$

• $P + \bar{P} \approx 2 \sin^2 \theta_{23} \sin^2 2\theta_{13} + 2P_\odot$

easily generalized
 • $18 \neq \frac{\pi}{2}$
 • off O.H.
 • matter

$a_{\mu \rightarrow e}^{atm} \propto U_{e3}$
 $a_{\mu \rightarrow e}^\odot \propto U_{e2}$



Asymmetry
 LARGE: \checkmark

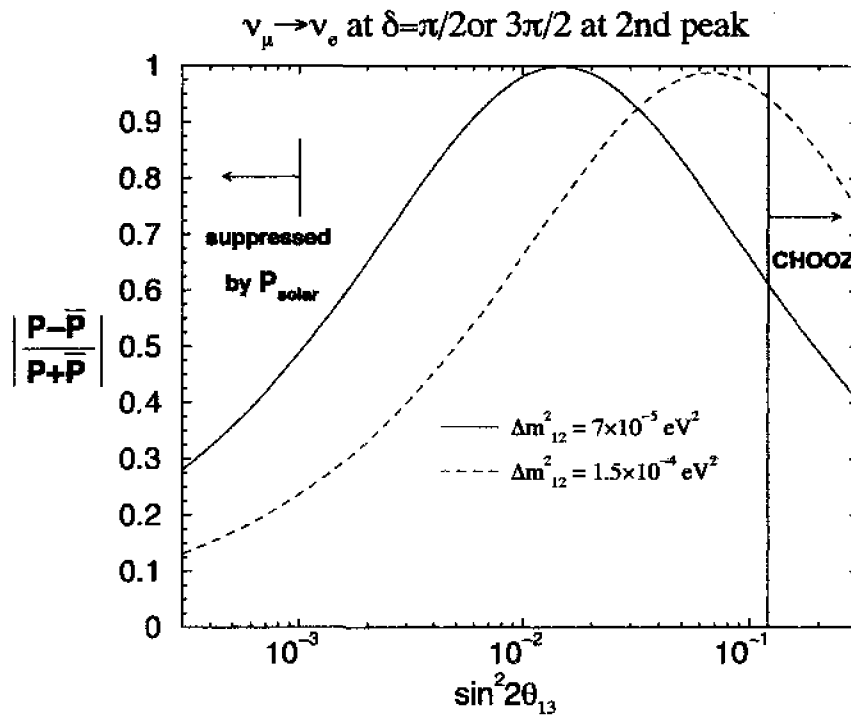
• Peak occurs at

$$\sin^2 2\theta_{13} \approx \frac{\sin^2 2\theta_{12}}{\tan^2 \theta_{23}} \left[\frac{\pi}{2} \frac{\delta m_{12}^2}{\delta m_{13}^2} \right]^2$$

at OM $\sqrt{P_\odot} = \cos \theta_{13} \cos \theta_{23} \sin 2\theta_{12} \sin \left(\frac{\pi}{2} \frac{\delta m_{12}^2}{\delta m_{13}^2} \right)$

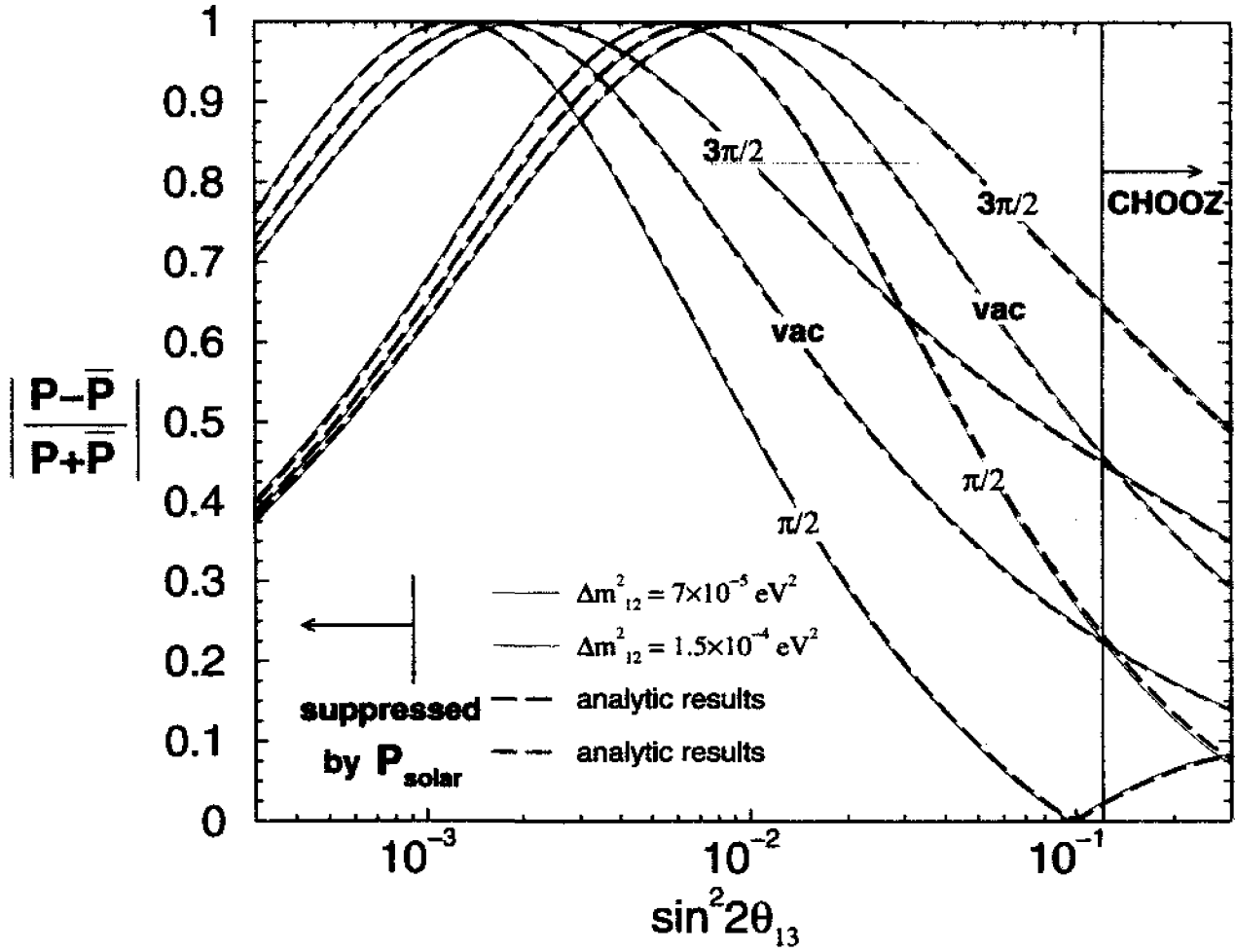
• For BK

2nd Peak



- Peak occurs at $\sin^2 2\theta_{13} \approx \frac{\sin^2 2\theta_{12}}{\tan^2 \theta_{23}} \left[\frac{3\pi}{2} \frac{\delta m^2_{12}}{\delta m^2_{13}} \right]^2$

$\nu_\mu \rightarrow \nu_e$ at $\delta = \pi/2$ or $3\pi/2$ in matter for $L = 732$ km



$$P_{\mu \rightarrow e} = P_{\text{atm}} + 2\sqrt{P_{\text{atm}}}\sqrt{P_{\odot}} \cos(\Delta_{32} \pm \delta) + P_{\odot} \quad 15$$

$$\cos(\Delta_{32} + \delta) = \cos \Delta_{32} \cos \delta + \frac{\sin \Delta_{32} \sin \delta}{\leftarrow}$$

CP violating term is

$$\sin \delta \cdot \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \\ * \sin \Delta_{21} \sin \Delta_{32} \sin \Delta_{31}$$

FULL EXPRESSION:

16

$$P_{\mu \rightarrow e} = P_{\otimes} - 2 S_{23}^2 S_{2(13)}^2 S_{12}^2 \sin \Delta_{31} \cos \Delta_{32} \underbrace{\sin \Delta_{21}}_{\text{small}}$$
$$+ P_{\odot} \left(1 - 2 S_{13} \tan \theta_{23} \tan \theta_{12} \cos \delta + S_{13}^2 \tan^2 \theta_{23} \tan^2 \theta_{12} \right)$$
$$+ 2 \sqrt{P_{\otimes} P_{\odot}} \cos (\Delta_{32} \mp \delta)$$

$$P_{\otimes} = S_{23}^2 S_{2(13)}^2 \sin^2 \Delta_{31}$$

$$P_{\odot} = C_{13}^2 C_{23}^2 S_{2(12)}^2 \sin^2 \Delta_{21}$$

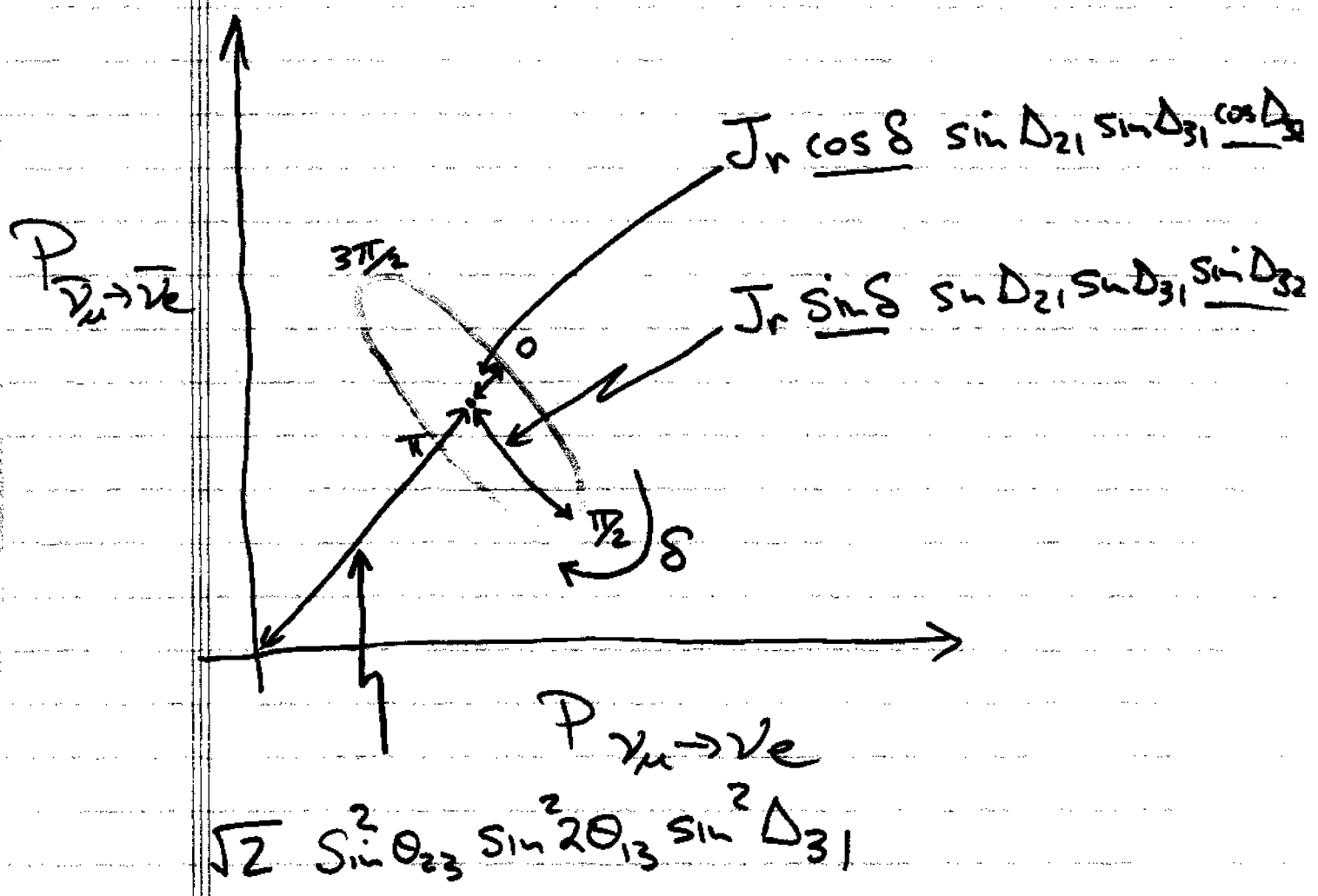
P_{\odot} is irrelevant unless S_{13} is small

where $(1 - 2S_{13} \dots) \approx 1$

$$\frac{\Delta_{21}}{\Delta_{31}} = \frac{\sin^2 \Delta_{21}}{\sin^2 \Delta_{31}} \approx \frac{1}{30} \quad \text{also } \sin \Delta_{31} \approx 1$$
$$\cos \Delta_{32} \approx 0$$

Bi-Probability Plot

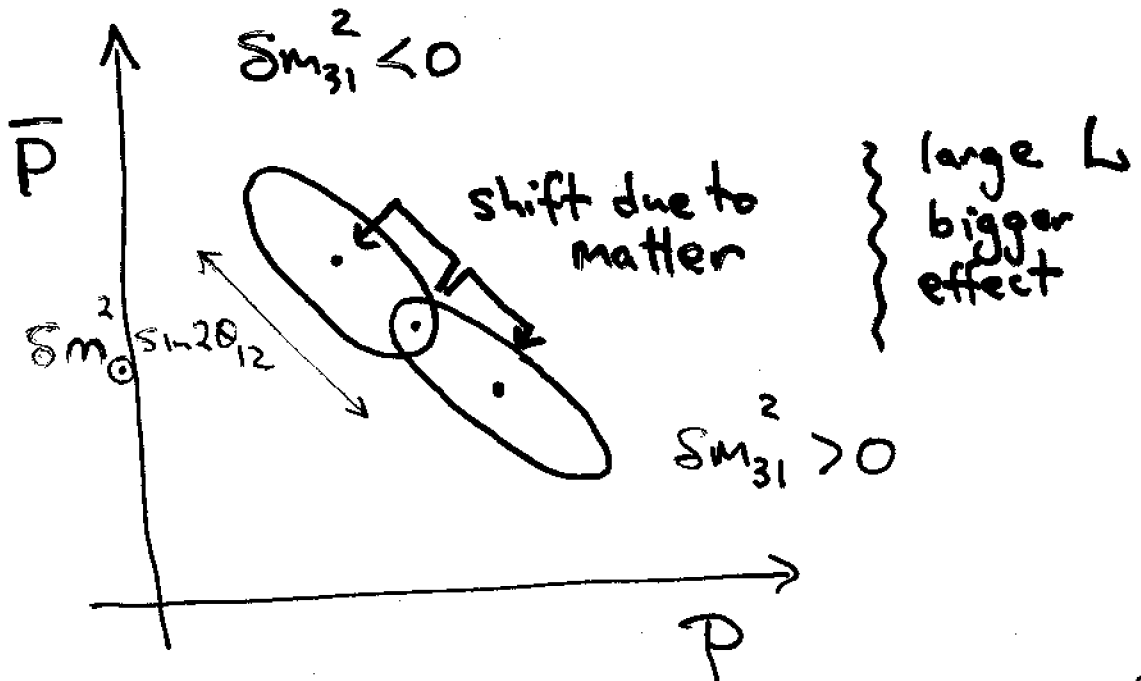
(P, \bar{P}) varying only δ_{CP}



IF SMA or LOW solar solⁿ ellipse collapses to point.

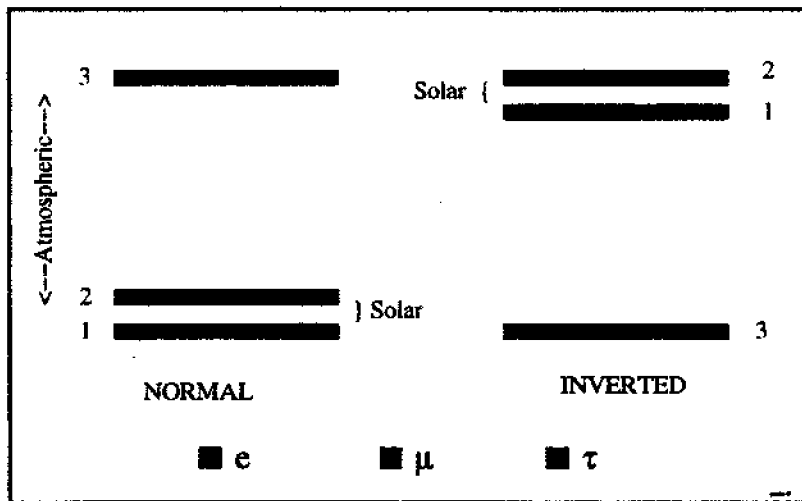
LMA - Waw $\frac{DD}{000}$

Matter Effects:



$$P_{\text{mat}}^{\text{center}} \approx \left(1 \pm \frac{E_\nu}{6 \text{ GeV}}\right) P_{\text{vac}}^{\text{center}}$$

O.M.
for small E_ν



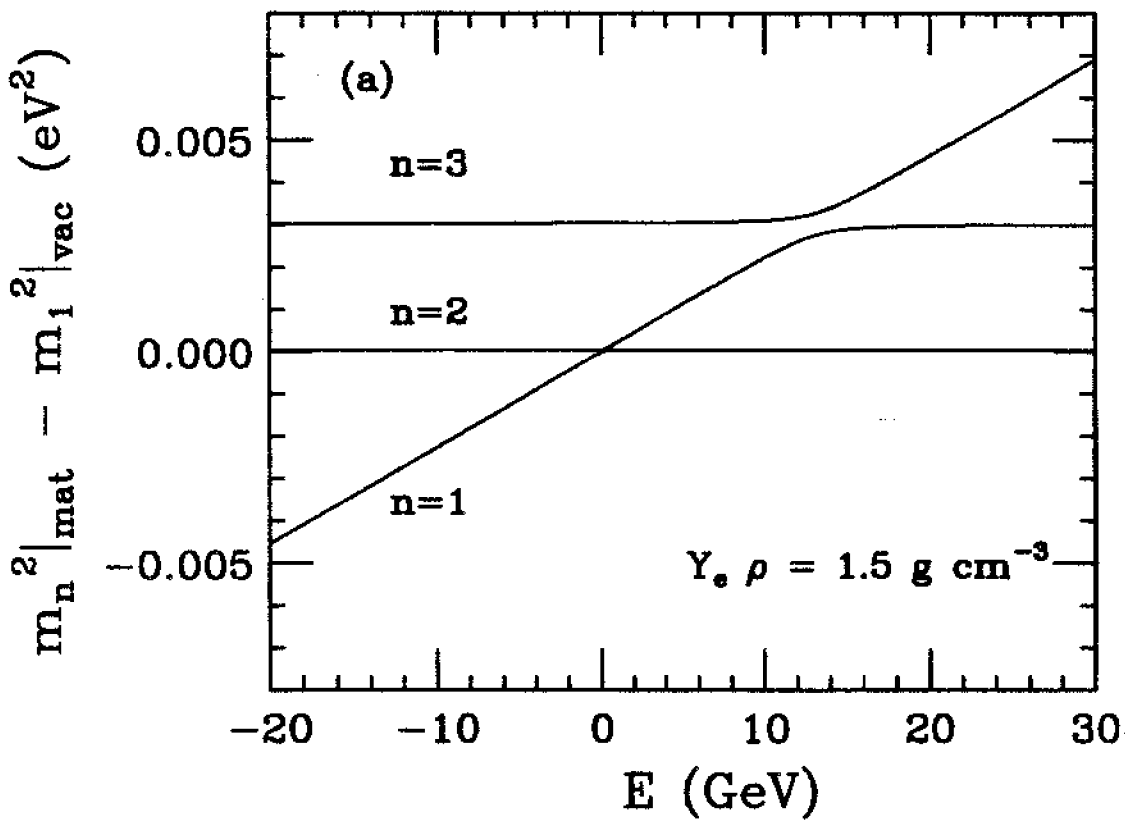
$$\delta m_{31}^2 > 0$$

$$\delta m_{31}^2 < 0$$

$$\left(\sin 2\theta_{13} \delta M_{31}^2 \right)_{\text{matter}} = \left(\sin 2\theta_{13} \delta M_{31}^2 \right)_{\text{vac}} \quad 19$$

and

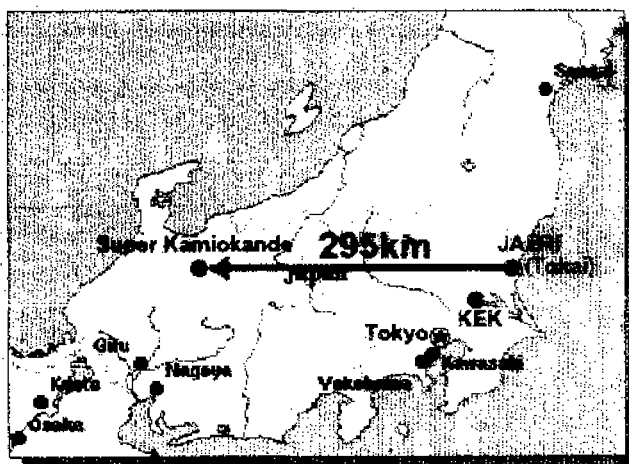
$$\left(\sin 2\theta_{12} \delta M_{21}^2 \right)_{\text{MATTER}} = \left(\sin 2\theta_{12} \delta M_{21}^2 \right)_{\text{vac}}$$



← antineutrinos | → neutrinos

JHF → Super-Kamiokande

- ✓ 295 km baseline
- ✓ Super-Kamiokande:
 - 22.5 kton fiducial
 - Excellent e/μ ID
 - Additional π^0/e ID
- ✓ Hyper-Kamiokande
 - 20× fiducial mass of SuperK
- ✓ Matter effects small
- ✓ Study using fully simulated and reconstructed data



Requires New Beamline:

~~<http://www-efc.ais.fnl.gov/>~~

LOI: hep-ex/0106019

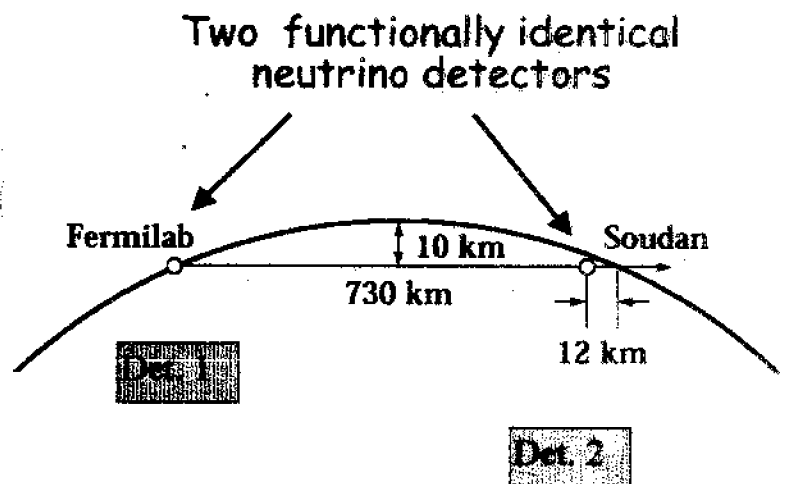
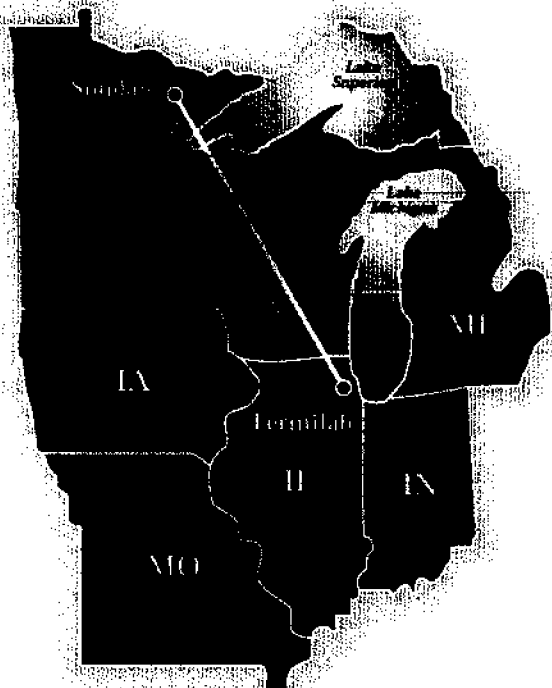
<http://www-nu.kek.jp/jhfnu/>

$$\bar{E}_\nu = 0.6 \text{ to } 1.0 \text{ GeV}$$

~20% spread

$$L = 295 \text{ km}$$

The NUMI Beamline



New Detector Required:

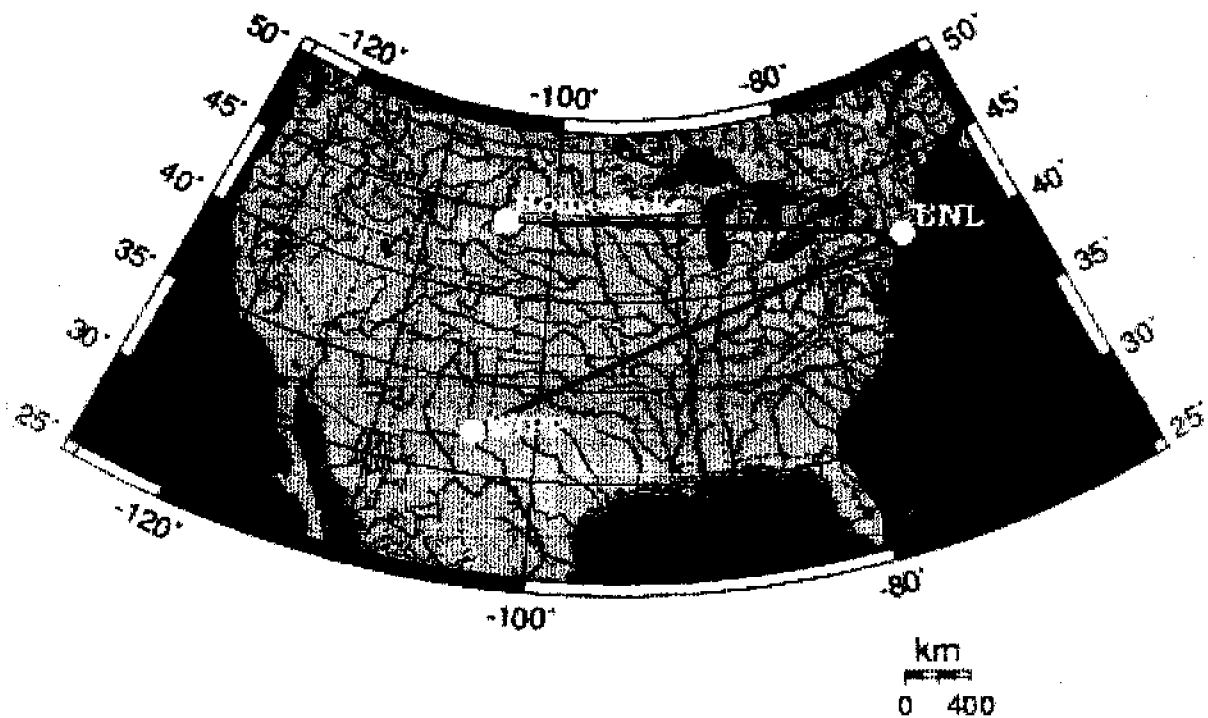
<http://www-off-axis.fnal.gov/>

LOI: hep-ex/0210005

$$E \sim 2 \text{ GeV}$$

$$L \sim 732 \text{ km} \\ \pm 200 \text{ km}$$

Brookhaven to Homestake OR WIPP



$L = \underline{2540 \text{ km}}$ or 2880 km

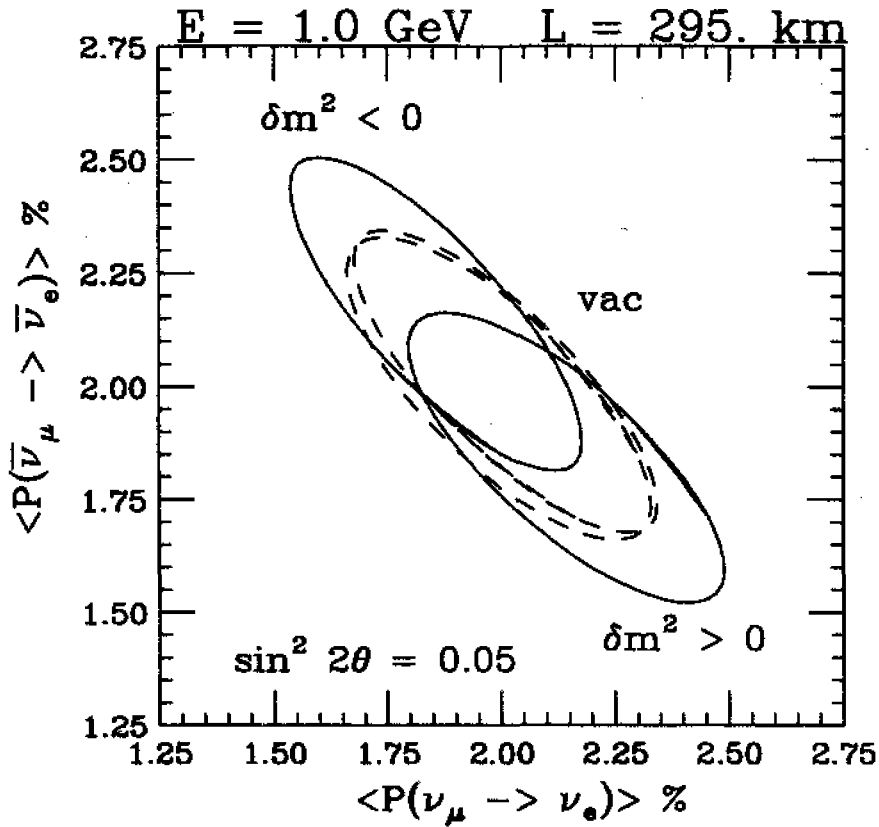
2nd peak 2 GeV:

New Beamline, New Detector:

<http://www.neutrino.bnl.gov/>

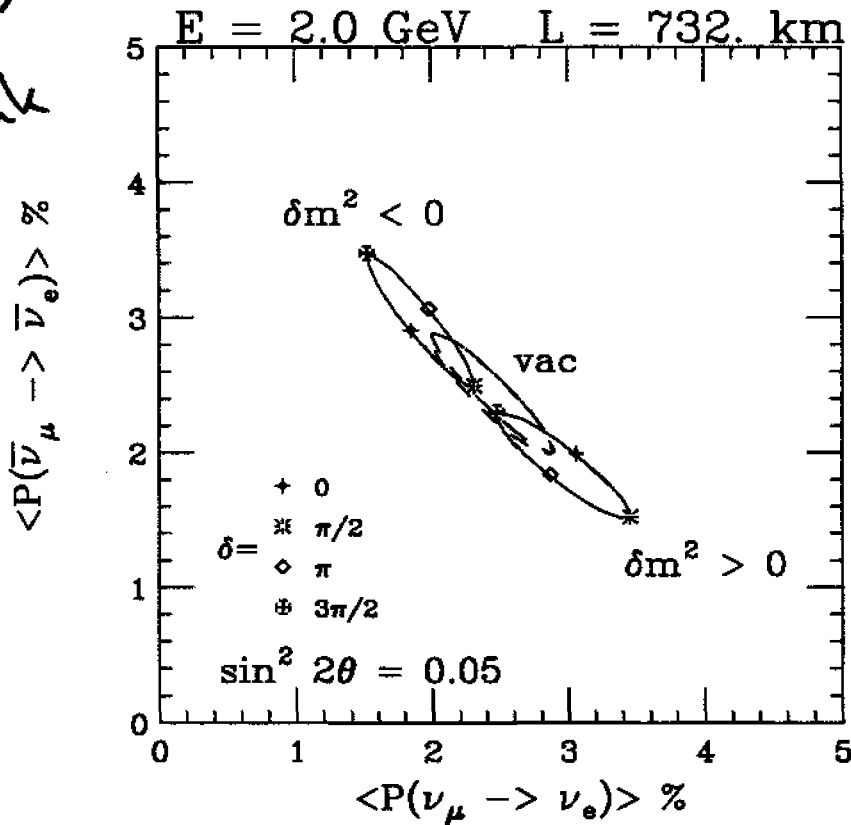
LOI: hep-ex/0205040

JHF \rightarrow SK
1st peak



20% Spread

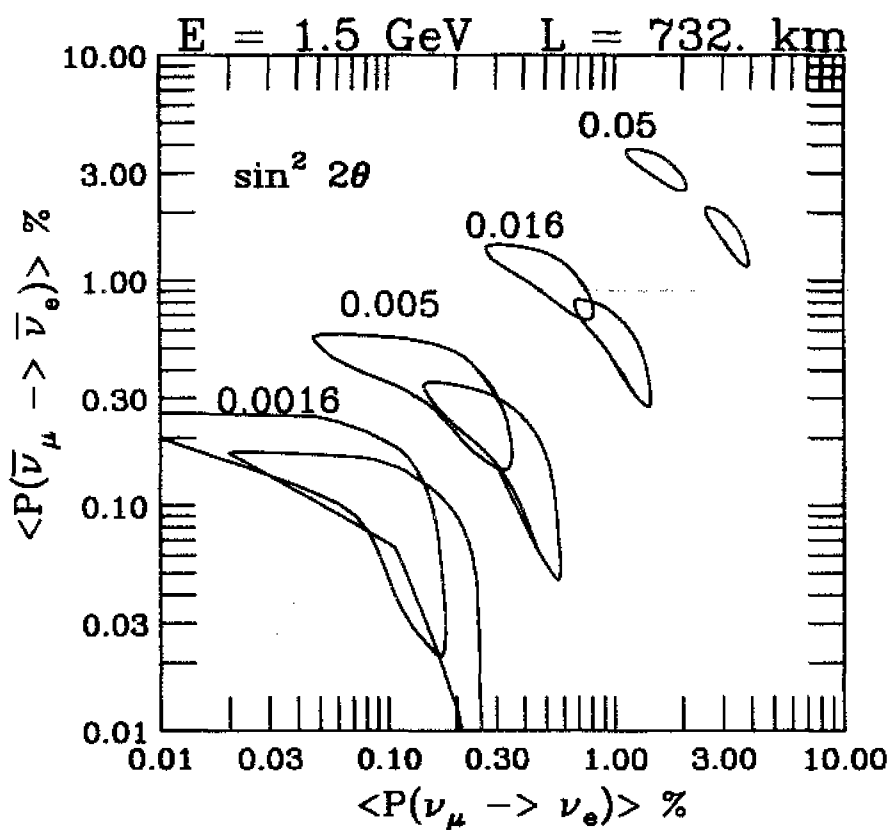
NuMI \rightarrow
1st peak



20% Spread.

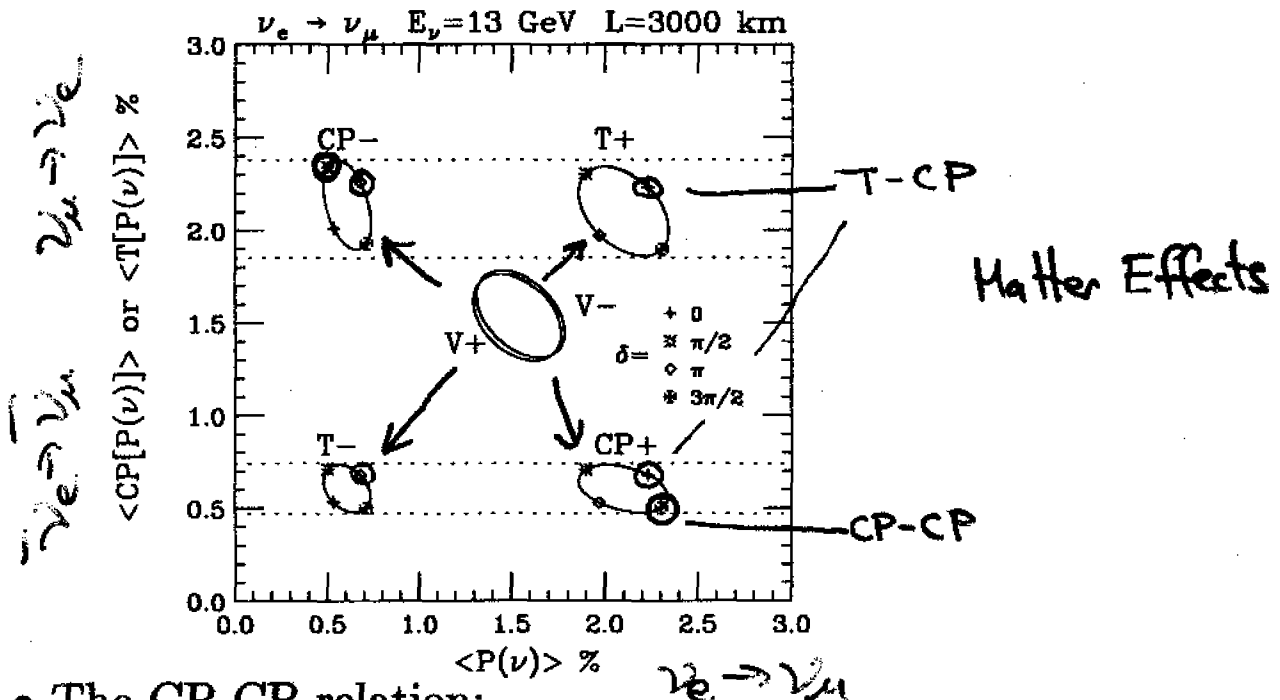
Matter Effects
separate
 $\delta m^2 > 0$
from
 $\delta m^2 < 0$

As $\sin^2 2\theta_{13}$ Varies:



NuMI off-Axis LOI
hep-ex/0210005

Anatomy of the Bi-Probability Plot:



- The CP-CP relation:

$$\begin{aligned}
 & P(\nu_e \rightarrow \nu_\mu; \Delta m_{31}^2, \Delta m_{21}^2, \delta, a) \\
 &= P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; -\Delta m_{31}^2, -\Delta m_{21}^2, \delta, a) \\
 &\approx P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; -\Delta m_{31}^2, +\Delta m_{21}^2, \pi + \delta, a)
 \end{aligned}$$

evolution eqn.

- The T-CP relation:

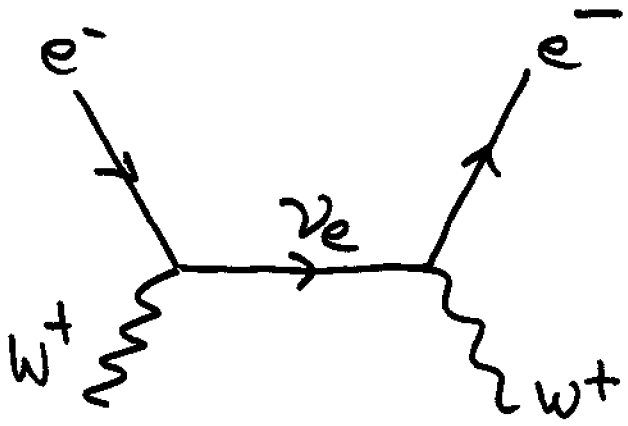
assuming symmetry matter distribution

$$\begin{aligned}
 & P(\nu_\mu \rightarrow \nu_e; \Delta m_{31}^2, \Delta m_{21}^2, \delta, a) \\
 &= P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; -\Delta m_{31}^2, -\Delta m_{21}^2, -\delta, a) \\
 &\approx P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; -\Delta m_{31}^2, +\Delta m_{21}^2, \pi - \delta, a)
 \end{aligned}$$

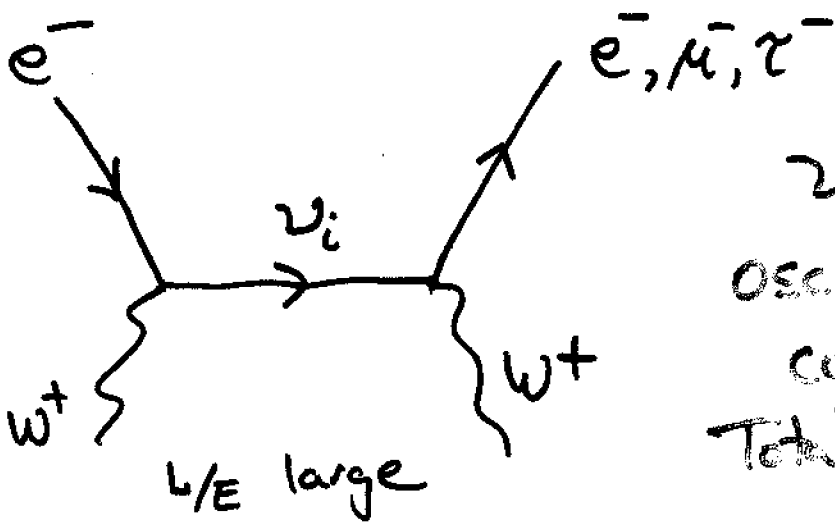
- \approx trade sign of δm_{12}^2 for shift by π of δ :

$$(\dots) + \delta m_{12}^2 [(\dots) \cos \delta + (\dots) \sin \delta]$$

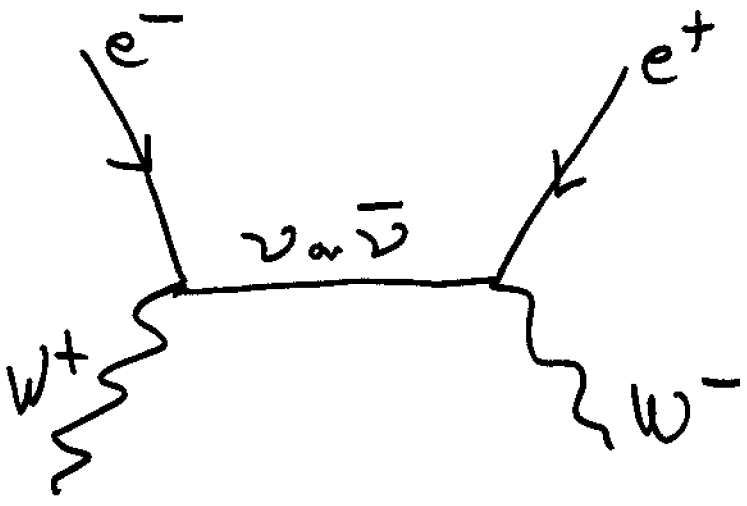
Small correction here



S.M.
flavor diagonal
conserves
 L_e, L_μ, L_τ



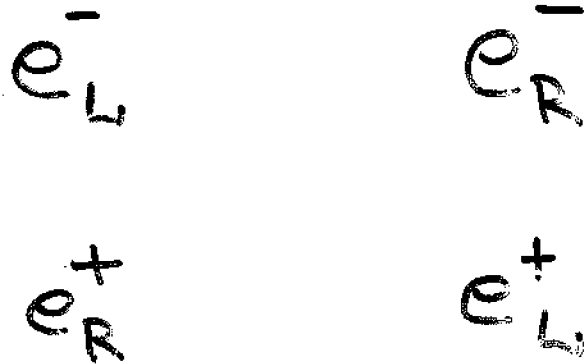
\Rightarrow MASS
oscillations ~~(L_e, L_μ, L_τ)~~
conserves
Total Lepton #



Majorana Mass
Lepton # Violating
(highly suppressed)
Why ???

Fermion Mass: (cartoon:) 27

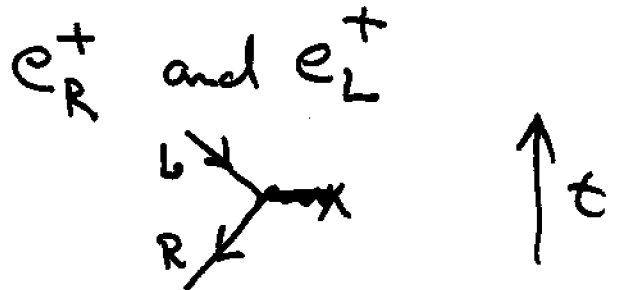
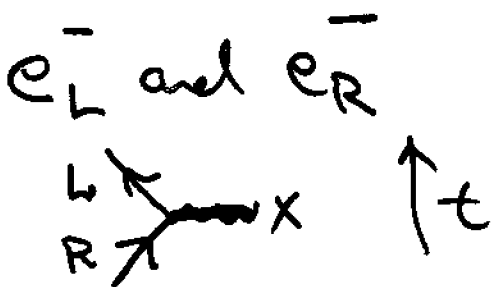
- Consider a massless electron:



- Four States: $2e^- + 2e^+$



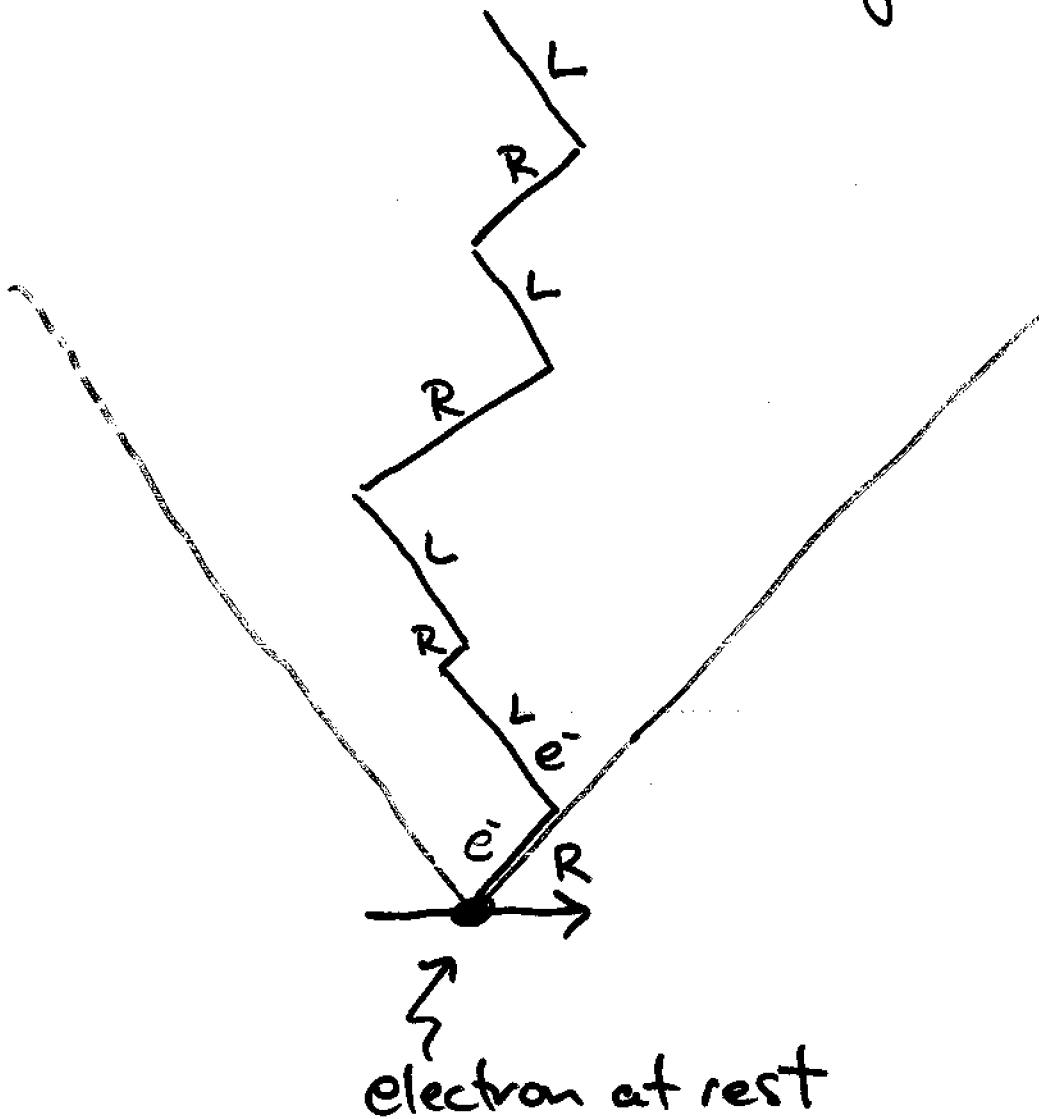
- Mass is a coupling between Left and Right. (chiral states)



CANNOT couple

e_L^- to e_R^+

because of electric charge conservation.



Massive Fermion with given Spin: 29

$$P^2 = M^2 \quad S^2 = -1 \quad P \cdot S = 0$$

e.g. (at rest $P = (M, 0, 0, 0)$ $S = (0, 0, 0, 1)$
Spin in z direction

$$P = \frac{P+MS}{2} + \frac{P-MS}{2}$$

$$\frac{P+MS}{2}$$

$$\text{and } \frac{P-MS}{2}$$

Massless

$$\begin{aligned} \left(\frac{P \pm MS}{2} \right)^2 &= \frac{P^2 \pm 2P \cdot S + M^2 S^2}{4} \\ &= \frac{M^2 \pm 2M \cdot 0 + M^2(-1)}{4} \end{aligned}$$

Solⁿ Dirac Eqn
Massive, Spin

$$= 0$$

massless spinors

$$U(P, S) = \frac{1+\gamma_5}{2} U\left(\frac{P+MS}{2}\right)$$

$$+ e^{i\phi} \frac{1-\gamma_5}{2} U\left(\frac{P-MS}{2}\right)$$

chiral projections

$$u(p, s) = \frac{1 + \gamma_5 \not{s}}{2} u(p)$$

$$= \frac{1 + \gamma_5}{2} \underbrace{\frac{1 + \not{s}}{2} u(p)}_{Q_+} + \frac{1 - \gamma_5}{2} \underbrace{\frac{1 + \not{s}}{2} u(p)}_{Q_-}$$

$$Q_+ \overline{Q_+} = \frac{p \pm Ms}{2}$$

$$\text{and } \frac{p \pm Ms}{2} Q_{\pm} = 0$$

$$\text{Therefore } Q_{\pm} = u\left(\frac{p \pm Ms}{2}\right)$$

Relative phase determined by

$$\overline{u(p, s)} u(p, s) = 2M$$

MASSIVE PARTICLE AT REST,
Spin in z direction:

31

$$P = \frac{P+MS}{2} + \frac{P-MS}{2}$$

$$(M, 0, 0) = \frac{M}{2} (1, 0, 0, 1) + \frac{M}{2} (1, 0, 0, -1)$$

BIG BOOST IN z-DIRECTION $\begin{pmatrix} \gamma & \beta\gamma \\ \beta\gamma & \gamma \end{pmatrix}$

$$\gamma M (1, 0, 0, \beta) = \frac{M}{2} (\gamma + \beta\gamma) (1, 0, 0, 1) + \frac{M}{2} (\gamma - \beta\gamma) (1, 0, 0, -1)$$

as $\beta \rightarrow 1$ $(\gamma + \beta\gamma) \rightarrow 2\gamma$ $(\gamma - \beta\gamma) \rightarrow \frac{1}{2}\gamma$

where $\gamma = E/M$

$$E (1, 0, 0, \beta) \approx E (1, 0, 0, 1) + \frac{M^2}{E} (1, 0, 0, -1)$$

$$U(P, S) = \frac{1+\gamma_5}{2} U\left(\frac{P+MS}{2}\right) + \frac{1-\gamma_5}{2} U\left(\frac{P-MS}{2}\right)$$

HELICITY
STATE

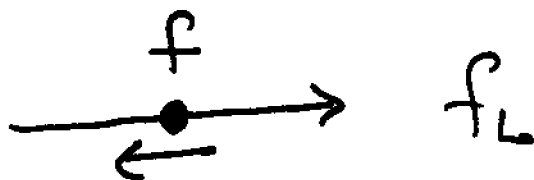
RIGHT

LEFT

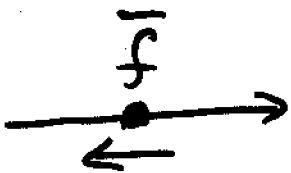
CHIRAL PROJECTIONS

HELICITY \neq CHIRALITY
 for massive particles

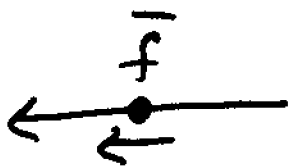
Massless Fermion:



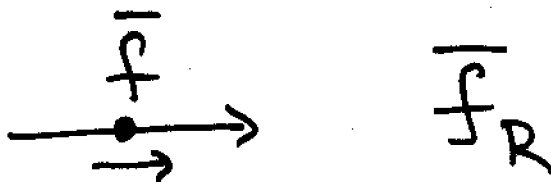
Charge
Conjugation (C)



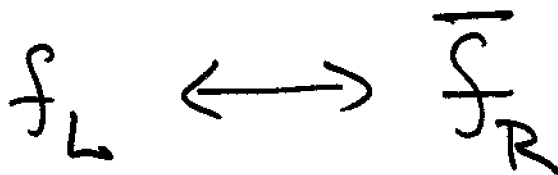
Parity (P)



Time
Reversal (T)



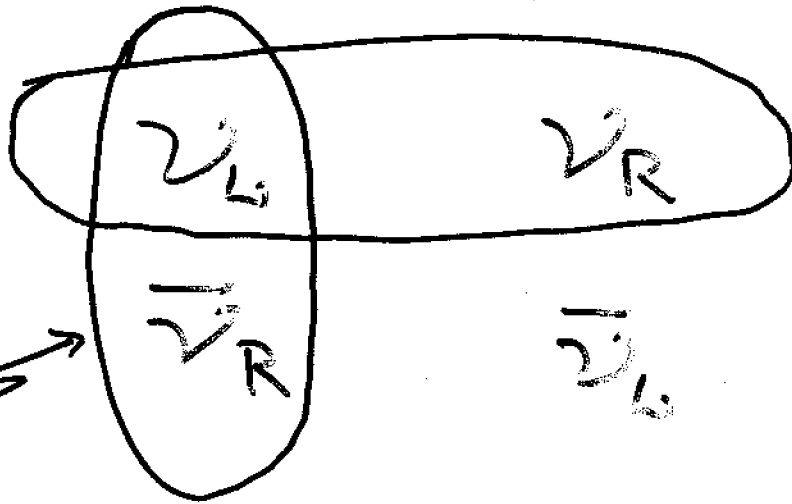
CPT



At a minimum by CPT

f_L, \bar{f}_R

For Neutral Fermions (neutrinos) ³



Dirac Mass.

required by weak interaction

Majorana Mass

(Violates $b \neq$)

See-Saw Mechanism gives

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} N_R \\ N_L \end{pmatrix}$$

light $\frac{m^2}{M}$ M

Neutrinos being Majorana

is the minimal solution

to giving ν mass.

$\nu = \bar{\nu}$ two states ν_L and ν_R

If Dirac then there is a global symmetry (lepton #) which needs to be explained.

$\nu \neq \bar{\nu}$ and four states

weak \rightarrow ν_L and $\bar{\nu}_R$
 ν_R and $\bar{\nu}_L$

Suppression factor:

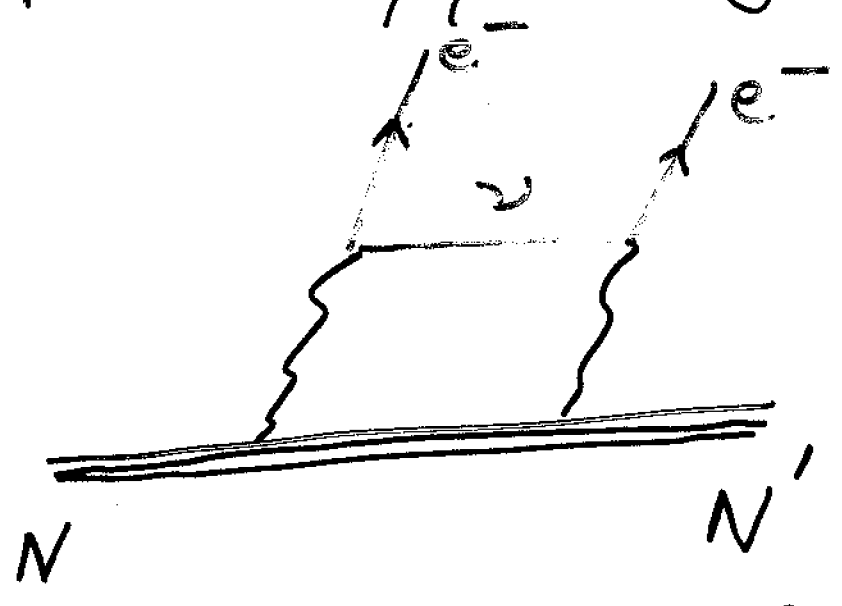
$$\left(\frac{\overline{M}_\nu}{E} \right)^2$$

chirality \neq helicity
for massive particles

$\overline{M}_\nu \sim 1 \text{ eV}$ $E = 1 \text{ GeV}$ $\left(\frac{M}{E} \right)^2 \approx \underline{\underline{10^{-20}}}$

BUT

~~$2\beta\beta$~~ decay



Same Nucleus also has $2\nu\beta\beta$ decay
→ end point:

WHAT WE DON'T KNOW:

36

- Majorana OR Dirac
- Absolute mass of lightest neutrino.
(except $< \sim 1\text{eV}$)
- Size of θ_{13} : (ν_e in the "3" state.)
 $\sin^2 \theta_{13} < 0.03$
- Is $\theta_{23} = \text{or } \lesseqgtr \frac{\pi}{4}$ the $\mu \leftrightarrow \tau$ symmetric point.
(maximal mixing)
 $0.35 < \sin^2 \theta_{23} < 0.65$
- Sign of Δm^2 (normal or inverted)
type of spectrum
- phase $\delta \Leftarrow$ if $\neq 0$ leads to CP violation
- Number of light Neutrinos: 3 or are there more than 3