NEUTRINO MASS PHYSICS

EXPLORING THE SEESAW MECHANISM

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STONY BROOK, 10/02.

THREE FACTS ABOUT NEUTRINO MASS :

(i) $m_\nu \lesssim 2-3\ \text{eV}$ $\lll m_{u,d,e}$

(ii) MIXING MATRIX : $\approx \begin{pmatrix} c & s & \varepsilon \\ \frac{s}{\sqrt{2}} & -\frac{c}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}} & -\frac{c}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$

$.77 \leq \sin 2\theta \leq .96$

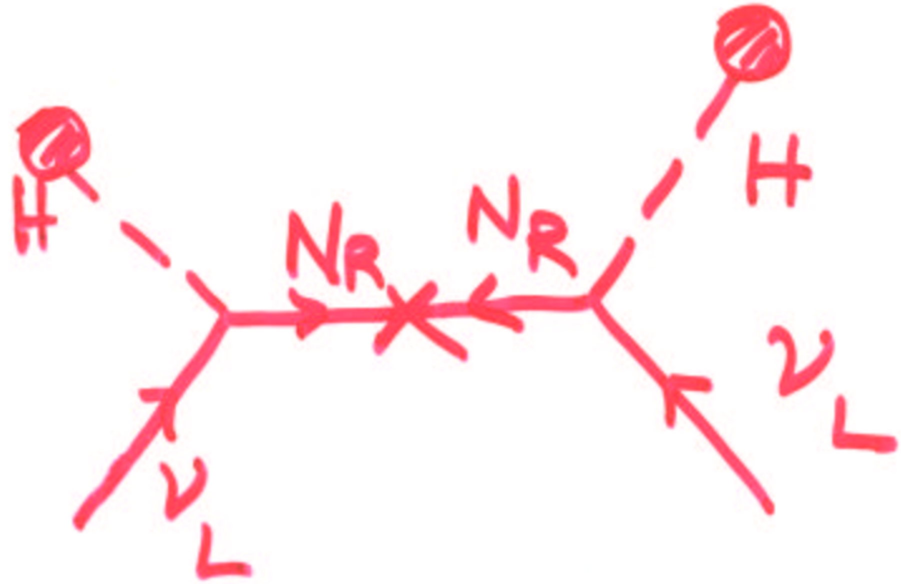
$U_{e3} \equiv \varepsilon < .16$

(VERY DIFF. FROM QUARKS)

(iii) $\dfrac{\Delta m^2_\odot}{\Delta m^2_A} \simeq 2\times 10^{-2} - 8\times 10^{-2}$ $\ll 1$

(i) WHY $m_\nu \ll m_{u,d,e}$?

• ADD RH NEUTRINO (N_R) TO SM



SEESAW MECHANISM

$$m_\nu = - M_{\nu D} M_R^{-1} M_{\nu D}$$

$\Rightarrow$ ATMOSPH. $\Rightarrow M_R \ll M_{Pl}$

• WHAT PROTECTS $M_R \ll M_{Pl}$?

: LOCAL B-L OR $SU(2)_H$:

(i) TESTING THE ORIGIN OF SEESAW:

a) $N - \bar{N}$

b) $\dfrac{B(\mu \to e\gamma)}{B(\tau \to \mu\gamma)}$

(ii) HORIZONTAL SYM $(SU(2)_H)$ AND $\sin^2 2\theta_{\odot}$, $\dfrac{\Delta m^2_{\odot}}{\Delta m^2_A} \ll 1$

(iii) A NATURAL UNDERSTANDING OF MAXIMAL (LARGE) θ_A IN SO(10):

LOCAL B-L

$$SM \xrightarrow{M \gg V_{WK}} SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

OR

$SO(10)$ OR

$SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$

- QUARK - LEPTON SYM. EXTENSION

$3\ N_R$

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2}$$

$\Rightarrow \Delta Q = 0;\ \Delta I_{3L} = 0$ FOR $\mu > V_{WK}$

$$\Rightarrow \boxed{2|\Delta I_{3R}| = \Delta L}$$

MARSHAK, R.N.M '80

LOCAL B-L SYMMETRY IS A SIMPLE AND ATTRACTIVE WAY TO UNDERSTAND THE OVERALL SIZE (SMALLNESS) OF m_ν !!

$$\Delta m_A^2 \Rightarrow M_R \sim 10^{12} - 10^{16}\ GeV$$

$$\Delta L = 2\,\Delta I_{3R}$$

TWO POSSIBILITIES:

(i) $\Delta I_{3R} = \frac{1}{2} \Rightarrow$ HIGGS χ^c B-L=1

$\Rightarrow$ ORIGIN OF N_R MASS FROM

$$\lambda \boxed{(\nu^c \chi^c)^2 / M} \Rightarrow M_R = \lambda \frac{\langle \chi^c \rangle^2}{M}$$

(ii) $\Delta I_{3R} = 1 \Rightarrow$ (Δ^c WITH B-L=2)

M_{N_R} FROM $\boxed{f\ \nu^c \nu^c \Delta^c}$

$$M_{N_R} = f \langle \Delta^c \rangle$$

$\Rightarrow$ PHYSICS IMPLICATIONS DIFFERENT.

- BOTH CAN BE GRANDUNIFIED!!

TESTING B-L=1 Vrs B-L=2 USING BARYON NONCONSERVATION:

$$\Delta(B-L) = 2\,\Delta I_{3R}$$

FOR HADRONS $\Rightarrow$ $\Delta B = 2\,\Delta I_{3R}$

(i) FOR $\Delta I_{3R} = \frac{1}{2}$ $\Delta B = 1$.

NON-SUSY CASE, $\Rightarrow$ $\Delta B = 0$ DUE TO LORENTZ INV.

SUSY CASE $\Rightarrow$ SUPERFIELDS BOSONIC

(BABU, R.N.M. '01)

$\Rightarrow$ $\Delta B = 1$ OPERATORS ALLOWED.

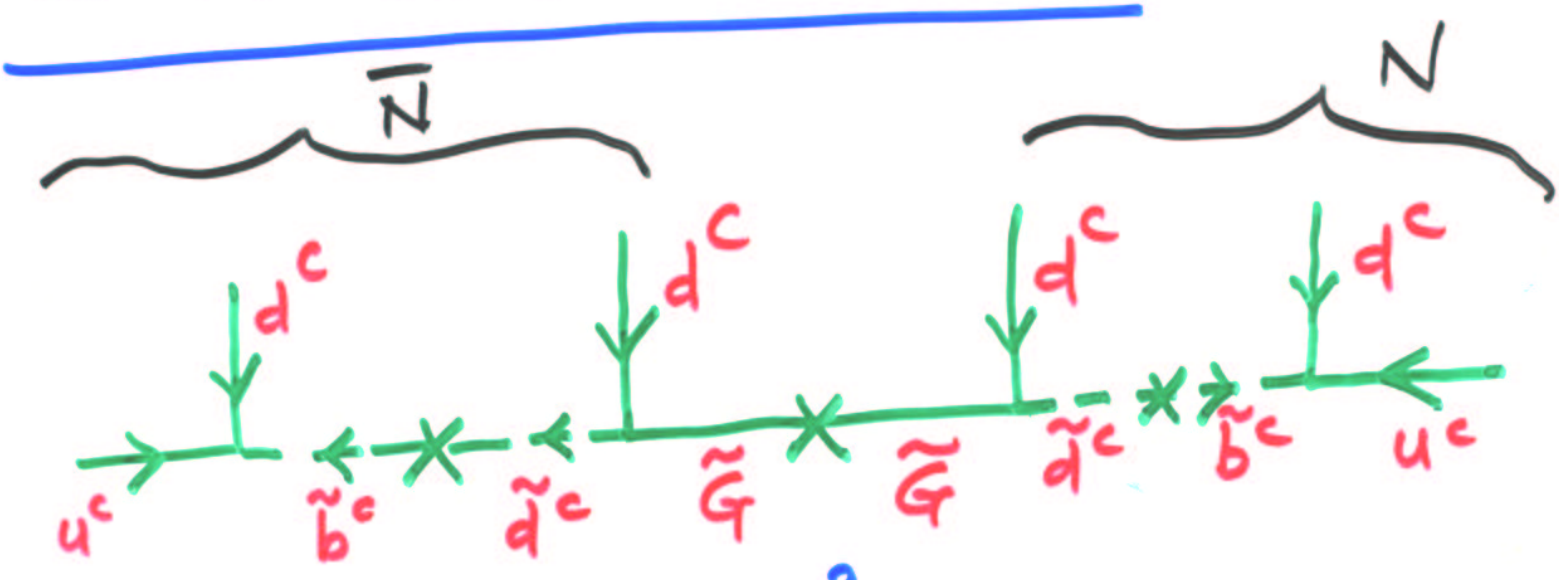
- $$\lambda \frac{Q^c Q^c Q^c \chi^c}{M_{Pl}} \Rightarrow u^c d^c d^c \frac{v_R}{M_{Pl}}$$

COLOR SYM $\Rightarrow \left(u^c d^c s^c \text{ OR } u^c d^c b^c \right) \frac{v_R}{M_{Pl}}$

R_p $\Rightarrow$ (ZWIRNER, GOITY, SHER)

Ⓐ

$N-\bar{N}$ AMPLITUDE:



$$\left[\left(\frac{v_R}{M_{Pl}} \right) \frac{m^2_{\tilde{b}\tilde{d}}\, g_3}{M^4_{\tilde{q}}} \right]^2 \frac{\lambda^2}{M_{\tilde{G}}} = G_{\Delta B=2}$$

DETAILED ESTIMATE OF $\tau_{N\bar{N}}$

SIX QUARKS TO $N-\bar{N}$ (RAO, SHROCK '82)

$$\delta m_{N-\bar{N}} \simeq 10^{-4}\, G_{\Delta B=2}\, \mathrm{GeV}$$

SEESAW

$$\frac{f V_R^2}{M_{Pl}} = \frac{m^2_{\nu_D}}{m_{\nu_\tau}} \Rightarrow \tau_{N\cdot\bar{N}} = C\, m_{\nu_\tau}$$

$$\frac{m^2_{\tilde{b}\tilde{d}}}{M^2_{SUSY}} \simeq \frac{V_{ub}}{16\pi^2} \ln \frac{M_{P\ell}}{v_R} \simeq 2\times 10^{-4}$$

$$M_{\tilde{q}} \simeq M_{\tilde{G}} \simeq 500 \text{ GeV}$$

$$\tau_{N-\bar{N}} = 2.8\times 10^{4} \text{ sec.} \left(\frac{m_{\nu_e}}{.06\text{eV}}\right) \frac{f}{\lambda^2} \left(\frac{m_t}{m_{\nu_\tau, D}}\right)^2$$
$$\times \left(\frac{M_{\tilde{G}}}{500\text{GeV}}\right)\left(\frac{M_{\tilde{q}}}{500\text{GeV}}\right)^4$$

e.g. $\lambda \sim 10^{-2}$ $\quad \tau_{N-\bar{N}} = 2.8\times 10^{8} - 10^{9}$ sec

$$\tau_{NN\to\pi's} \simeq 10^{34} \text{ yrs.}$$

PRESENT LIMIT : $\tau > 10^{8}$ sec. ILL

$\geq 1.2\times 10^{8}$ sec. SOUDAN II

CASE (ii) : $\Delta(B-L)=2$ HIGGS

$$f\, L^c L^c \Delta_R \Rightarrow M_{N_R} = f\, v_R$$

$Q^c Q^c Q^c$ OPERATOR

FORBIDDEN; $(Q^c)^6$ SUPPRESSED DUE TO SEESAW!

$\Rightarrow$ NO $N-\bar{N}$ OSCILLATION!

LEPTON FLAVOR VIOLATION AS A B-L "BAROMETER".

BABU, DUTTA, R.N.M. '02

- MASSLESS ν

  $\Rightarrow$ NO LFV $\Rightarrow B(\mu \to e\gamma) = 0$,

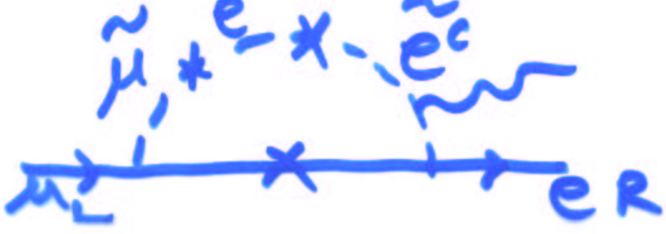
  $B(\tau \to {}^{\mu}_{e}\gamma) = 0$

- ν - MIXING $\Rightarrow$ LFV
- BUT NO SUSY

  $B(\mu \to e\gamma) \propto m_\nu^2$ (TINY)

- WITH SUSY

  ν-MIXING $\Rightarrow$ SLEPTON MIXING.



$\Rightarrow l_j \to l_i + \gamma.$

HOW TO TEST $\Delta(B-L)=1$ vrs 2?

PROCEDURE:

AT $\mu = M_U$, $m^2_{\tilde{L}} = m_0^2 \mathbb{1}$

(i) $\Delta(B-L)=1$

$$\Rightarrow \quad M_{N_R} \Leftarrow \frac{(\nu^c \chi^c)^2}{M_{P\ell}}$$

NO EFFECT ON RUNNING

$$m_\nu = v_{wk}^2 \, Y_\nu M_R^{-1} Y_\nu$$

$$Y_\nu \Rightarrow m^2_{\tilde{L}} = m_0^2 + \delta m^2_{ij}$$

$$\delta m^2_{ij} \propto (Y_\nu^\dagger Y_\nu)_{ij}$$

(ii) $\Delta(B-L)=2$, $M_{N_R} \Leftarrow f \nu^c \nu^c \Delta$

f EFFECTS $m^2_{\tilde{L}}$ RUNNING:

$$\delta m^2_{ij} \propto (Y_\nu^\dagger Y_\nu)_{ij} + (f^\dagger f Y_\nu^\dagger Y_\nu)$$

CHOOSE $Y_\nu \Rightarrow$ DIAGONAL.

RATIO INDEP. OF OVERALL SCALE FREEDOM (V_{B-L})

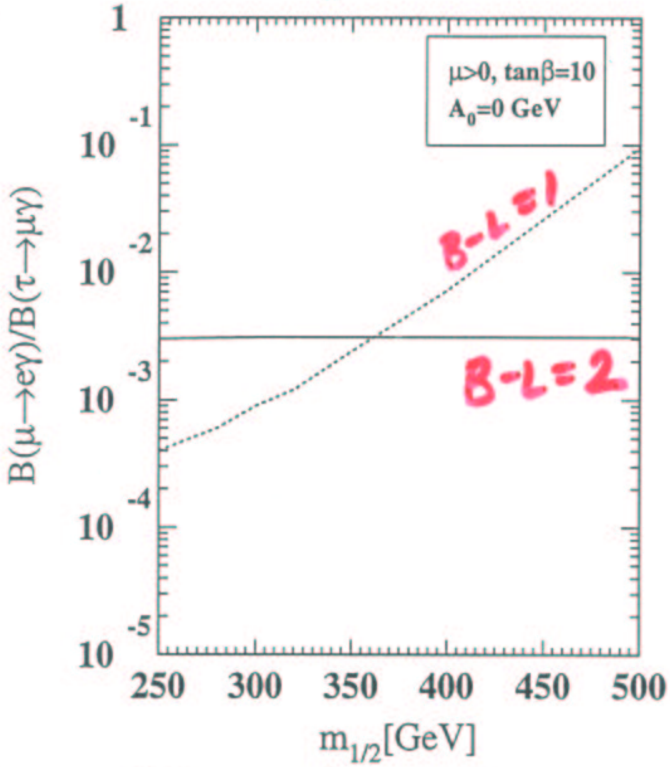


FIG. 6. $B(\mu \to e+\gamma)/B(\tau \to \mu+\gamma)$ vs $m_{1/2}$. The solid line correspond to the Majorana alternative case and the dashed line corresponds to the Dirac alternative.

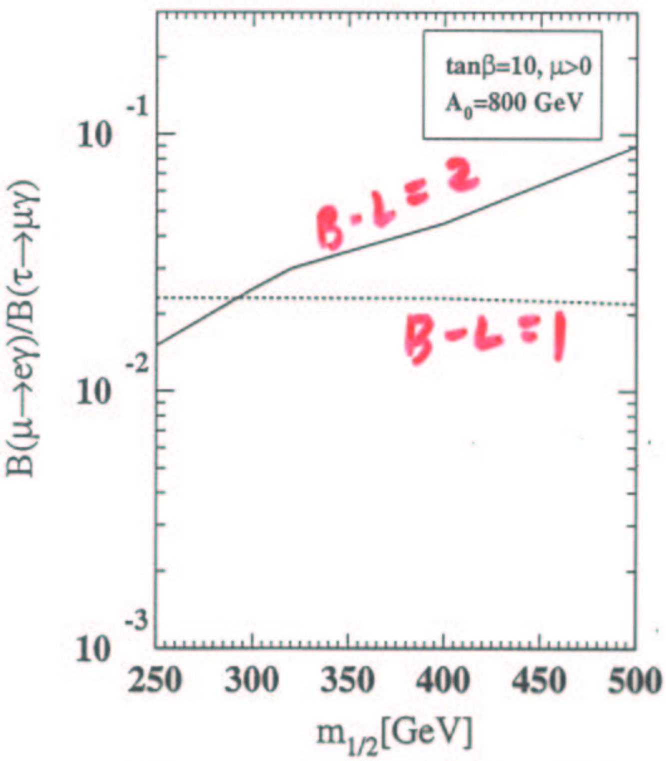


FIG. 7. $B(\mu \to e+\gamma)/B(\tau \to \mu+\gamma)$ vs $m_{1/2}$. The solid line correspond to the Majorana alternative case and the dashed line corresponds to the Dirac alternative.

GIVEN INFO ON $m_{1/2}$, A, $\tan\beta \Rightarrow$

B-L=1 vrs B-L=2 CAN BE DISTINGUISHED

SEESAW EXPLAINS THE OVERALL SIZE OF m_ν ; BUT HOW TO UNDERSTAND

(i) NEAR BIMAXIMAL MIXING

(ii) SMALL U_{e3}

(iii) SMALL $\Delta m^2_\odot / \Delta m^2_A$?

AN INTERESTING POSSIBILITY :

$\approx L_e - L_\mu - L_\tau$ SYMMETRY OF M_ν

ii) INVERTED HIERARCHY AND $L_e - L_\mu - L_\tau$:

$$\mathcal{M}_\nu = \sqrt{\Delta m_A^2} \begin{pmatrix} z & \sin\theta_A & \cos\theta_A \\ \sin\theta_A & x & d \\ \cos\theta_A & d & y \end{pmatrix}$$

$$z, x, y, d \ll 1$$

- CHARGED LEPTON MASSES DIAGONAL!!

- FOR $z, x, y, d = 0$, $\mathcal{M}_\nu$ IS $L_e - L_\mu - L_\tau$ SYMMETRIC.

- PROVIDES RATIONAL FOR SMALL x, y, z, d.

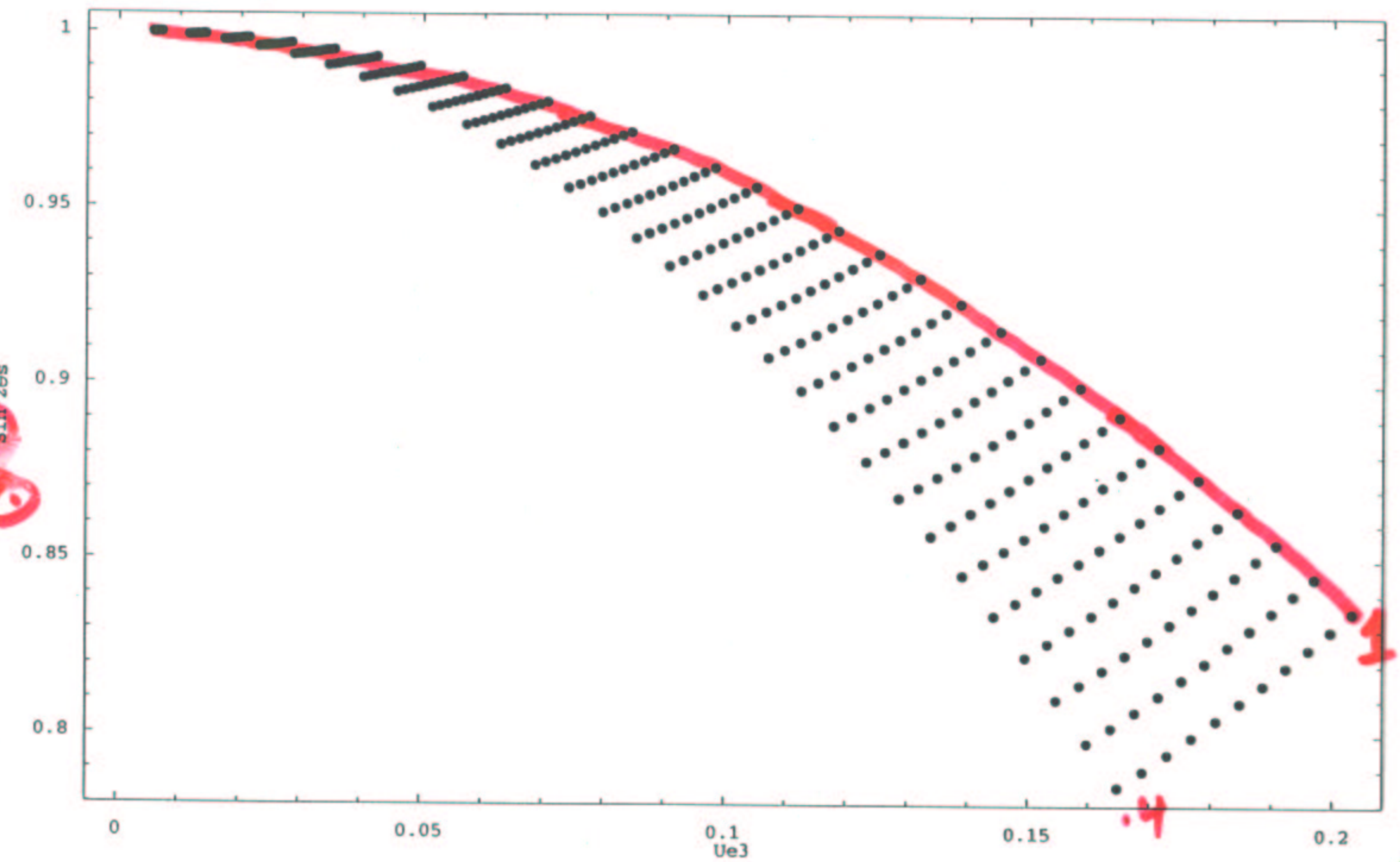
EXPLAINS:

- NEAR BIMAXIMAL MIXING
- $\Delta m^2_\odot = 0$ IN THE SYM. LIMIT; ITS SMALLNESS HAS A SYMMETRY EXPLANATION
- $U_{e3} = 0$ IN SYM. LIMIT.

- ADD SMALL SYM. BREAKINGS i.e. $x, y, z, d \lesssim .2$
- $\Delta m^2_\odot \neq 0$ AND SMALL $\Rightarrow \sin^2 2\theta_\odot \gtrsim .95$

- $x = y = z = d = 0$ BUT SMALL BREAKIN IN CHARGED LEPTONS.

BABU, R.N.M; GOH, NG, R.N.M. 2002



$\sin^2 2\theta_\odot$

$\tan^2\theta_A$

U_{e3}

$M_\ell = \begin{pmatrix} 0 & 0 & x \\ 0 & y & 0 \\ x & 0 & 1 \end{pmatrix} m_\tau$

$\boxed{\sin^2 2\theta_\odot - U_{e3} \text{ CORRELATION}}$

$U_{e3} < .15 \Rightarrow \sin^2 2\theta_\odot > .9$

$< .22 \qquad > .80$

CAN WE GET INVERTED MASS HIERARCHY FROM SEESAW MECHANISM ?

$SU(2)_H$ SCENARIO:

(R. KUCHIMANCHI, R.N.M. 2002)

MOTIVATION:

$SU(2)_H \supset (e_R, \mu_R)$

REQUIRES $(N_{eR}, N_{\mu R})$ FOR NO GLOBAL ANOMALIES.

$$\cdots \times U(1)_{B-L} \times SU(2)_H$$

$$\uparrow$$

$$SM \otimes SU(2)_H \qquad \sim 10^{11}\text{-}10^{12}\ \text{GeV}$$

$$\uparrow$$

$$\boxed{SM}$$

$$\Rightarrow \quad M_{N_{\tau R}} \gg M_{N_{e,\mu R}}$$

⇛ $\boxed{\text{3X2 SEESAW}}$

⇛ APPROX. $L_e - L_\mu - L_\tau$ MASS TEXTURE WITH CHARGED LEPTON BREAKING.

EXPLAINS:
- BIMAXIMAL
- SMALL $\Delta m^2_\odot / \Delta m^2_A$
- SMALL U_{e3}

3X2 SEESAW

$$\begin{pmatrix} a & 0 \\ 0 & a \\ b & c \end{pmatrix} \begin{pmatrix} 0 & M_R^{-1} \\ M_R^{-1} & 0 \end{pmatrix} \begin{pmatrix} a & 0 & b \\ 0 & a & c \end{pmatrix}$$

$$= \frac{1}{M_R} \begin{pmatrix} 0 & a^2 & ac \\ a^2 & 0 & ab \\ ac & ab & 2bc \end{pmatrix}$$

$$b, c \approx \frac{v_{H1,2}\, K_{WK}}{M}$$

$b \ll c \approx a$

$\Rightarrow$ APPROX $L_e - L_\mu - L_\tau$ SYMMETRIC MATRIX.

(i) $$\frac{\Delta m_\odot^2}{\Delta m_A^2} \simeq \frac{bc}{a^2} \ll 1.$$

(ii) $\theta_\odot, \theta_A$ LARGE !! $(\sin^2 2\theta_\odot \gtrsim .95)$

ADDITIONALLY,

$$M_\ell = \begin{pmatrix} a' & 0 & +\alpha b \\ 0 & a' & \alpha c \\ -\alpha' c & \alpha' b & d \end{pmatrix}$$

$\Rightarrow$
- SUPPRESSES $\sin^2 2\theta_\odot$
- CORRELATES IT TO U_{e3}:

ROUGHLY $$\theta_\odot \approx \frac{\pi}{4} - U_{e3}$$

$\Rightarrow \sin^2 2\theta_\odot \simeq 0.89$ for $U_{e3} \simeq 0.16$

- PREDICTS

$$\langle m \rangle_{\beta\beta} \simeq \sqrt{\Delta m^2_A} \cos 2\theta_{\odot} \simeq .016 \text{ eV}$$

- POTENTIAL TO RELATE BARYON ASYMMETRY TO LOW ENERGY NEUTRINO PHASE !!

(YANAGIDA et. al.) 02

A PREDICTIVE MINIMAL SO(10) MODEL:

BABU, R.N.M. '92: $\{10\}$ $\{126\}$

$$h\,\psi\psi\{10\} + f\,\psi\psi\{126\}$$

$$\kappa_{u,d} \qquad v_{u,d}$$

$$\Rightarrow \quad M_u = h\,\underset{10}{\kappa_u} + f\,\underset{126}{v_u}$$

$$M_d = h\,\kappa_d + f\,v_d$$

$$M_\ell = h\,\kappa_d - 3f\,v_d$$

$$M_{\nu D} = h\,\kappa_u - 3f\,v_u$$

$$m_\nu = M_{\nu D}\,\frac{1}{f\,v_R}\,M_{\nu D}.$$

- CURES THE FERMION MASS PROBLEM
- EXTREMELY PREDICTIVE FOR ν'S.

$h \to 3$; $f \to 6$ + 3 vev's $\Rightarrow$ 12

INPUTS: 9 masses & 3 CKM ANGLES.

NATURAL UNDERSTANDING OF LARGE MIXING ANGLES!

BAJC, SENJANOVIĆ, VISSANI

$$M_u = h\,\langle 10\rangle_u + f\,\langle 126\rangle_u$$
$$M_d = h\,\langle 10\rangle_d + f\,\langle 126\rangle_d$$
$$M_\ell = h\,\langle 10\rangle_d - 3f\,\langle 126\rangle_d$$
$$M_{\nu D} = h\,\langle 10\rangle_u - 3f\,\langle 126\rangle_u .$$

h, f HAVE SMALL BUT ARBITRARY OFF DIAGONALS:

$$\Rightarrow \qquad M_d - M_\ell = 4\,\langle 126\rangle_d\, f$$

USE TYPE II SEESAW FOR m_ν:

$$m_\nu = f\,\underbrace{V_L}_{\langle 126\rangle} - M_D M_R^{-1} M_D$$

$\Rightarrow$

$$M_\nu \approx c(M_d - M_\ell)$$

2-3 SECTOR:

$$M_d = \begin{pmatrix} \varepsilon & \varepsilon' \\ \varepsilon' & 1 \end{pmatrix} m_b$$

ε's $\ll 1$

$$M_\ell = \begin{pmatrix} \varepsilon''' & \varepsilon'' \\ \varepsilon'' & 1 \end{pmatrix} m_\tau$$

AT GUT SCALE, $m_b = m_\tau$

$$\Rightarrow \quad M_d - M_\ell = \begin{pmatrix} \varepsilon & \tilde{\varepsilon} \\ \tilde{\varepsilon} & 0 \end{pmatrix} \approx M_\nu$$

$\Rightarrow$ LARGE MIXING ANGLE NATURALLY IN A MINIMAL MODEL:

$\theta_{12} = ?$

CONCLUSION

TWO INTERESTING SCENARIOS FOR SEESAW:

(i) B-L $\quad$ 3 x 3 SEESAW

(ii) $SU(2)_H$ OR $SU(2)_H \times U(1)_{B-L}$

$\Rightarrow$ 3x2 SEESAW

(ii) CAN EXPLAIN NOT ONLY WHY $m_\nu \ll m_{u,d,e}$ BUT ALSO NEAR BIMAXIMAL MIXING +

$$\frac{\Delta m^2_\odot}{\Delta m^2_A} \ll 1 .$$

(i) NATURE OF B-L BREAKING TESTABLE IN $N-\bar{N}$ OSC. + LFV PROCESSES !!