NEUTRINO MASSES AND SUPERSYMMETRIC GRAND UNIFICATION

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R.N. MOHAPATRA

- HOW TO UNDERSTAND WHAT IS OBSERVED ABOUT NEUTRINOS
- WHAT DOES IT TELL US ABOUT PHYSICS BEYOND THE STD MODEL

EVIDENCES FOR $m_\nu \neq 0$

- SOLAR + ATMOSPHERIC
  KAMLAND + K2K
  $\Rightarrow \quad m_\nu \neq 0 \quad \& \quad \theta_{\alpha i} \neq 0$.

- $\boxed{\text{MIXING MATRIX}}$ (IN THE BASIS WHERE e, μ, τ MASS EIGENSTATES)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\alpha i} \approx \begin{pmatrix} c & s & \varepsilon \\ -\frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \qquad S^2_{2\theta} \approx .8 - .9$$

$\sin^2 2\theta_\odot \approx .8 - 1$; $\sin^2 2\theta_A \approx .85 - 1$

$$U_{e3} \equiv \varepsilon \leq .16 - .2$$

- $m_\nu \lesssim eV$

ν-MASS PATTERN

UNKNOWN AND IS AN IMPORTANT SOUGHT AFTER ITEM !!

POSSIBILITIES:

(i) NORMAL :

$$m_1 \ll m_2 \ll m_3$$

$\Rightarrow$ $m_3 \simeq .05\,eV$; $m_2 \simeq .009 - .006\,eV$

$0 \leq m_1 \leq .005\,eV$

(ii) INVERTED :

$$m_1 \simeq m_2 \simeq .05\,eV \gg m_3$$

(iii) DEG. $m_1 \simeq m_2 \simeq m_3$

WMAP $\Rightarrow$ $m_i \lesssim .23 - .7\,eV$

- $\boxed{\nu\text{-MASSES}}$:

$$\Delta m^2_{\odot} \approx 3\text{-}8 \times 10^{-5}\, eV^2$$

$$\Delta m^2_A \approx 2.5 \times 10^{-3}\, eV^2$$

$$\Rightarrow \quad \frac{\Delta m^2_{\odot}}{\Delta m^2_A} \simeq \text{few } \%.$$

- TRITIUM DECAY $\leq 2.2\, eV$

- $\beta\beta_{0\nu}$ DECAY

$$^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}$$
$$\rightarrow {}^{76}Se + 2e^-$$

HEIDELBERG-MOSCOW (KLAPDOR-K et.
IGEX (MORALES et. al.)

$$\sum_i U^2_{ei}\, m_i \leq .3\ eV$$

CHALLENGES FOR THEORY:

(i) WHY $m_{\nu_i} \ll m_\ell, m_u, m_d$

(ii) WHY θ^{ν}_{ij} SO DIFF. FROM θ_{CKM}. ?

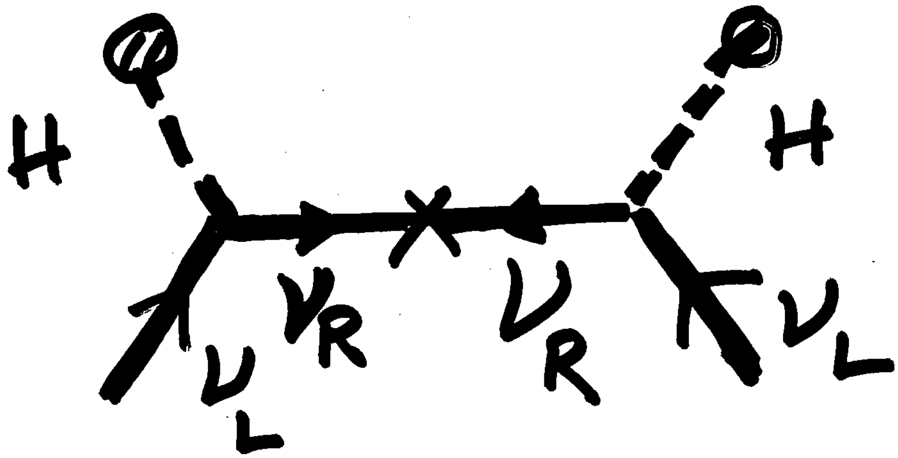
(iii) WHY $\dfrac{\Delta m^2_{\odot}}{\Delta m^2_A} \ll 1$?

(iv) HOW DOES ν-MASS PHYSICS FIT INTO THE BROAD FRAMEWORK OF OTHER PHYSICS e.g. SUSY GUTS, INFLATION, BARYOGENESIS etc.

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

SEESAW MECHANISM:

STD MODEL + ν_R



$$m_\nu \simeq - M_{\nu D} \cdot M_R^{-1} M_{\nu D}^T$$

GELL-MANN, RAMOND, SLAŃSK
YANAGIDA
R. N. M., SENJANOVIĆ, 7

$$M_R \gg M_W \sim M_{\nu D}$$

$$\Rightarrow \quad m_\nu \ll m_{e,u,d}.$$

RAISES TWO QUESTION

(i) IS THERE AN INDEPENDENT ARGUMENT FOR ν_R ?

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(i) LEFT-RIGHT SYM., ('74)
SO(10) etc ('74)

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \xleftrightarrow[\text{PARITY}]{} \begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$\Rightarrow$ ν_R /GEN. $\Rightarrow$ 3×3 SEESAW.

(ii) $SU(2)_{\text{HORIZONTAL}}$:

$$\begin{pmatrix} \nu_{eL} & \nu_{\mu L} \\ e_L & \mu_L \end{pmatrix} \quad (e_R, \mu_R)$$

$$\longleftrightarrow \; SU(2)_H \; \longleftrightarrow$$

GLOBAL WITTEN ANOMALY $\Rightarrow$ $(\nu_{eR}, \nu_{\mu R})$
KUCHIMANCHI, R.N.M. (2002)
$\Rightarrow$ 3×2 SEESAW

(iii) $SU(3)_{\text{HOR.}}$ $\Rightarrow$ $(\nu_{eR}, \nu_{\mu R}, \nu_{\tau R})$
KRIBS, (2003).

$$\sqrt{\Delta m_A^2} \simeq .05\,\mathrm{eV}$$

SEESAW $\Rightarrow$ $M_R \leq 10^{15}\,\mathrm{GeV}$

$\ll M_{Pl}$

2. WHAT PROTECTS M_R FROM BEING EQUAL TO M_{Pl} ?

LOCAL SYM :

(i) B-L

(ii) $SU(2)_H$

(iii) $SU(3)_H$

IS IT POSSIBLE TO DISTINGUISH BETWEEN THEM?

A. NATURE OF SEESAW

TYPE I:

$$\mathcal{M}_\nu \simeq - M_{\nu D} M_R^{-1} M_{\nu D}^T$$

(IN THEORIES WITHOUT PARITY)
$SU(2)_H, SU(3)_H$

TYPE II

$$\mathcal{M}_\nu \simeq f \frac{v_{wk}^2}{v_R} - M_{\nu D} \frac{1}{f v_R} M_{\nu D}^T$$

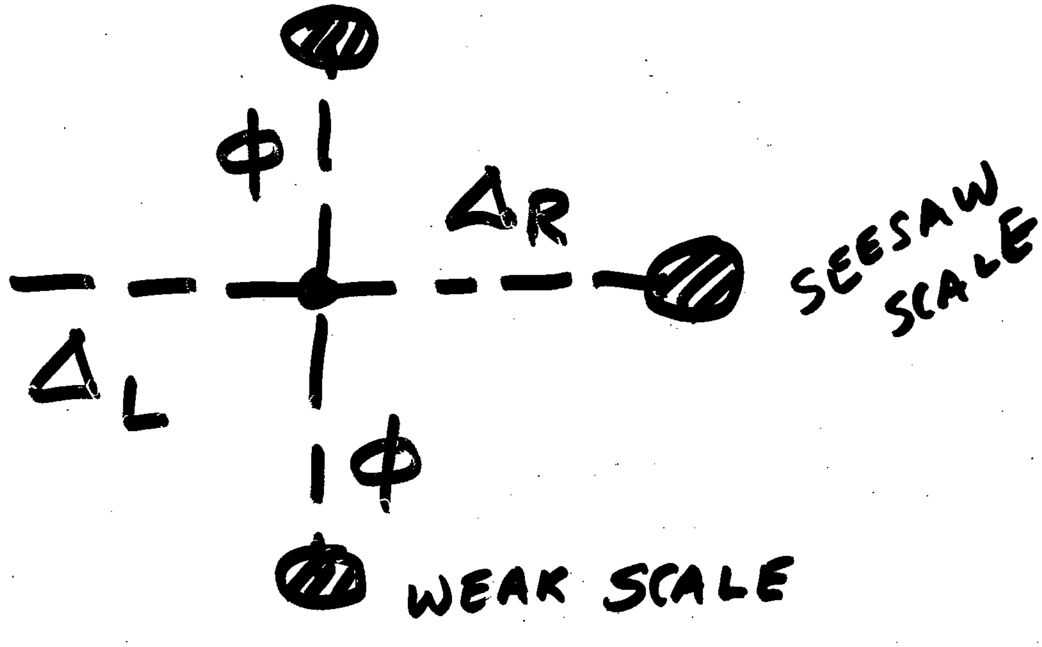
(THEORIES WITH PARITY
e.g. LR, SO(10), E_6 ...).

PARITY

$$\nu_R \nu_R \Delta_R + \nu_L \nu_L \Delta_L$$

$$\langle \Delta_R \rangle \neq 0^{\,B-L=+2} \Longrightarrow M_{\nu_R}$$

HIGGS POT. TERMS



R.N.M. SENJANOVIĆ '80

$$\Downarrow \langle \Delta_L \rangle \neq 0 \equiv \frac{\langle \phi \rangle^2}{V_R}$$

→ TYPE II SEESAW

ALSO WORKS FOR DOUBLET HIGGS.

b) $SU(2)_H$ SYMMETRY $\Rightarrow$

INVERTED HIERARCHY

<u>WHEREAS</u> $\underset{\times}{SO(10)} \Rightarrow$ <u>NORMAL H.</u>

$SU(2)_H$ ON 1st AND 2nd GEN:

e.g. $(L_e, L_\mu) \quad L_\tau$

$(e_R, \mu_R) \quad \tau_R$

$\Rightarrow$ GLOBAL WITTEN ANOMALY

$\pi_4(SU(2)) = Z_2$

$\Rightarrow$ THERE MUST BE A

$(N_{eR}, N_{\mu R})$ TO MAKE TH[E] ANOMALY FR[EE]

$\Rightarrow$ 3 X 2 SEESAW

IMPLICATIONS FOR ν-MASS

$$SU(2)_H \supset U(1)_{e-\mu}$$

$$\Big\downarrow \text{SYM. BR.}$$

APPROX. $L_e - L_\mu - L_\tau$ SYM.

$$M_{\nu D} = \begin{pmatrix} a & 0 \\ 0 & a \\ 0 & b \end{pmatrix} ; \quad M_{N_R} = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}$$

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

$$\Rightarrow \text{(i)} \quad \mathcal{M}_\ell = \begin{pmatrix} a & 0 & e \\ 0 & a & f \\ -\alpha f & \alpha e & d \end{pmatrix}$$

$$\Rightarrow \quad \boxed{\theta_\odot \approx \frac{\pi}{4} - U_{e3}} \quad \text{LARGE } U_{e3} \text{ !!}$$

DUTTA, R.N.M
'03

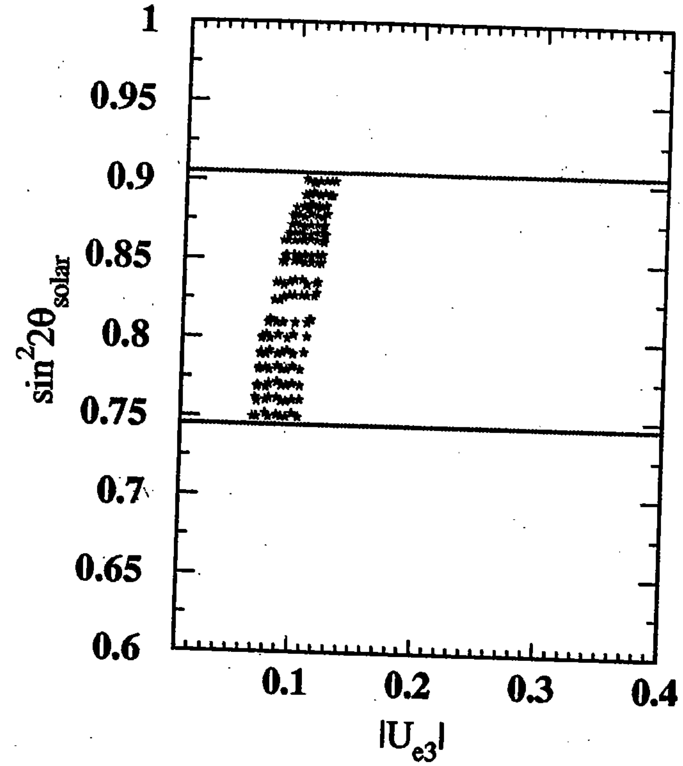


FIG. 2: $sin^2 2\theta_\odot$ vs $|U_{e3}|$. The stars show the model points. The horizontal solid lines show the current experimental limits.

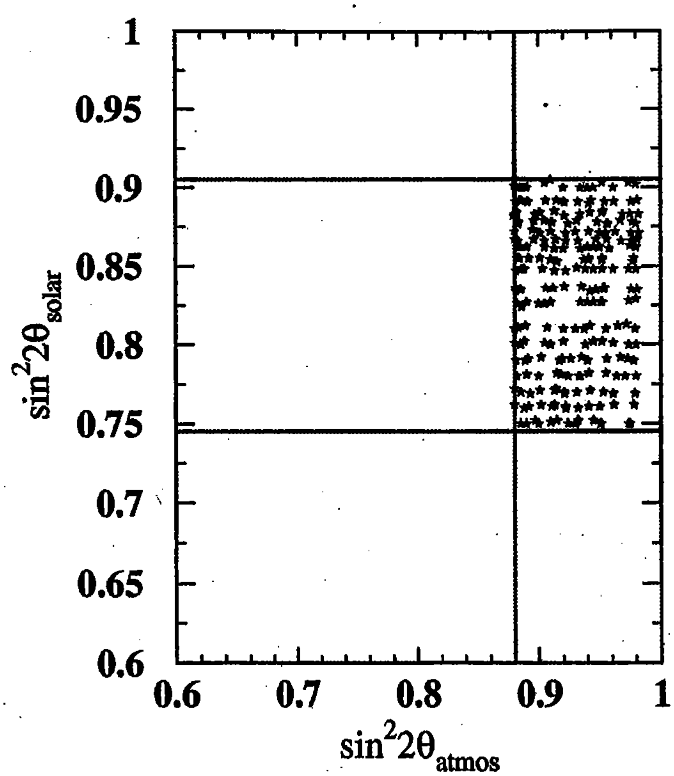


FIG. 1: $sin^2 2\theta_\odot$ vs $sin^2 2\theta_{\rm atmos}$. The stars show the model points. The horizontal and vertical solid lines show the current experimental limits.

SEESAW AND SUSY GRAND UNIFICATION

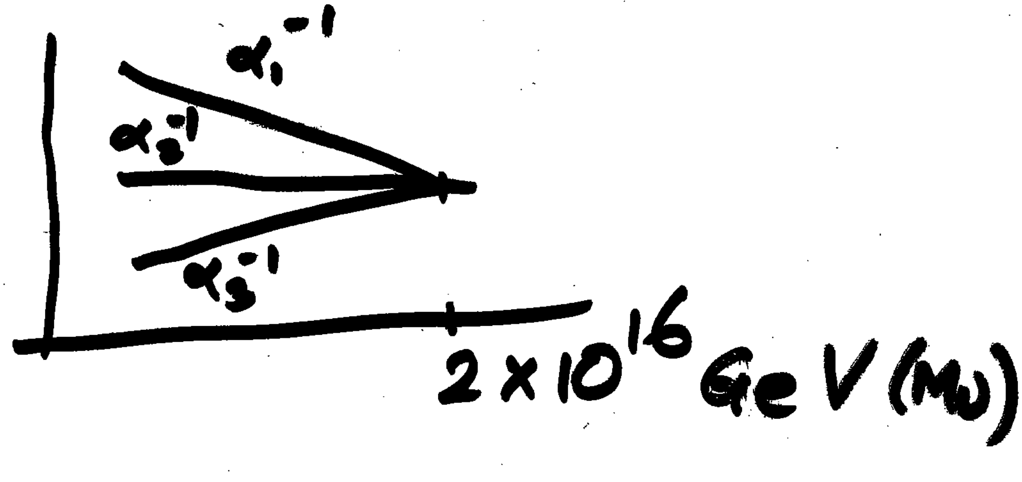
WHY?

$$m_{\nu_\tau} \simeq \sqrt{\Delta m^2_{ATM}} \simeq \frac{m^2_{\nu_3 D}}{M_R} \simeq .05\ eV$$

$$m_{\nu_3 D} \lesssim 200\ GeV \Rightarrow M_R \lesssim 10^{15}\ GeV$$

COUPLING UNIFICATION:

SUSY ~ TeV



ARCIANO, SENJANOVIĆ
LANGACKER, LUO
AMALDI et. al.
ELLIS et. al.

$$\Rightarrow \quad M_R \sim M_U$$

CONNECTION OF SUSY TO ν - PHYSICS

SUSY $\quad F \leftrightarrow \tilde{F}$

R-PARITY $\quad +1 \quad\quad -1$

- EXACT R-P $\Rightarrow$ STABLE DM
- MSSM WITHOUT R-P

$\Rightarrow$ RAPID PROTON DECAY.

CURE:

$$R\text{-}P = (-1)^{3(B-L)+2S}$$

$$\Delta(B-L) = 0 \ (\mathrm{MOD}\ 2)$$

$\Rightarrow$ EXACT R-P.

$$\text{MSSM} \xrightarrow[\mu \gg M_{SUSY}]{} \text{TH. WITH } B-L$$

$$\boxed{m_\nu \Leftarrow (B-L) \Rightarrow \text{SUSY}}$$

SO(10) AND m_ν

(i) $\nu_R \subset \{16\}_F : \begin{pmatrix} u \\ d \end{pmatrix}_{i, {}^L_R} \begin{pmatrix} \nu \\ e \end{pmatrix}_{{}^L_R}$.

(ii) $U(1)_{B-L} \subset SO(10)$

- ALL INGREDIENTS FOR SEESA[W]
AND "NATURAL" MSSM •

TWO WAYS TO BREAK B-L:

$16_H \supset \tilde{\nu}_{R,H} \Rightarrow \langle \tilde{\nu}_{R,H} \rangle \neq$[0]

(ALBRIGHT, BARR)
BABU, PATI, WILCZEK

B-L=1

$(126)_H \supset \Phi_{\nu_R \nu_R}$

B-L=2

$\{16\}_H$ BREAKS R_P $\left(\psi_m^3 \psi_H / M_{Pl} \ldots\right.$

WHEREAS

$\{126\}_H$ GUARANTEES EXACT R-PARITY !!

$$\because \quad R = (-1)^{3(B-L)+2S}$$

$\langle 126_H \rangle \neq 0$ BREAKS B-L BY 2 UNIT
$\Rightarrow$ R-PARITY IS A GOOD SYM. OF LOW ENERGY THEORY.

PARAMETER COUNTING AND MINIMAL SO(10)

OBSERVABLES: $m_{u,c,t}$; $m_{d,s,b}$; $m_{e,\mu,\tau}$
θ_{ij} ; $\Delta m^2_{A,\odot}$, θ^{ν}_{ij}

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THEORY	# OF PARAMETERS	# OF PREDICTIONS
1. MINIMAL SU(5)	9	6 ⇒ $m_{\nu_i} = 0$; $m_{d_i} = m_{\ell_i}$
2. SO(10) WITH $\{10\}_H$ $\{126\}_H$	12	5 $\Delta m^2_{\odot, A}$ θ^{ν}_{ij}
3. SO(10) WITH $2\{10\}_H + \{126\}_H$	20	
4. SO(10) WITH $\{10\}_H + \{16_H\}$	30	(NEED EXT SYM. TO PREDICT
5. SO(10) " $2\{10\} + \{16\}_H$	32	"

A MINIMAL SO(10) EXAMPLE

BABU, R.N.M. '92

MINIMAL HIGGS: $\{10\}$ $\{\overline{126}\}$

(WITH STABLE DARK MATTER)

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

$$\Rightarrow M_u = h\langle 10\rangle_u + f\langle\overline{126}\rangle_u$$

$$M_d = h\langle 10\rangle_d + f\langle\overline{126}\rangle_d$$

$$M_\ell = h\langle 10\rangle_d - 3f\langle\overline{126}\rangle_d$$

$$M_{\nu D} = h\langle 10\rangle_u - 3f\langle\overline{126}\rangle_u$$

$$M_\nu = f\langle 126\rangle_{LL} - M_{\nu D}(fV_R)^{-1} M_{\nu D}^T$$

BOTH $M_{\nu D}$ AND $M_{N_R}(= f V_R)$

FLAVOR STRUCTURE PREDICTED!

TYPE II SEESAW AND A SUMRULE FOR M_ν:

IF $\quad M_\nu = f \langle 126 \rangle_{LL} + \text{SMA}$

$$\Rightarrow \quad M_\nu \simeq c(M_d - M_\ell)$$

A NEW WAY TO UNDERSTAND LARGE MIXINGS

$$M_d = m_b \begin{pmatrix} \lambda^2 & \lambda^2 \\ \lambda^2 & 1 \end{pmatrix}$$

$\lambda \sim .22$

$$M_\ell = m_\tau \begin{pmatrix} \lambda^2 & \lambda^2 \\ \lambda^2 & 1 \end{pmatrix}$$

HJC, SENJANOVIĆ, VISSANI '02

SUM RULE

$$\boxed{M_\nu = c\,(M_d - M_\ell)}$$

$\Rightarrow$ $M_{\nu,33} \simeq m_b - m_\tau$

PHENOMENOLOGICALLY WE KNOW:

MSSM

$$m_b(M_U) = m_\tau(M_U) + \varepsilon$$

$$\varepsilon \approx -.09 \text{ to } .2$$

$$\Rightarrow \quad M_\nu = c\,(M_d - M_\ell)$$

$$= c \begin{pmatrix} \lambda^2 & \lambda^2 \\ \lambda^2 & \lambda^2 \end{pmatrix}$$

$$\Rightarrow \quad m_2 \ll m_3 \approx \lambda^2$$

θ_{23} LARGE.

DOES IT WORK FOR 3-GENERATIONS ?

GOH, R.N.M., NG
hep-ph/0303055

TYPICAL M_d & M_ℓ : $(\lambda \equiv .22)$

$$M_{d,\ell} = m_{b,\tau} \begin{pmatrix} \lambda^3 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\Rightarrow \theta^q_{12} \sim \lambda; \ \theta^q_{23} \sim \lambda^2; \ \theta^q_{13} \sim \lambda^3.$$

$$M_\nu = c \left(M_d - M_\ell \right)$$

$$M_\nu \simeq c \begin{pmatrix} \lambda^3 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}$$

$\Rightarrow$ <u>θ_{12}, θ_{23} LARGE;</u> $m_1 \lesssim m_2 \ll m_3$.

GUT SCALE VALUES:

DAS, PARIDA
hep-ph/0010004

input observable	$tan\beta = 10$
m_u (MeV)	$0.7238^{+0.1365}_{-0.1467}$
m_c(MeV)	$210.3273^{+19.0036}_{-21.2264}$
m_t(GeV)	$82.4333^{+30.2676}_{-14.7686}$
m_d (MeV)	$1.5036^{+0.4235}_{-0.2304}$
m_s (MeV)	$29.9454^{+4.3001}_{-4.5444}$
m_b (GeV)	$1.0636^{+0.1414}_{-0.0865}$
m_e (MeV)	0.3585
m_μ(MeV)	$75.6715^{+0.0578}_{-0.0501}$
m_τ (GeV)	$1.2922^{+0.0013}_{-0.0012}$

INPUT

$$V_{CKM} = \begin{pmatrix} 0.974836 & 0.222899 & -0.00319129 \\ -0.222638 & 0.974217 & 0.0365224 \\ 0.0112498 & -0.0348928 & 0.999328 \end{pmatrix}$$

FITS TO $m_{e,\mu,\tau} \Rightarrow r, k$

$m_{s,d,c} < 0$

$-.78 \leq r \leq -.74$

$.23 \leq k \leq .26$

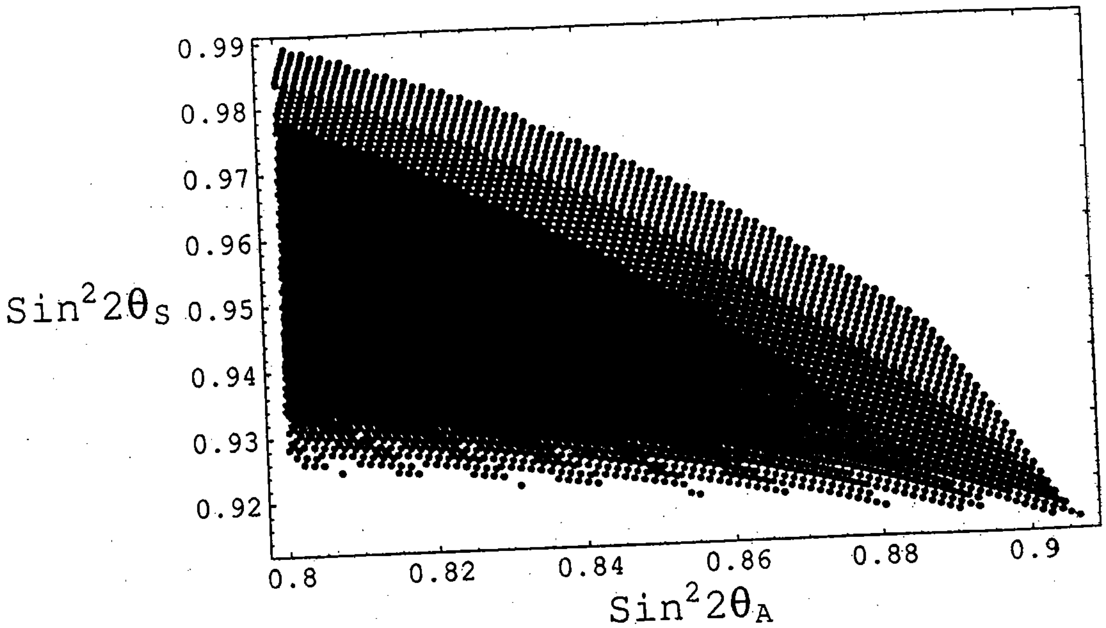


FIG. 1. The figure shows the predictions for $sin^2 2\theta_\odot$ and $sin^2 2\theta_A$ for the range of quark masses in table I. Note that $sin^2 2\theta_\odot \geq 0.9$ and $sin^2 2\theta_A \leq 0.9$

ALLOWED $Sin^2 2\theta_A$: .84 – 1 99% C.L

K2K, SUPER-K, COMBINED. FOGLI et. al.

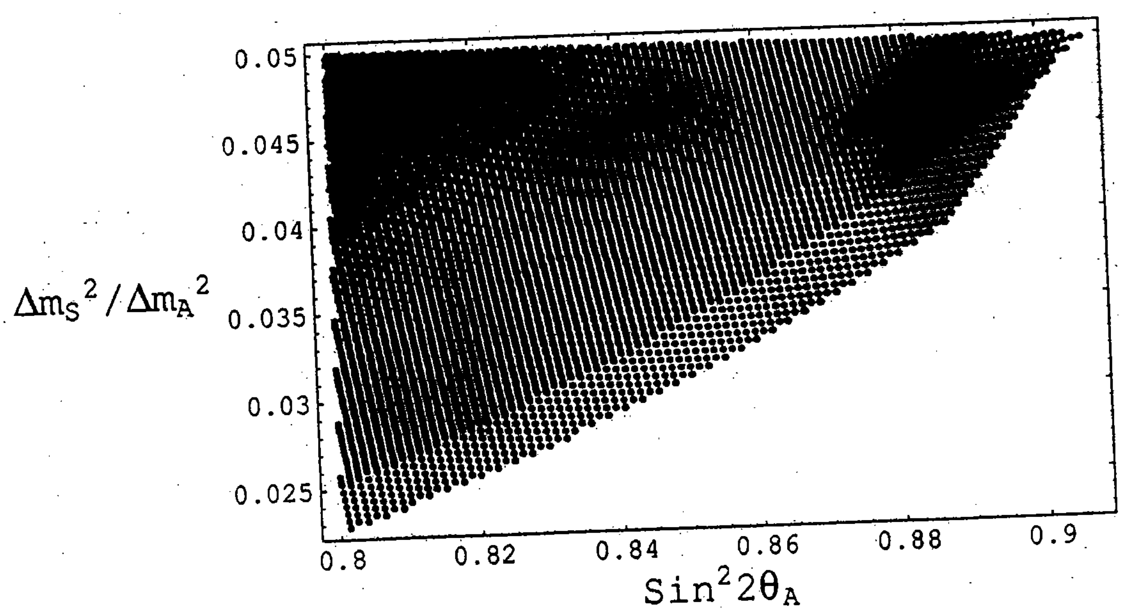
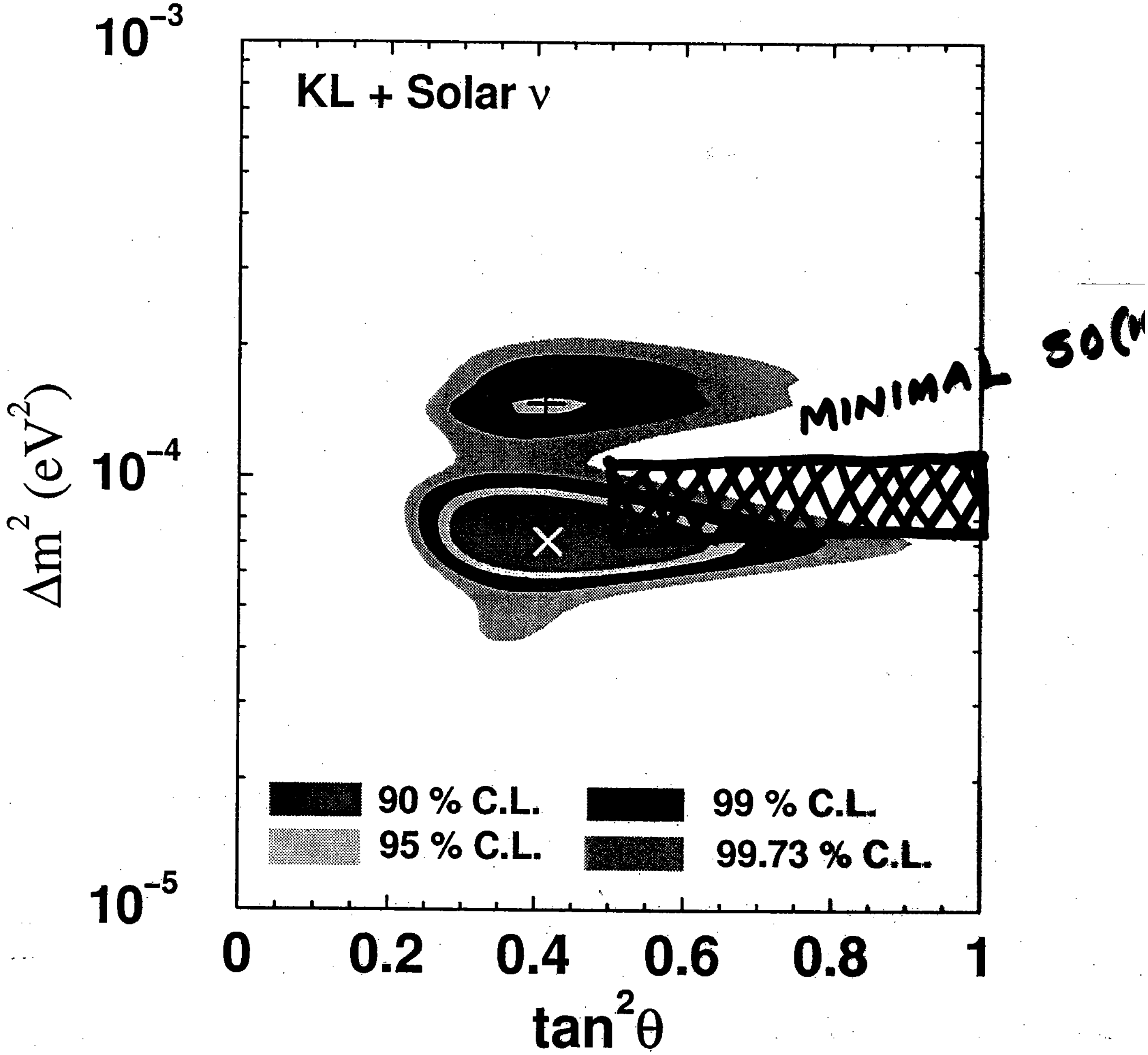


FIG. 2. The figure shows the predictions for $sin^2 2\theta_A$ and $\Delta m^2_\odot/\Delta m^2_A$ for the range of quark masses and mixings that fit charged lepton masses.

GONZALES-GARCIA et. al
DE HOLANDA, SMIRNOV,
VALLE et. al.
BANDOPADHYAYA et. al.



$$U_{e3} \simeq \frac{V_{ub}}{\frac{m_b}{m_\tau} - 1} \approx \frac{\lambda^3}{\lambda^2} \approx \lambda$$

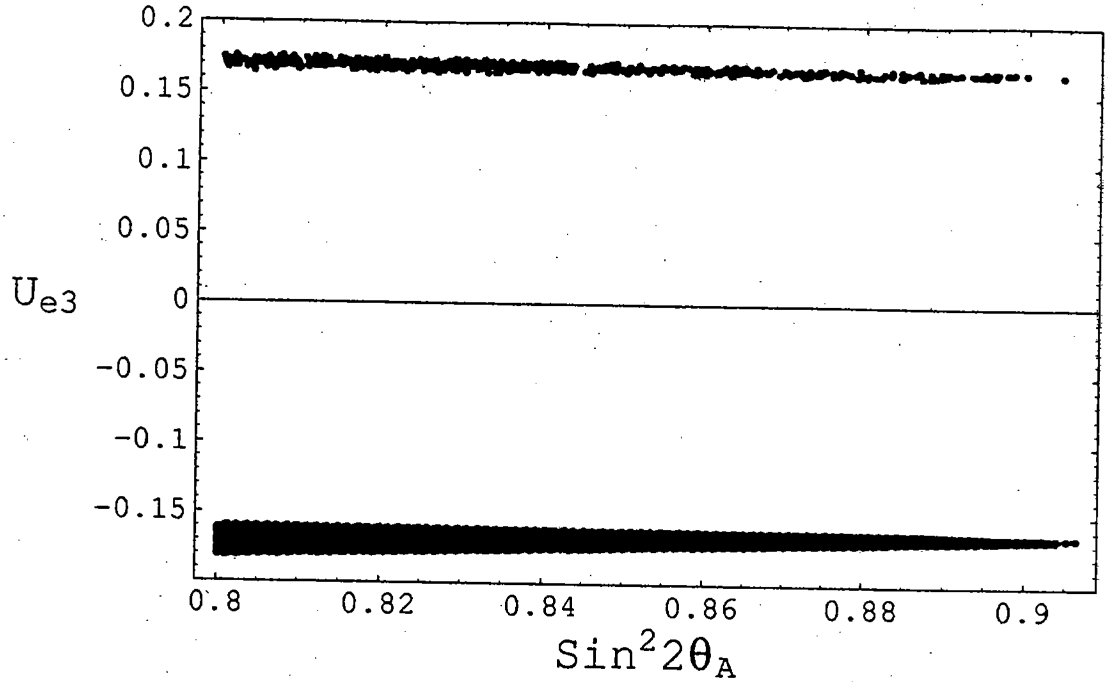


FIG. 3. The figure shows the predictions of the model for $sin^2 2\theta_A$ and U_{e3} for the allowed range of parameters in the model. Note that U_{e3} is very close to the upper limit allowed by the existing reactor experiments.

PROPOSED EXPTS.

- MINOS
- NUMI - OFF AXIS
- JHF
- CERN - GRAN SASSO
- BNL

$U_{e3} \gtrsim .04 - .01$

WE NEED TO KNOW

(i) SIGN OF Δm^2_{32}

NORMAL VRS INVERTED

(ii) U_{e3}

(iii) $\beta\beta_{0\nu}$ DECAY.

$(\nu = \bar{\nu}\ ?)$

SOME MODEL PREDICTIONS FOR U_{e3}:

		U_{e3}
1. $SO(10)_{16_H}$	ALBRIGHT-BARR	.035
2. $SO(10)_{16_H}$	ROSS- VILASCO-	.01
3. $SO(10)_{(126)_H}$	GOH, R.N.M., NG	.16
4. $SO(10) \times U(2)_F$ $(126)_H$	CHEN, MAHANTHAPPA	.158
5. DISCRETE SYM.	OHLSSON, SEIDL	.15 - .2
6. $SU(2)_H$	KUCHIMANCHI- R.N.M.	.04 - .15
7. ANARCHY	de GOUVEA, MURAYAMA	$\gtrsim .14$

CONCLUSION

(i) $m_\nu \longrightarrow$ SEESAW + GCU
DM
⋮

$\Rightarrow$ STRONG CASE FOR
SO(10) WITH 126_H

MINIMAL MODEL TESTABLE!!

(ii) KEY LESSON:

ANY MODEL WHERE

$$\mathcal{M}_\nu = c\,(M_d - M_\ell) \quad \text{AT } M_{\mathrm{I}}$$

$\Rightarrow$ EASY UNDERSTANDING OF LARGE $\theta_{\text{ATMOS.}}$ AND θ_{SOLAR}.

- $2\{10\}_H + \{126\}_H$
- DOES NOT WORK FOR 16_H.

(iii) NORMAL VRS INVERTED
SO(10) $\leftrightarrow$ $SU(2)_H$.