UNDERSTANDING

ν- MASSES

AND

MIXINGS

R. N. MOHAPATI
SUSY'02
DESY

- NEUTRINOS HAVE MASS AND THEY MIX (LIKE QUARK.

- <u>TWO QUESTIONS</u> :

i) HOW DO WE UNDERSTAND WHAT WE KNOW ABOUT ν MASSES AND MIXINGS ?

ii) WHAT DOES IT TELL US ABOUT PHYSICS BEYOND STAND MODEL ?

NOTATION :

- ASSUME ν = MAJORANA

  (OR $\nu = e^{i\alpha} C \bar{\nu}^T$)

  4-COMP

- GAUGE TH. $\Rightarrow$

$$\mathcal{L}_{mass} = \nu_L^T C^{-1} M_\nu \nu_L + \bar{\ell}_L M_\ell \ell_R + h.c$$

DIAGONALIZE :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \vdots \end{pmatrix} = U_\nu \begin{pmatrix} \nu_1 \\ \nu_2 \\ \vdots \end{pmatrix} ; \ \ell$$

MIXING MATRIX : $U_{PMNS} = U_\ell^\dagger U_\nu$ $\quad (U_{\alpha \ldots}$

$\alpha = e, \mu, \tau, \ldots$

MASSES: $m_1, m_2, \ldots$

PATTERNS OF MIXINGS SUGGESTED BY DATA:

DEPENDS ON WHETHER LSND IS CORRECT OR NOT,

A) WITHOUT LSND:

ν_e, ν_μ, ν_τ SUFFICIENT TO EXPLAIN ALL DATA.

B) INCLUDE LSND

$\nu_e, \nu_\mu, \nu_\tau + \nu_s$

(A)

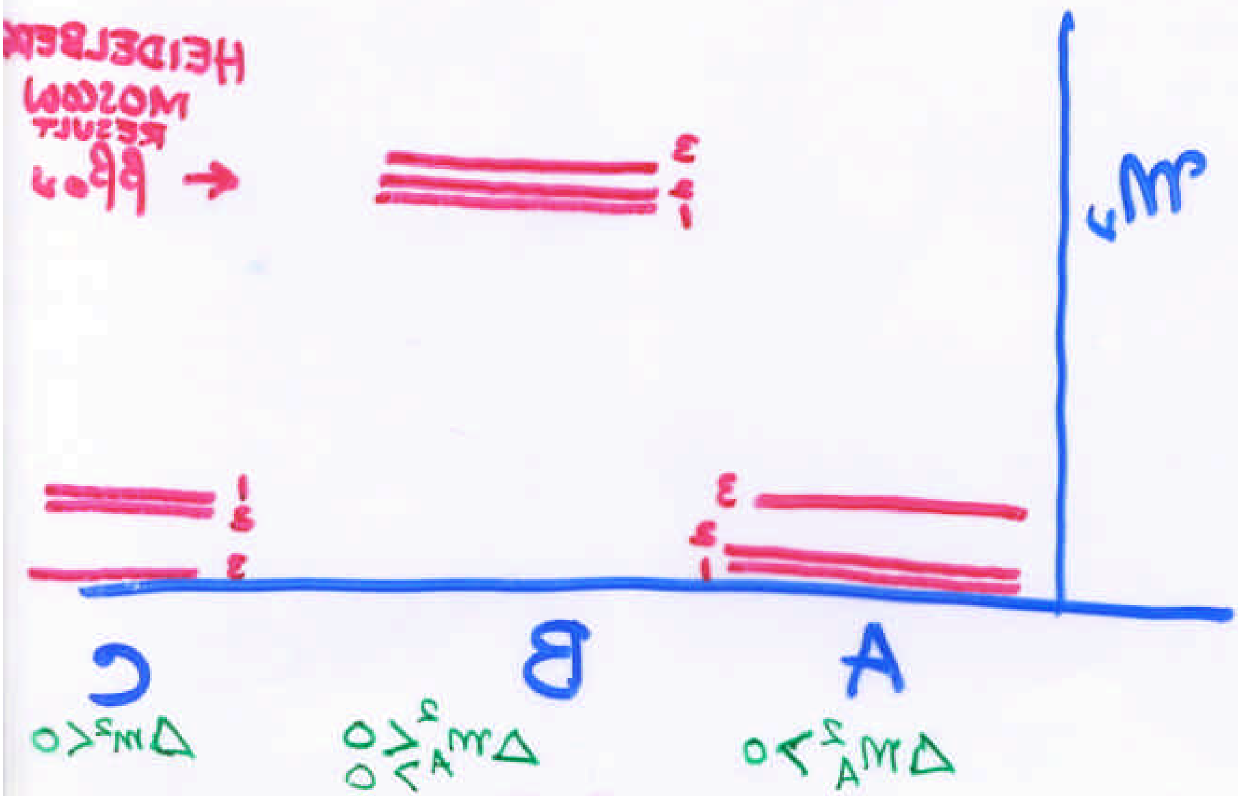
THREE ν CASE:

MASS PATTERNS

(A) $m_{\nu_1} \ll m_{\nu_2} \ll m_{\nu_3}$ (HIERARCHICAL)

(B) $m_{\nu_1} \simeq m_{\nu_2} \simeq m_{\nu_3}$ (DEGENERATE)

(C) $m_{\nu_1} \simeq m_{\nu_2} \gg m_{\nu_3}$ (INVERTED)



MIXING PATTERN

SOLAR: PRESENT FAVORIT

$\nu_e \, \nu_\mu$ MIXING (U_{e2}) LARGE

$$.55 \leq \sin^2 2\theta_{e\mu} \leq .95$$

ATMOSPH:

$\nu_\mu - \nu_\tau$ MIXING MAXIMAL

REACTOR EXPT. CHOOZ, PALOVERDE

$U_{e3} < .16$ FOR $\Delta m^2 \gtrsim 1$

$$\Rightarrow \; U_{MNSP} = \begin{pmatrix} c & -s & \varepsilon \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

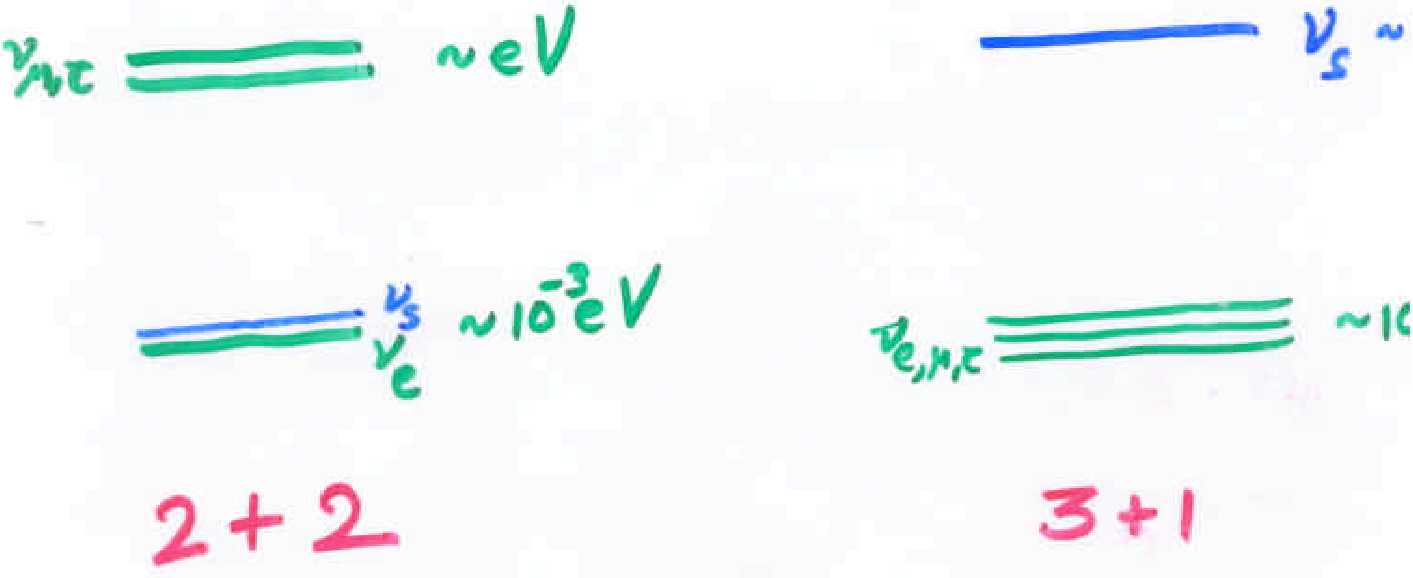
BIMAXIMAL (BILARGE)

(B)

IF LSND IS INCLUDED

$\Rightarrow \quad \nu_e, \nu_\mu, \nu_\tau \oplus \nu_s$

MASS PATTERN:



- SNO HAS NOT RULED OUT STERILE ν_s.
- WAIT FOR MINI-BOONE
- ISSUE IS WHY ν_s ULTRA-LIGH

TOWARDS A FUNDAMENTAL THEORY

HOW TO UNDERSTAND

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

(ii) BIMAXIMAL MIXING ;

(iii) MASS PATTERN AND THEORY

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

m_ν IN THE STANDARD MODE

$SU(2)_L \times U(1)_Y$:

$$Q \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{matrix} u_R \\ d_R \end{matrix}$$

$$L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

- HAS GLOBAL B-L SYM.

GRAVITY INDUCED BREAKIN OF B-

$$O \equiv \frac{LH\,LH}{M_{Pl}} \Rightarrow m_\nu \simeq \frac{v_{wk}^2}{M_{Pl}} \simeq 2\times 1$$

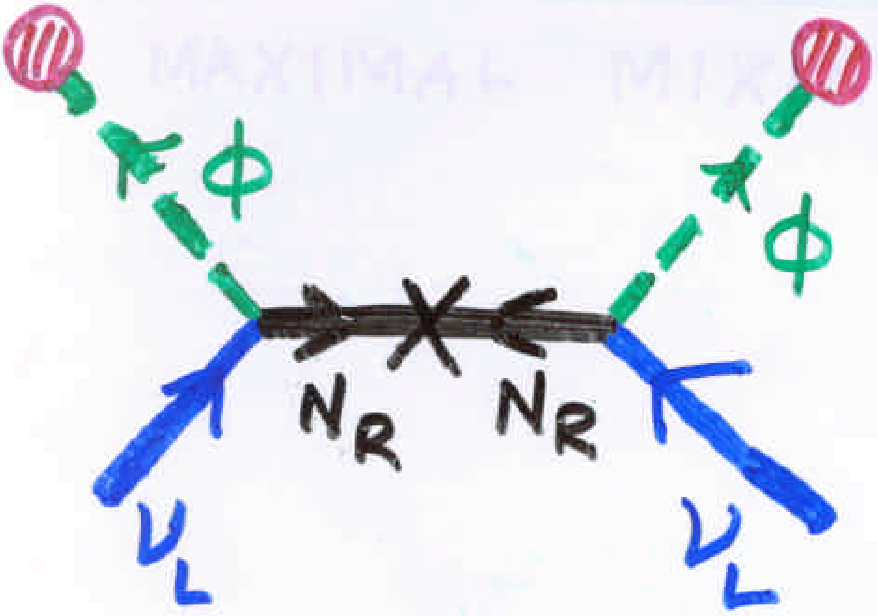
WEINBERG '79
(BARBIERI, ELLIS, GAILLARD '79)

ATMOSPHERIC DATA $\Rightarrow m_\nu \approx 0.05\,eV$

NEW PHYSICS AT INT. SCALE !

- INTRODUCE ν_R SUGGESTED BY QUARK-LEPTON SYM.
- GIVE IT A LARGE MAJORANA MAS

(NEW SCA



$$m_\nu \simeq M_{\nu D}^T \frac{1}{M_R} M_{\nu D} \ll m_{\ell,q,}$$

(FOR M_R

SEESAW MECHANISM: (TYPE I) $M_R \ll M_{P\ell}$ WHY LOCAL B

GELL-MANN, RAMOND, SLANSKY; YANAGIDA; R.N.M. SENJAN (197

(ii) WITH TRIPLET HIGGS

$$m_\nu \simeq \frac{v_{WK}^2}{M_{TRIPLET}}$$

$M_T \ll M_{Pl}$; WHY ??

WETTERICH; R.N.M., SENJANOVIĆ; SCHECTER, VALLE; (80-81)
MA, SARKAR (1998)

NEUTRINO MASS AND LEFT-RIGHT SYMMETRY.

x

SM + N_R → $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

MINIMAL ANOMALY FREE EW SYM.

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \begin{pmatrix} N_R \\ e_R \end{pmatrix}$$

LEFT-RIGHT SYM. PREDICTS LOCAL B-L SYM.

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

$\Rightarrow 2\Delta I_{3R} = |\Delta L| \Rightarrow$ MAJORANA NEUTRINO.

m_ν AND SPONTANEOUS BREAKING OF PARITY:

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

$\downarrow$ v_R (NEW SCAL

$$\begin{array}{cc} \nu_L & N_R \end{array}$$
$$\begin{pmatrix} 0 & 0 \\ 0 & f v_R \end{pmatrix}$$

$$SU(2)_L \times U(1)_Y$$

$\downarrow$ v_{wk}

$$U(1)_{em}$$

$$\begin{array}{cc} \nu_L & N_R \end{array}$$
$$\begin{pmatrix} f v_L & m_{\nu D} \\ m_{\nu D} & f v_R \end{pmatrix}$$

$$m_{\nu_D} \simeq h\, v_{wk} \ll f v_R$$

$$m_\nu = f \frac{v_{wk}^2}{v_R} - M_{\nu D}^T \frac{f^{-1}}{v_R} M_{\nu D}$$

(TYPE

PARITY SYM. $\Rightarrow$ BOTH TERMS

m_ν PROBES THE SCALE OF

W_R (PARITY BREAKING)

e.g.

ATMOS. $m_{\nu_\tau} \sim 10^{-1}\,eV$

(IF $m_{\nu_e} \ll m_{\nu_\mu} \ll m_{\nu_\tau}$)

$$M_{W_R} \gtrsim 10^{12} - 10^{14}\,GeV$$

FITS VERY WELL WITH:

(i) BARYOGENESIS VIA LEPTO GENESIS

FUKUGITA, YANAG

(DI BARI TAL

(ii) UNIFICATION OF GAUGE COUP

SUGGESTS SO(10) GUT

DOES SEESAW HELP IN DETAILED UNDERSTANDING OF WHAT WE KNOW ?

$$M_\nu = - M_D^T M_R^{-1} M_D$$

9 OBSERV. 9 + 9 PARAMETERS

MORE ASSUMPTIONS NEEDED !

- $SO(10) \Rightarrow$ QUARK-LEPTON UNIFICATION

$$\Rightarrow \quad M_D = M_u^{(0)} + O(\varepsilon).$$

- LEFT-RIGHT + SUSY

$$M_D = M_\ell^{(0)} + O(\varepsilon)$$

LOWEST ORDER

ONLY UNKNOWN M_R

$\Rightarrow$ 9 OBSERVABLES $\leftrightarrow$ 9 PARAMET

- M_ν DETERMINES M_R :
- THE HIGH SCALE PHYSICS MAY HELP US UNDERSTAN M_R AND HENCE M_ν
- $M_R \Rightarrow$ LEPTOGENESIS

CONSISTENCY BETWEEN LEPTOGENESIS AND ν - MIXIN

- SINGLE ν_R DOMINANCE (KING '9… KING, SIN…

SEESAW + $M_{N_3} \ll M_{N_2}$, $M_{N\ldots}$

$$\Rightarrow \mathcal{M}_\nu \simeq \frac{m_{D_3}^2}{M_{N_3}} |3\rangle\langle 3| + \cdots$$

$$|3\rangle = \begin{pmatrix} \varepsilon_\tau \\ \varepsilon_\mu \\ \varepsilon_e \end{pmatrix}$$

IF $\varepsilon_\tau \approx \varepsilon_\mu$; $\varepsilon_e \approx 0$ WHY

$\Rightarrow$ FITS ATMOSPH. MIXIN…

ONE LESSON :

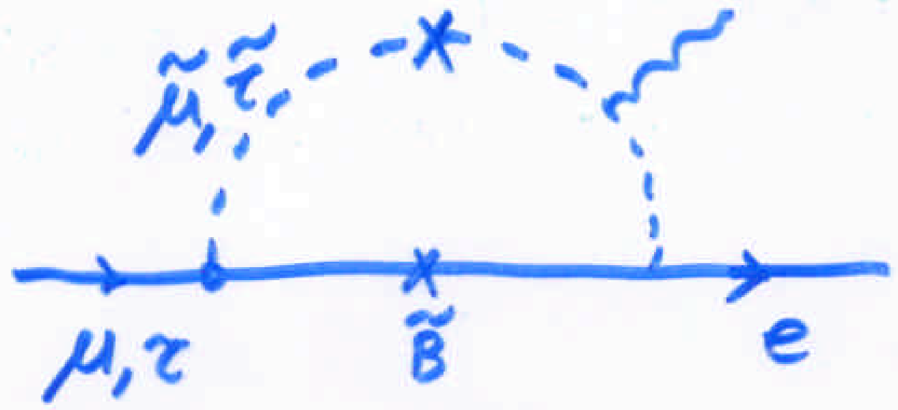
DATA REQUIRES LARGE DEPAR…
FROM QUARK-LEPTON UNIFIC…
WHICH PREDICTS $\varepsilon_\tau \gg \varepsilon_\mu \gg \varepsilon_e$

(iii) LEPTON FLAVOR VIOLATION PROBE OF NEUTRINO MIXINGS:

(MASINA'S T

$\theta_{ij}^{(\nu)}$ + SUSY + RGE

⇒ LEPTON FLAVOR VIOL



TWO CLASSES OF MODE

AND LFV OBSERVATIONS MAY THROW LIGHT ON THE ORIGIN OF M_R IN THE SEESAW:

$\underline{M_R}$: (i) $\frac{(L^c \chi^c)}{M_{Pl}}$ OR (ii) $L^c L^c \Delta$

(i)

$$W = h_\nu^{ij} L_i H_u \nu_j^c + M_R^d \nu^c \nu^c$$

$\nwarrow \frac{(L^c \chi^c}{M}$

$\Rightarrow$ BOTH $B(\tau \to \mu\gamma)$ AND

$B(\mu \to e\gamma)$ CAN BE LAR

HISANO, MOROI, KOBE, YAMAGUCHI '95 ;
ELLIS, HISANO, RAIDAL, SHIMIZU '02
PÄS, REDELBACH, RUCKL, SHIMIZU '02

$\frac{B(\tau \to \mu\gamma)}{B(\mu \to e\gamma)} \propto$

(ii) WITH MAJORANA-YUKAWA COUPL

$$W = h_\nu^d L H_u \nu^c + f^{ij} \nu^c \nu^c \Delta$$

$$M_R = f \langle \Delta \rangle$$

ONLY $B(\tau \to \mu\gamma)$ LARGE !!

BABU, DUTTA, R.N.M. '99.

$$\frac{B(\tau \to \mu\gamma)}{B(\mu \to e\gamma)} \propto \left(\frac{m_{D_3}}{m_{D_2}}\right)^6$$

UNDERSTANDING BIMAXIMAL MIXING FROM BOTTOM UP:

$\mathcal{M}_\nu$ (9 PARAMETERS

3 MASSES, 3 ANGLES, 3 PH

CP - CONSERVATION
+ BIMAXIMAL $\Rightarrow$ ONLY 3 PARAM

$$\mathcal{M}_\nu = \begin{pmatrix} C+D & F & F \\ F & C & D \\ F & D & C \end{pmatrix} + O(\varepsilon$$

R.N.M., NUSSINOV; ALTARELLI, FERUGLIO (98)

TWO LIMITS :

(i) $F \ll c, D$

NORMAL HIERARCHY

(NO APPARENT SYMMETRIES)

(ii) $F \gg c, D$

INVERTED HIERARCHY

(ii) INVERTED CASE AND LEPTONIC SYMMETRI

SET $C = D = 0$.

$$\Rightarrow \quad \mathcal{M}_\nu = \begin{pmatrix} 0 & m_1 & m_2 \\ m_1 & 0 & 0 \\ m_2 & 0 & 0 \end{pmatrix}$$

$$\Rightarrow \quad \tan\theta_A = \frac{m_1}{m_2}$$

$$\theta_\odot = \frac{\pi}{4}$$

$$\Delta m_A^2 = m_1^2 + m_2^2 \simeq 3\times$$

$$\Delta m_\odot^2 = 0. \quad \leftarrow$$

$$U_{e3} = 0$$

SYMMETRY : $L_e - L_\mu - L_\tau$

SMALL BREAKING OF $L_e - L_\mu - L_\tau$:

BABU, R.N.M '0
W/ GOH, NG '02

$$\Rightarrow \mathcal{M}_\nu^{(0)} + \mathcal{M}_\nu^{(1)} = \begin{pmatrix} \delta_1 & m & m \\ m & \delta_2 & \delta_4 \\ m & \delta_4 & \delta_3 \end{pmatrix}$$

$\delta_i \ll m$.

SUM RULES FOR δ_i ($\delta \lesssim \frac{m}{3}$

- $\sin^2 2\theta_\odot = 1 - \left(\frac{\Delta m_\odot^2}{4\Delta m_A^2} - \delta_1\right)^2 + O(\delta^3)$
- $\frac{\Delta m_\odot^2}{\Delta m_A^2} = 2\left(\delta_1 + \frac{\delta_2 + \delta_3}{2} + \delta_4\right) + O($
-
- $\sin^2 2\theta_{e\mu} \gtrsim .95$

WHAT IF $\sin^2 2\theta_{e\mu} < .95$

NOTE $U_{MNSP} = U_\ell^{+} U_\nu$

$\Rightarrow$ $L_e - L_\mu - L_\tau$ BREAKING IN (e, μ, τ) SECTOR !!

EXAMPLE: $\mathcal{M}_\ell = m_\tau \begin{pmatrix} 0 & 0 & x \\ 0 & y & 0 \\ x' & 0 & 1 \end{pmatrix}$

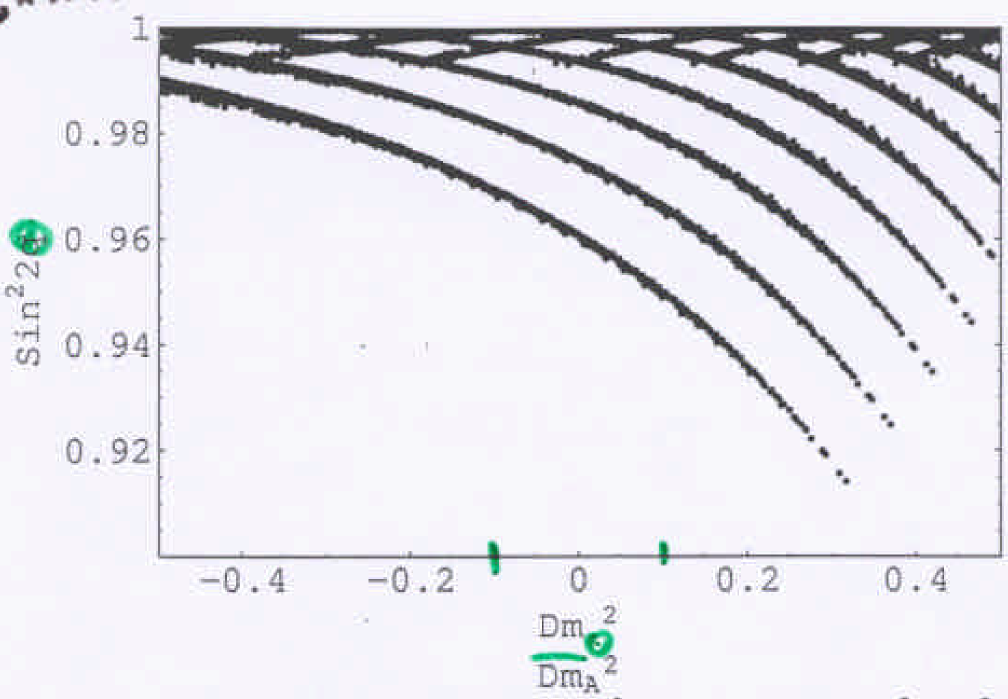
$\Rightarrow$ RGE'S CHANGE $\mathcal{M}_\nu$

- LOWER $\sin^2 2\theta_\odot$

e.g. $\sin^2 2\theta_\odot \gtrsim .85$ FOR $U_{e3} \lesssim .1$

LEADS TO OBSERVABLE $\tau \to e\gamma$.

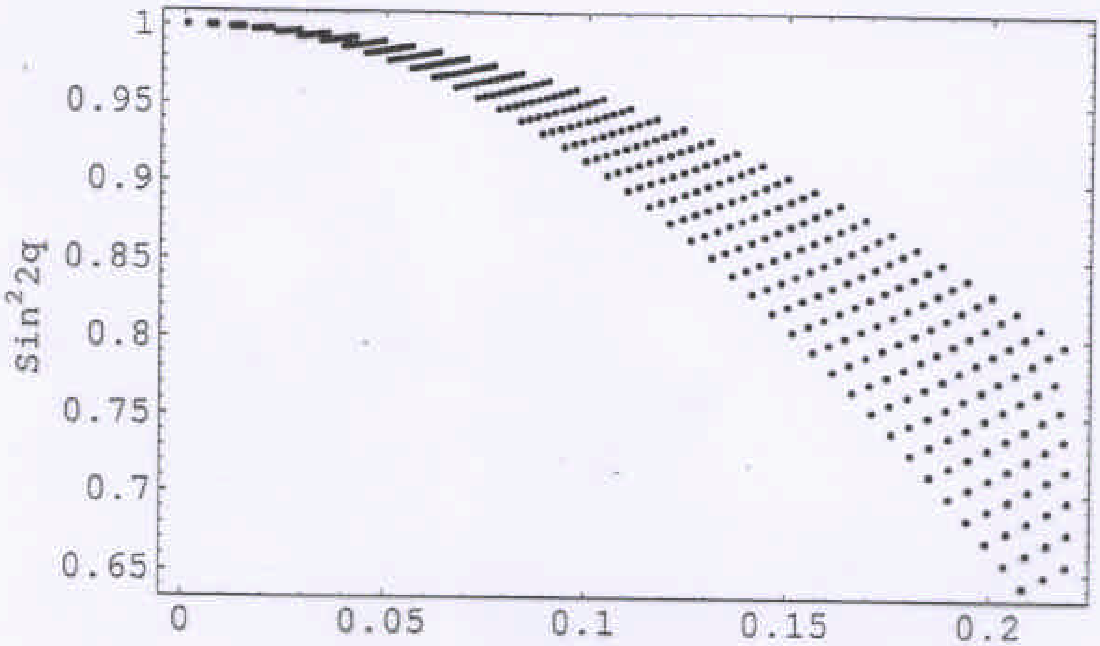
GOH, NG, R.N.M '02



SYM. BR. IN M

FIG. 1. The figure shows the predictions for $sin^2 2\theta_\odot$ as a function $\Delta m^2_\odot/\Delta m^2_A$ for different values for the symmetry breaking parameters. The left most line corresponds to $z = -0.2$ and the right most (only partially visible) to $z = 0.16$. The thickness of the individual lines reflect the higher order contributions.

$\sin^2 2\theta_\odot \gtrsim 0.95$ ±0.



SY BR. IN M

FIG. 3. This figure shows the correlation between U_{e3} and $sin^2 2\theta_\odot$ for the model where $L_e - L_\mu - L_\tau$ symmetry is broken by the charged lepton sector. Note that present upper limit of 0.22 corresponds to a minimum value of $sin^2 2\theta_\odot \geq 0.80$ and $U_{e3} \leq 0.16$ corresponds to $sin^2 2\theta_\odot \geq 0.90$. The different lines in the figure correspond to various values for the $sin^2 2\theta_A$ with the rightmost line corresponding to the maximal value of 1. The lines in this figure correspond to the following relation between U_{e3} and $sin^2 2\theta_\odot$ i.e. $sin^2 2\theta_\odot = \left[1 - \frac{1+cos^2 2\theta_A}{sin^2 \theta_A} U^2_{e3}\right]^2 / \left(1 - U^2_{e3}\right)^2$.

KAMLAND ⇒ $\sin^2 2\theta_{\odot} \lesssim .91$

(3σ)

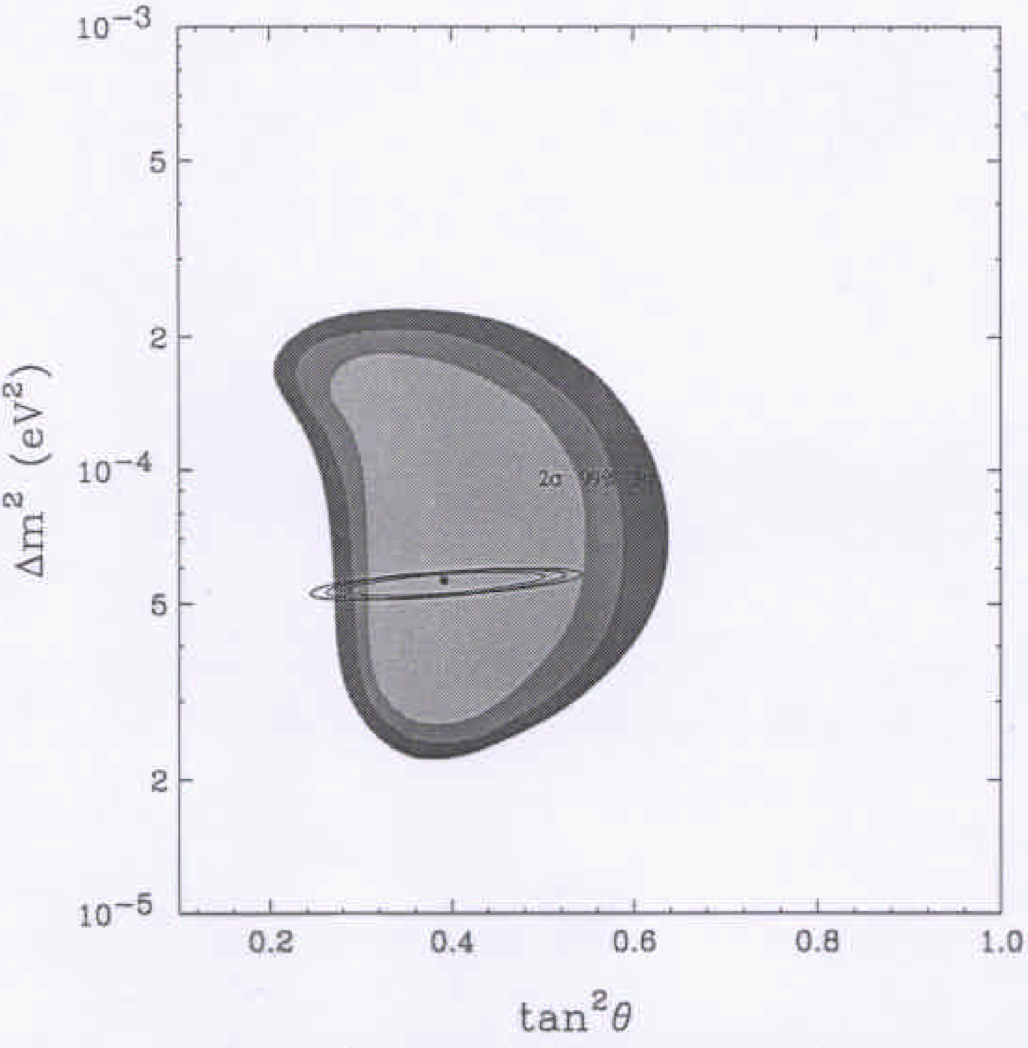


FIG. 4. Projection of how well KamLAND will determine the oscillation parameters with three years of data accumulation assuming an LMA solution. Data were simulated at the best-fit LMA parameters. The ellipses are the 2σ, 99% C.L. and 3σ KamLAND regions.

CONSEQUENCES OF EMBEDDIN[G] $L_e - L_\mu - L_\tau$ INTO COMPLETE Q-L[EPTON] SYM. SEESAW MODEL

SEESAW: $\mathcal{M}_\nu = - M_{\nu D} M_R^{-1} M_{\nu[D]}^T$

$L_e - L_\mu - L_\tau \Rightarrow \text{Det } \mathcal{M}_\nu = \text{Det } M_R = [0]$

CONSISTENCY $\Rightarrow \text{Det } M_{\nu D} = 0$

$\Rightarrow$ ONE ν_R HAS ZERO MASS.

(R.N.M[...]

- COULD THIS ν_R BE THE ULTRA-LIGHT ν_s ?

COULD CHARGED LEPTONS BE PLAYING A DOMINANT ROLE?

EX. 1. FRITZSCH, XING '97

$$M_\ell^{(0)} = \begin{pmatrix} a & 1 & 1 \\ 1 & a & 1 \\ 1 & 1 & a \end{pmatrix}$$

S_3 SY

$$U_{PMNS} \approx U_\ell^{+}$$

$$\Rightarrow \quad m_e^{(0)} = m_\mu^{(0)} \quad \Rightarrow \quad (?)$$

EX. 2: JEZABEK '02 ; JEZABEK, URBAN '02 .

SEESAW + $M_R = \mathbb{1} M$

$$\Rightarrow \quad m_\nu = - U_L D U_R^T U_R D U_L^T$$

$U_R^T U_R$ + HELP FROM U_ℓ

EX. 3: LOPSIDED MODELS

ALBRIGHT, BABU, BARR ; ...

CP-VIOLATION IN THE ν'SECTOR:

IMPORTANT ISSUE BUT
VERY LITTLE KNOWN !!

BARYOGENESIS VIA LEPTOGENESI

$\Rightarrow$ THERE MUST BE ~~CP~~ IN
ν - MASS.

BUCHMULLER, PLU
BRANCO et. al.
W. RODEJOHANN, JO
PR

3-ν CASE : 3 PHASES :

- $\beta\beta_{0\nu} \rightarrow \sum U_{ei}^2 m_i$ 1-PHAS
- LBL, MATTER EFFECT $\rightarrow$ SECOND PHASE !

<u>NOTE</u>: $J_{CKM} \approx 10^{-5}$ WHEREAS $J_\nu < 2\times$

LARGE EXTRA DIM. AND

- LOW STRING SCALE

  $M_* \sim$ few TeV's

- ONE OR TWO LARGE EXTRA D : $R \sim$ mm.

SEESAW DOES NOT WORK !

HOW TO UNDERSTAND SMALL m_ν ?

SMALL m_ν IN EXTRA DIM. MODELS

MINIMAL MODEL :

STD MODEL IN BRANE

\+ ν_B IN BULK :

$$\mathcal{L}_{eff} = \frac{1}{M_*^{n/2}} \int d^n y \, \delta(\vec{y}) \, h L H \nu_B(x,y)$$

$$\Rightarrow m_\nu \simeq \frac{h \, v_{wk}}{(M_* R)^{n/2}} \simeq \frac{h \, v_{wk} M_*}{M_{Pl}}$$

DIENES, DUDAS, GHERGHETTA

ARKANI-HAMED, DIMOPOULOS, DVALI

MARCH-RUSSELL

TOO LARGE m_ν FROM $(LH)^2/M_*$?

PHENOMENOLOGY :

MINIMAL MODEL: R.N.M., PEREZ-LORENZAN

$1\ \nu_B$ /FAMILY. DAVUDIASL, LANGACKER, PERE

BARBIERI, CREMINELLI, STRUMI

7- PARAMETER THEORY

3 masses m_1, m_2, m_3

3 MIXING ANGLES

R

SNO, ATMOSPH. ⇒

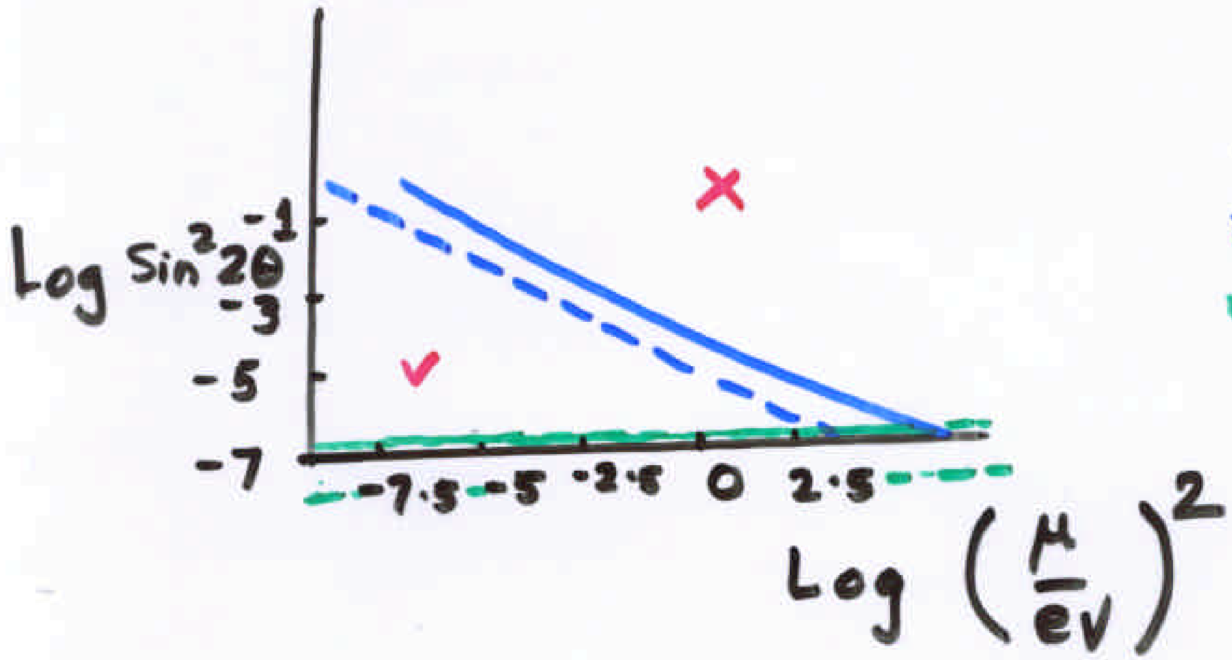
$$\sqrt{2}\, m_i R \ll 1$$

ATMOSPH. ⇒ $m_3 \simeq .05\,\text{eV}$

⇒
- $M_* \gtrsim 550$ TeV
- CANNOT EXPLAIN LSND
- $R^{-1} \gtrsim .5\,\text{eV}$

BBN CONSTRAINTS ON $R^{-1} (\equiv \mu)$ AND $\theta_{\nu_e \nu_{KK}}$ IN XTRA-D MODELS

ABBAJIAN, FULLER, PATE[L] '0[0]
GOH, R.N.M. '01



$n=1$
$n=2$

MINIMAL MODEL:

$$3\nu_\alpha + 3\nu_B \Rightarrow \mu\,\theta_\alpha \approx m_\alpha$$

$$\mu \sin^2 2\theta \lesssim 4\times10^{-4}\,eV$$

$$\Rightarrow R^{-1} \gtrsim 4\ eV$$

$R \lesssim .05$ microns

POSSIBLE WAY AROUND THIS

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ IN 5D
(OR 6

HIGGS: $\phi\,(2,2,0)$

$\chi_L(2,1,1) \oplus \chi_R(1,2$

TAKE $S_1/Z_2 \times Z_2'$ $\chi_L\begin{pmatrix} + & - \\ + & - \end{pmatrix}$

$\chi_R\begin{pmatrix} + & - \\ + & + \end{pmatrix}$

$\phi\begin{pmatrix} ++ & +- \\ ++ & +- \end{pmatrix}$

- $(L\phi)^2$ FORBIDDEN BY B-L
- $(L\chi_L)^2$ ABSENT AT $y=0$ BR

LOWEST ORDER OPERATOR: $\dfrac{(L\phi\chi_R)^2}{M_*^5}$ $\Rightarrow$ $m_\nu \sim 1$

(R.N.M., PEREZ-LORENZANA '02) (NO ν_B) FOR $M_* = 10$

OTHER ISSUES:

(i) STRING U(1)-SYM. APPROA TO MIXINGS:

- ASSIGN U(1)-CHARGES TO Q, L, N & CONSTRAIN MASS MATRICES.

BINETRUY, LAVIGNAC, RAMOND; BEREZHIANI, TAVARTKILIDZE; NIELSEN, TAKANISHI; KING, SINGH; TANIMOTO; BANDO, MAEKAWA;

(ii) RADIATIVE EFFECTS (RGE) FROM SEESAW TO WEAK SC

- CAN DESTABILIZE MASS PATTERN OR CAN GENERATE LARGE MIXI FROM SMALL ONES.

BABU, LEUNG, PANTALEONE; CHANKOWSKI, PLUCINIEK; ELLIS, LOL HABA, MATSUI, OKAMURA, SUGIMURA; CASAS, ESPINOSA, IBARRA, NA BALAJI, DIGHE, PARIDA, R.N.M.; KUO, PANTALEONE, WU; ANTU KERSTEN, LINDNER, RATZ; POKORSKI, VALLE.

ISSUES THAT WILL BE SETTLED SOON:

(i) KAMLAND ⇒ LMA
VRS
LOW OR ....

(ii) MINI BOONE ⇒
LSND, ν_s etc.

IMPORTANT ISSUES FOR FUTU

(i) U_{e3} (NUMI OFFAXIS, JHF→ ν-FACTO

(ii) INVERTED OR NORMAL ↑ HIERA

(iii) ABSOLUTE SCALE $\beta\beta_{0\nu}$ DEC
(GENIUS, EXO, MAJORANA, MOON, ...)

(iv) CP VIOLATION

CONCLUSION

(ii) WHAT DOES M_ν TELL US ABOUT PHYSICS BEYOND SM

A) LOCAL B-L SYM ; PERHAP[S] LEFT-RIGHT SYM. WITH SUSY BEYOND MSSM.

B) SEESAW + ASSUMPTION[S]

$\Rightarrow M_R$

LOW SCALE PHYSICS $\Rightarrow$ HIGH SCALE PH[YSICS]

(i) UNDERSTANDING MIXINGS

LEPTONIC SYM. MAY BE HELPF[UL]

$(L_e - L_\mu - L_\tau)$

- LEPTON FLAVOR VIOLATION AS A PROB
OF THE ORIGIN
OF SEESAW

HI SCALE ↔ LO SCALE CONNECTIO