Neutrino Masses in Grand Unified Theories

R. N. Mohapatra

UNIVERSITY OF MARYLAND

NuFact 2011 , Geneva

Topics of interest

- **Tiny masses and Mass hierarchy**: $\Delta m_{31}^2 > or < 0$
- **Majorana, Dirac or neither**
- **Mixings:** $U_{PMNS} = U_\ell^+ U_\nu$

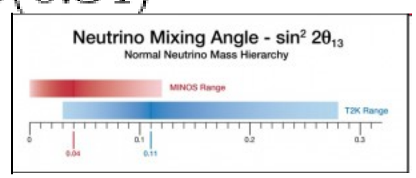
  U_{PMNS} Strikingly close to: $= \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}$

  Tri-bi-maximal mixing(TBM)

(Harrison, Perkins, Scott; Xing;He, Zee; Pakvasa, Sugawara and Yamanaka; Wolfenstein)

- θ_{13} **T2K result** : $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$

  MINOS best fit: $\sin^2 2\theta_{13} = 0.04(0.08)$;



- Also θ_{12} outside 90%c.l. (Fogli et al.arXiv:1102.6028)

→ U_{PMNS} **Surely not TBM but close**

Could it be close to Bi-Maximal (BM)?

- Alternative possibility:

$$U_{PMNS} = U_{BM} + \delta U \qquad U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- With δU such that $\theta_{12} = \frac{\pi}{4} - \theta_C ; \theta_{23} = \frac{\pi}{4} - \theta_C^2 \equiv \frac{\pi}{4} - V_{cb}$

- **Quark-lepton complimentarity:** Smirnov; Raidal; Minakata, Smirn

Other Topics of interest

- Leptonic CP phase
- Unitarity of PMNS
- Are there sterile neutrinos ?
- Do neutrinos have nonstandard interactions ?
- This talk:

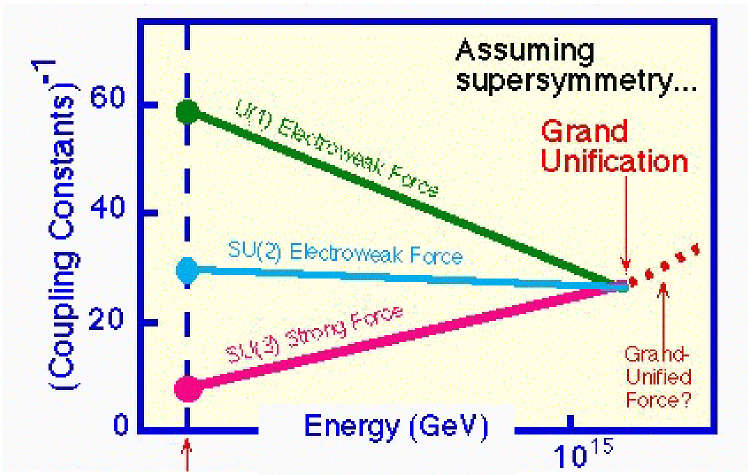
-What can grand unified theories tell us about any of these topics ?

-What can <u>more precise</u> determination of neutrino mixings say about grand unification ?

-Three issues: θ_{13} ; $\not{CP}$; unitarity of PMNS

Grand Unification: the grand vision of Physics

★ $\alpha_i(M_Z)$ + SUSY at TeV→ couplings unify



$$M_U \approx 10^{16} GeV$$

-Explains electric charge quantization

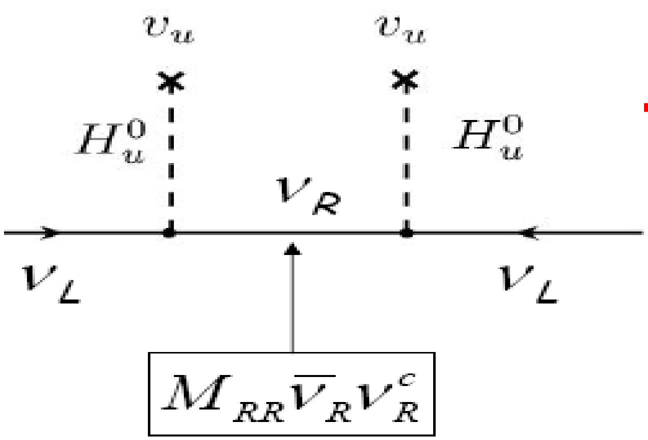
-Unifies all matter- possible hints:

at GUT scale→ $m_b \approx m_\tau$ $m_\mu = -3m_s$

★ **Are neutrinos leading us towards this grand vision ?**

Why neutrino masses are so small - $m_\nu << m_{q,l}$?

- **Seesaw paradigm:**
- **Add right handed neutrinos N_R to SM with Majorana mass:**



→ $$m_\nu \cong -\frac{h_\nu^{\ 2} v_{wk}^{\ \ 2}}{M_R}$$ (Type I)

→ **neutrinos necessarily Majorana**

→ **MR large so that nu mass small**

How Large ? **GUTs→** $h_{\nu,33} \approx h_t$ **;** Δm^2_{atm} → $M_R \approx 10^{14} GeV$

- **GUTs appealing and natural for seesaw !**

Challenges for GUTs

- **Why are PMNS and CKM so different ?**

$$U_{PMNS} = \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix} \quad \textbf{vs} \quad U_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda \cong 0.22$$

i.e. Quark mass matrix hierarchical –

but neutrino mass matrix non-hierarchical ?

- **Why is** $\frac{m_{solar}}{m_{atm}} \approx \theta_C >> \frac{m_\mu}{m_\tau}$ **,** $, \frac{m_s}{m_b}$ **?**

SO(10) SUSY GUT for neutrinos

- SU(5) does not unify neutrinos with quarks !
- SO(10) unifies all fermions/family (including RH nu) in single rep.

$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

- **Contains all the ingredients for seesaw mechanism:**
- **Minimal Renormalizable version predictive for nu masses and mixings:** Babu, Mohapatra'92

Seesaw: Type I or II ?

- **Type I** Seesaw formula:

Flavor sensitive

$$m_\nu \cong -\frac{h_\nu^{\,2} v_{wk}^{\,2}}{M_R}$$

Flavor sensitive

- GUTs relate $h_\nu \approx h_{up}$ - hence hierarchical
- So M_R must be **"doubly hierarchical"**-

Seesaw: Type I or II ?

- **Type I** Seesaw formula:

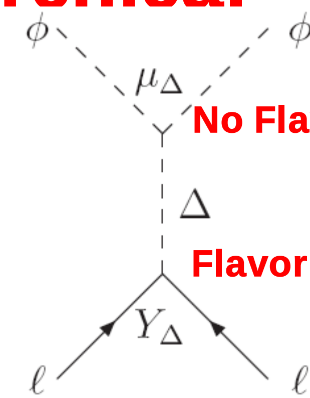
Flavor sensitive

$$m_\nu \cong -\frac{h_\nu^2 v_{wk}^2}{M_R}$$

Flavor sensitive

- GUTs relate $h_\nu \approx h_{up}$ - hence hierarchical
- So M_R must be **“doubly hierarchical”**-
- **Type II bypasses** h_ν

no such hierarchy issue!



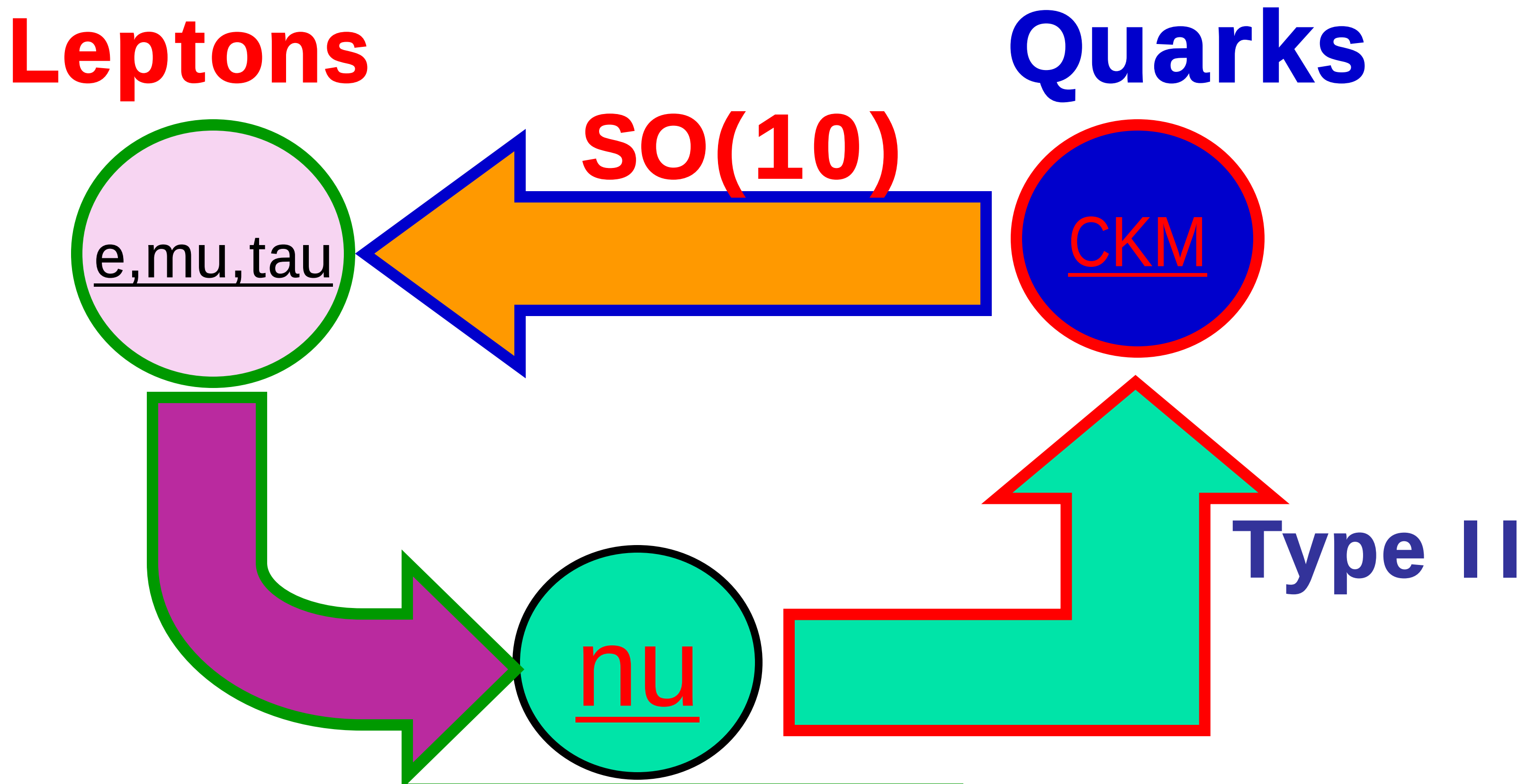
No Flavor dep.

Flavor sensitive

$$M_\nu \cong f_{126} \frac{v_{wk}^2}{M}$$

flavor independent

Intimate quark-lepton connection in SO(10)-II



$$U_{PMNS} = U_{\ell}^{+} U_{\nu}$$

Large mixings in minimal SO(10)

- **II seesaw** $M_\nu \cong c(M_d - M_l)$
- **GUT relation** $m_b \approx m_\tau (1+\lambda^2) \rightarrow \lambda = \theta_C$

$$M_\nu \propto m_b \begin{pmatrix} \lambda^5 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2+\lambda^3 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} - m_\tau \begin{pmatrix} \lambda^6 & \sim\lambda^3 & \sim\lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \sim\lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\Rightarrow \sim \lambda^2 \begin{pmatrix} \lambda^3 & \sim\lambda & \sim\lambda \\ \lambda & 1+\lambda & -1 \\ \lambda & -1 & 1 \end{pmatrix}$$

non-hierarchical

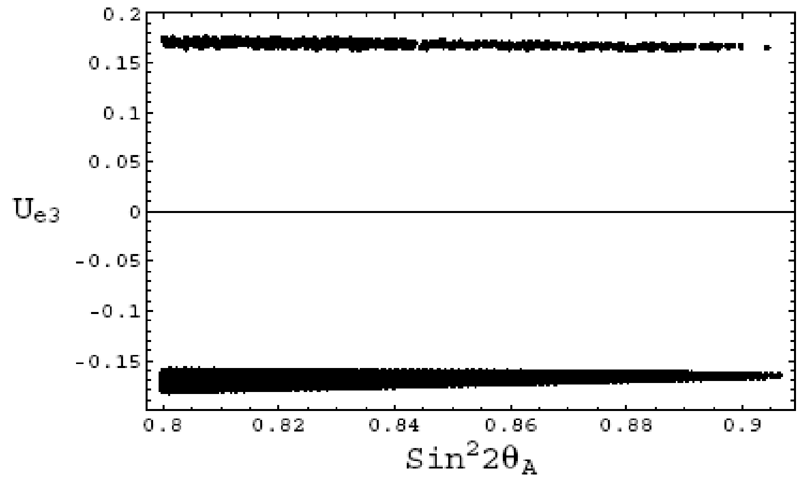
(Bajc, Senjanovic, Vissani'02)

Predictions

- **Works qualitatively and quantitatively**
- **Predictions:**
- ★ θ_{12}, θ_{23} **large**

★ $\theta_{13} \approx \lambda$ **"large"**

★ $\frac{m_{solar}}{m_{atmos}} \sim \lambda$



(Goh, RNM, Ng, PLB, 570 (2003))

no CKM CP

$\theta_{13} \cong 0.15$

Current Status

- Subsequent analysis of fermion masses with CKM:
- **Pros:** (Fukuyama, Okada; Babu, Macesanu;Bertolini, Malinsky, Schwetz;)

Fits to charged fermions ➡ $\theta_{12} = 32^0$ $\theta_{23} = 37^0$ $\theta_{13} = 6^0$ $\delta_{PMNS} = 4^0$

Bertolini,Malinsky fit

- **Cons:** -very limited parameter space;

  -proton decay requires cancellations

- **Improved minimal model:**
- **Add 120 Higgs or extra 10**; broadens parameter space; solves p-decay issues and still predictive.

Oshimo; Dutta, Mimura, RNM; Bertolini, Frigerio Malinsky; Yang, Wang; Grimus, Kuhboch;Aulakh, Garg;Joshipura, Kodrani, Patel;

Quantitative analysis of improved SO(10)

- **Two classes of SO(10) type II models with TBM by choice of basis/or symmetry**

(i) SO(10)-type II with 120 (17 param) $\theta_{13} \geq 0.07$

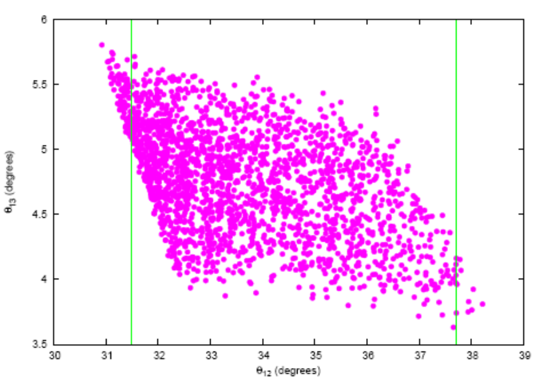
$\delta_D \approx 274^0$

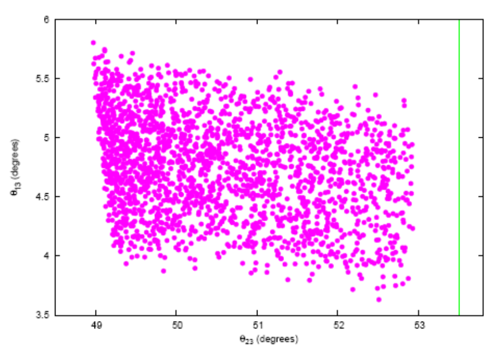
Altarelli, Blankenburg'10; Joshipura, Patel'11

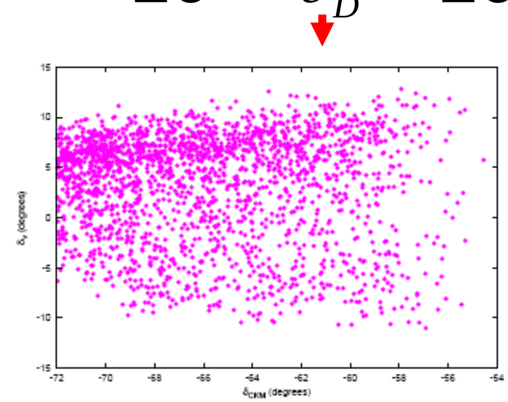
(ii) SO(10) type II + 10's: (13 param) θ_{13} ~4-5^0

$-10^0 < \delta_D < 10^0$

θ_{13}



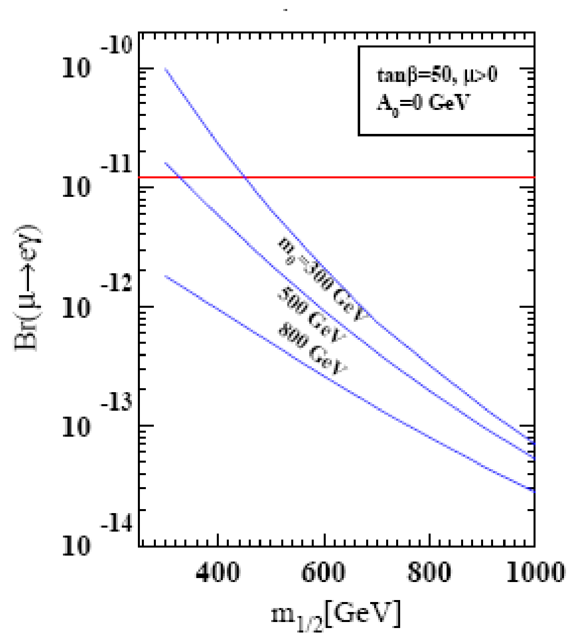




(Dev, RNM, Severson arXiv:1107.2378)

Predictions for $\mu \to e + \gamma$

- **mu→ e+gamma for typical SO(10) theories with type II seesaw:**



- $B(\mu \to e + \gamma) > 10^{-14}$ within range of MEG
- No $\mu \to e + \gamma$ → nonsusy GUT with seesaw !

Bottom line for SO(10)

Generic to all SO(10) with type I or II seesaw

- **Naturally explains small neutrino masses;**
- **Neutrinos all Majorana:**
- **But mass hierarchy generally normal →No Signal in ongoing nu-less double beta decay searches !!**
- **No TeV scale signal at LHC**
- Observable $\mu \rightarrow e + \gamma$ with SUSY

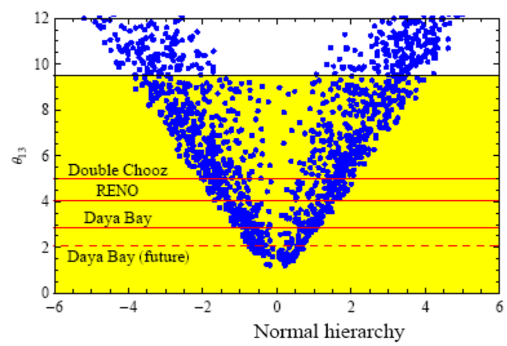
Specific to type II models

- Predicts $\theta_{13} >$ 0.07 ; good news for ~~CP~~ searches.
- Bimaximal starting point does not work- too large solar angle→ Expt telling us how to build theory !!

Discriminating between models

- **Many models for** θ_{13} - how to tell the difference ?
- θ_{13} - θ_{23} correlation –testable feature of models

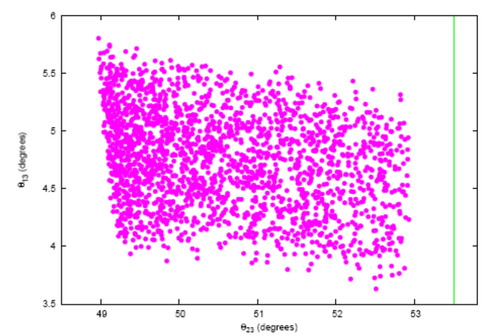
Approx $\mu - \tau$



(figure from He, Yin'11)

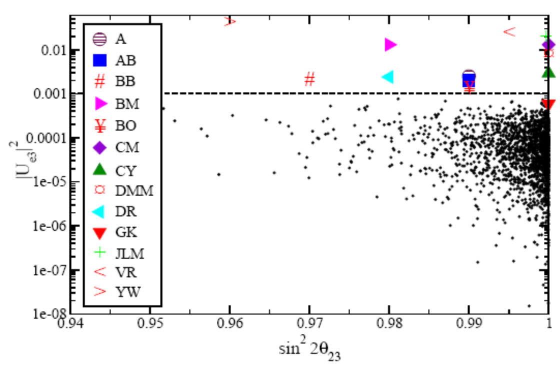
SO(10)xS4

(Dev, RNM, Severson)



- GUTs vs ~TBM

(Albright, Rodejohann)



SU(5)xT'

(Pakvasa, Bjorken,King, Chen, Mahanthappa,..)

$$\theta_{13} = \frac{\theta_C}{3\sqrt{2}} \sim 3^0$$

Non-unitarity of PMNS

- **Is U_{PMNS} unitary ?**: Seesaw → No !!
- **Type I case- tiny and unobservable!**
- With inverse seesaw **can be significant:** $\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix}$ (RNM, Valle'86)
- **Parameterize** $N = (1 + \eta)U$
- **→ subset of possible non-standard interactions:**

$$\mathcal{L}_{NSI} = -\varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F \left(\bar{\nu}_\alpha \gamma_\mu L \nu_\beta\right)\left(\bar{f}\gamma^\mu P f\right)$$ with $\varepsilon^{fP}_{\alpha\beta} = \eta_{\alpha\beta}$

Non-unitarity in oscillations

- Lepton flavor violation, muon and pion decays:

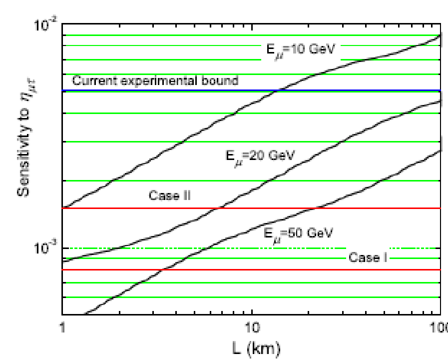
$$\Rightarrow \quad |\eta| < \begin{pmatrix} 2.0\times10^{-3} & 6.0\times10^{-5} & 1.6\times10^{-3} \\ \sim & 8.0\times10^{-4} & 1.1\times10^{-3} \\ \sim & \sim & 2.7\times10^{-3} \end{pmatrix} .$$

$\not{C}\not{P}$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta L}{2}\right) - 4|\eta_{\alpha\beta}|\sin\delta_{\alpha\beta}\sin(2\theta)\sin\left(\frac{\Delta L}{2}\right) + 4|\eta_{\alpha\beta}|^2,$$

Yasuda, Gavela, Martinez, Pavon'07

- $\eta_{\mu\tau} < 10^{-4}$ Observable in oscillations in neutrino factories with OPERA type near detector.



Malinsky, Ohlsson, Zhang

Antusch, Biggio, Fernandez-Martinez, Gavela, J. Lopez-Pavon

Goswami, Ota; Meloni;, Xing; Kopp, Lindner; Winter; de Gouvea ,..

Inverse seesaw in SO(10) and non-unitarity

- Allows TeV scale seesaw inspite of GUT constraint:

(unlike type I)

- Inverse seesaw: $m_\nu \simeq -m_D^T M^{-1} \mu M^{-1} m_D$

μ breaks lepton number→nu mass- so m_D can satisfy GUT rel.

- TeV M consistent with coupling unification (Dev, RNM'09) →

Predicts large η_{ij} as well as new CP phase.

m_{N_1}	m_{N_2}	m_{N_3}	$\|\eta_{e\mu}\|$	$\|\eta_{e\tau}\|$	$\|\eta_{\mu\tau}\|$
1100	1100	1100	3.7×10^{-7}	1.5×10^{-5}	6.5×10^{-5}
100	100	1100	7.9×10^{-7}	1.6×10^{-5}	8.9×10^{-5}
50	50	1200	2.5×10^{-6}	2.2×10^{-5}	1.6×10^{-4}
30	30	2100	6.7×10^{-6}	4.4×10^{-5}	3.2×10^{-4}

Summary

- SO(10)-type II- "Big Picture Dream Scenario" for neutrino masses !
- 'Larger θ_{13} ' fits very well into it !!
- Further test→ Precise measurement of angles, mass hierarchy and Majorana nature !
- Non observation of $(\mu \rightarrow e + \gamma)$ could indicate nonsusy GUT seesaw→ no susy at LHC !!
- Predictions for CP phase-model dependent –
- True test of GUT- observation of proton decay.

Summary: contd

- . Unitarity in SBL expts would be a sign of low seesaw scale as any signal of W_R, Z_{LR} at LHC

- Sterile nus would require significant change in GUT model bldg-

Extra slides

Could neutrinos be not Dirac nor Majorana("*Schizophrenic*")

- Possible if there are ν_R 's that form Dirac mass with one or two active mass eigenstates $(\nu_1, \nu_2 \nu_3)$

$$L_m = m_1 \nu_1 \nu_R + m_2 \nu_2 \nu_2 + m_3 \nu_3 \nu_3$$

Dirac mass **Majorana**

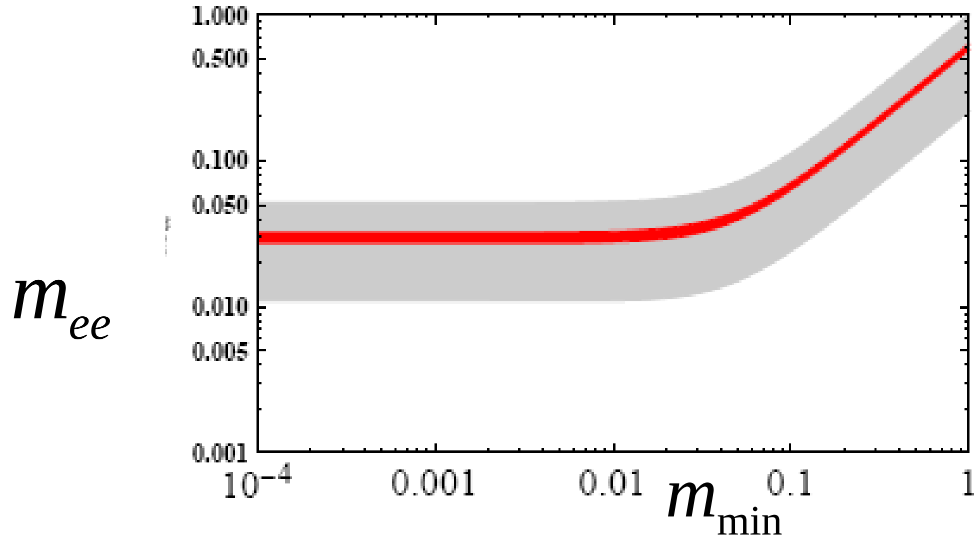
(Usual Majorana case: L*m* $\equiv m_1 \nu_1 \nu_1 + m_2 \nu_2 \nu_2 + m_3 \nu_3 \nu_3$**)**

- Oscillation phenomenology, MSW effect in Sun etc remain unaffected !! **(Allahverdi, Dutta, Mohapatra'10)**
- **Different from Pseudo-Dirac**

Nu-less double beta decay- *Majorana vs Schizophrenic*

- **Higher lower bound on M_ee for IH**

  (Allahverdi, Dutta, RNM)



- **17 meV** (usual IH) vs **34 meV** (Schizo-nu IH) as lower bound: schizo-nu can be ruled out if IH from LBL expts.
- One loop Dirac→pseudo-Dirac **(Leung,Petcov'83)** →affects extragalactic neutrino flux in Km^3 detectors

  (Barry, RNM, Rodejohann'10)
- Several particle physics models already constructed-

  (Pleitez, Machado; Haba, Shindou; Morisi, Peinado; Chen, Lin; Ghosh et al.)

SO(10) with 120

- :(Dutta, Mimura, RNM,2005,06,07,10)
- **Solving proton decay using flavor texture:**

$$h_{10} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}; \; h_{126} = \begin{pmatrix} 0 & 0 & \lambda^3 \\ 0 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix};$$

$$h_{120} = \begin{pmatrix} 0 & \lambda^3 & \lambda^3 \\ -\lambda^3 & 0 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 0 \end{pmatrix};$$

The Neutrino Matrix:

- **Flavor of the Neutrino flavor research**

Generic mass matrix (NH) $\varepsilon_i \approx \lambda_{Cabibbo} << 1$

θ_{23} **NEAR MAXIMAL** θ_{23} **maximal**

TBM

$$\begin{pmatrix} \varepsilon_5^{n\geq 1} & \varepsilon_4 & \varepsilon_3 \\ \varepsilon_4 & 1+\varepsilon_1 & -1 \\ \varepsilon_3 & -1 & 1+\varepsilon_2 \end{pmatrix} \rightarrow \begin{pmatrix} \varepsilon_5^{n\geq 1} & \varepsilon_3 & \varepsilon_3 \\ \varepsilon_3 & 1+\varepsilon_1 & -1 \\ \varepsilon_3 & -1 & 1+\varepsilon_1 \end{pmatrix} \rightarrow \begin{pmatrix} \varepsilon_1 & \varepsilon_3 & \varepsilon_3 \\ \varepsilon_3 & 1+\varepsilon_1 & -1+\varepsilon_3 \\ \varepsilon_3 & -1+\varepsilon_3 & 1+\varepsilon_1 \end{pmatrix}$$

$\rightarrow \mu \leftrightarrow \tau$ **sym.**

5 parameters **3 param.** **2 param.**

Two incarnations of SO(10)

I

(16-Higgs)

- B-L breaks 1 unit
- no susy DM
- low representations:

  (an advantage)

- String compatible

Early papers:

Albright, Barr'99; Babu,Barr'98; Dermisek,Raby'00......

II

(126-Higgs)

- B-L breaks by 2 units
- **SUSY DM automatic**
- Minimal version: few parameters<17 –

  hence more predictive

- ??

Babu, Mohapatra'92

TBM vs BM in GUTs

What starting point

- **SO(10) +type II seesaw, neutrino mass matrix in TBM or BM form <u>without sym</u>:**
- Since $U_{PMNS} = U_\ell^+ U_{TBM}$ and $m_\mu = -3m_s$

  fitting charged fermions is expected to give:
- $\theta_{13} = \frac{\theta_C}{3\sqrt{2}}$ ~0.05 ; $\delta_D \approx$ model dep.

(Bjorken, Pakvasa, King, Chen, Mahanthappa)

- $\sin\theta_{12} \sim \frac{1}{\sqrt{3}} + \frac{\theta_C}{3\sqrt{3}}$ TBM; $\sin\theta_{12} = \frac{1}{\sqrt{2}} + \frac{\theta_C}{6}$ **BM**

~BM in SO(10) unlikely to fit solar;

New physics implied by Neutrino Mass

- Standard model- no ν_R → $m_\nu = 0$
- Two possibilities for m_ν
- **(i)** SM + ν_R → $L_Y = h_\nu \bar{L} H \nu_R + h.c.$ → $m_\nu = h_\nu v_{wk}$

Observations→ $h_\nu \cong 10^{-12}$ (neutrino Dirac)

★ Since in GUTs, all couplings are expected to be same order, **Dirac neutrino not "GUT friendly"**

(ii) Alternative: Mass from high scale physics: $\frac{LHLH}{M}$

(Neutrino Majorana)

Large mixings from symmetries vs dynamics ?

- many sym models with SM,MSSM,GUTs
- Sym. candidates:

$$S_{2(\mu-\tau)} \subset S_3, S_4, A_4, \Delta(3n^2),...$$

(Ishimori, Saga, Shimizu,Tanimoto; Altarelli, Feruglio,Hagedorn; Morisi, Picarello; King, Luhn; Chen, Mahanthappa; Hagedorn, Smirnov, Schmidt, Dutta, Mimura,R.N.M.; Bazzocchi et. Al.; Joshipura, Kodrani, patel,……)

- Fitting quarks and CKM in GUTs “shatters” sym

- Generically predict much smaller θ_{13}
- Perhaps another lesson for model building !!