GUT-model Building

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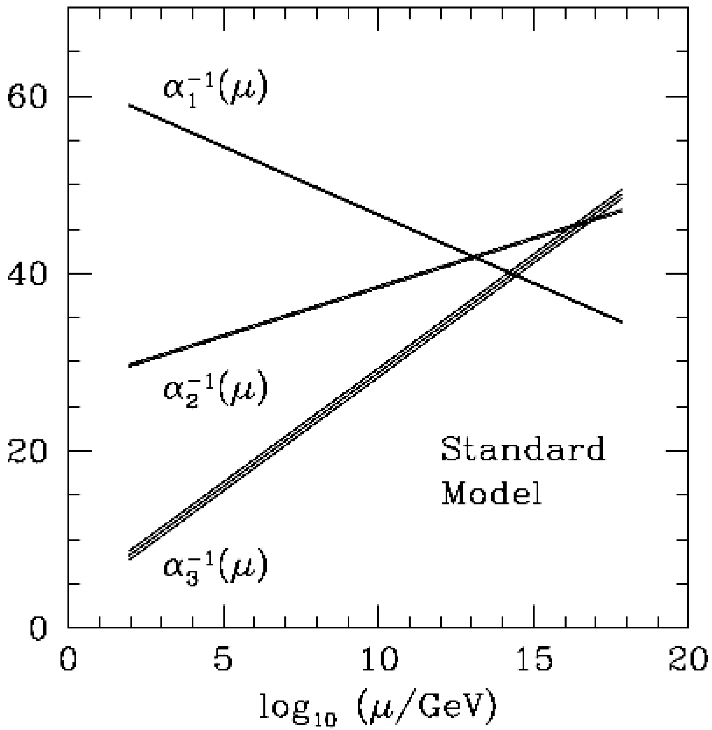
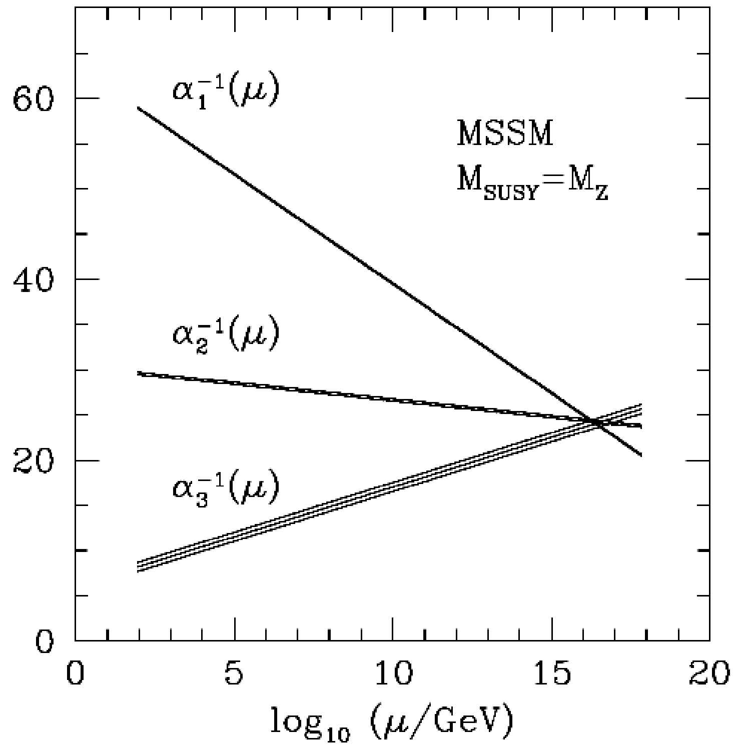
Outline

- Motivation/"Evidence"
- Model Building Issues:
  - Gauge group
  - Matter multiplets
  - Symmetry breaking
  - Doublet—triplet splitting
  - Fermion masses and mixings
  - Flavor violation
  - Leptogenesis
  - Proton decay
- Realistic GUTs
- Experimental tests
- Conclusions

Evolution of Gauge Couplings





Standard Model

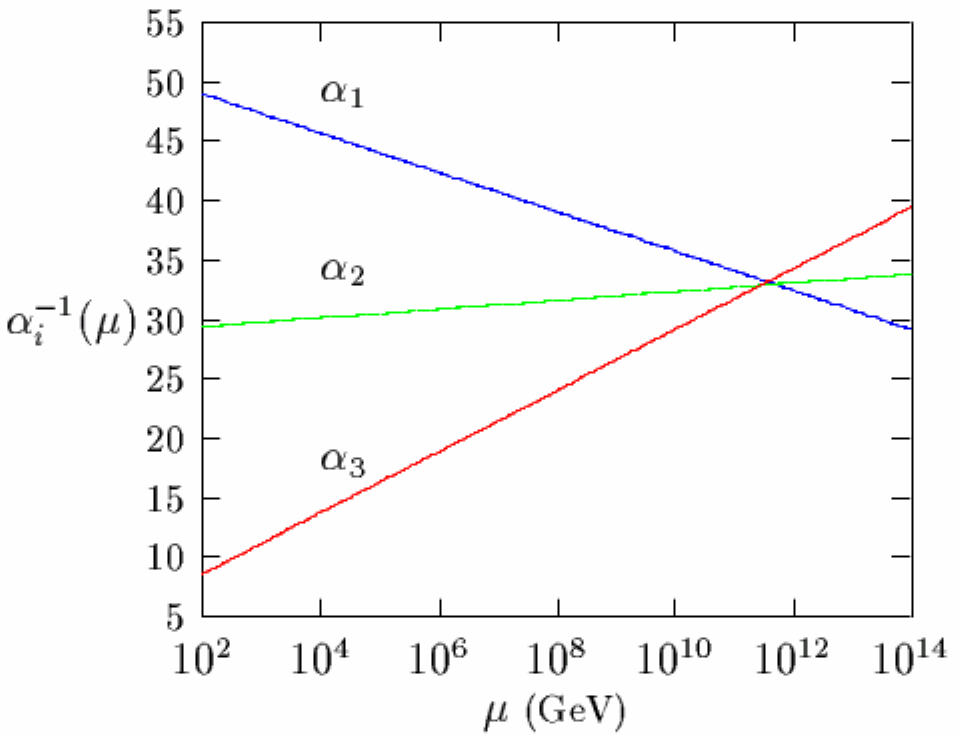
Supersymmetry

SUSY Spectrum

SM Particles		SUSY Partners	
Spin = 1/2	Q	$\tilde{Q}$	Spin = 0
	u^c	$\tilde{u}^c$	
	d^c	$\tilde{d}^c$	
	L	$\tilde{L}$	
	e^c	$\tilde{e}^c$	
Spin = 0	H_u	$\tilde{H}_u$	Spin = 1/2
	H_d	$\tilde{H}_d$	
Spin = 1	g	$\tilde{g}$	Spin = 1/2
	W	$\tilde{W}$	
	B	$\tilde{B}$	

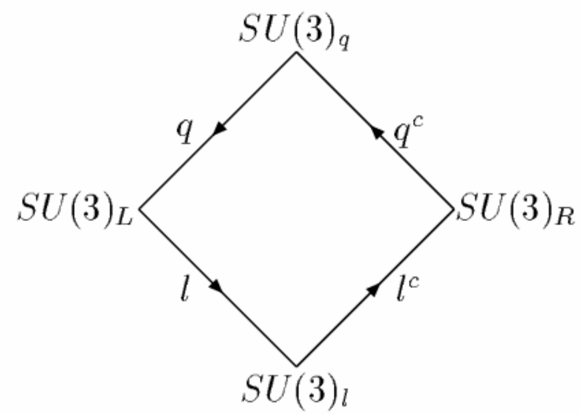
$$R = (-1)^{3B+L+2S}$$

Gauge Coupling Unification in $[SU(3)]^4$ Quartification



K.S. Babu, Ernest Ma, S. Willenbrock, **hep-ph/0307380**

$SU(3)_q$ x $SU(3)_L$ x $SU(3)_l$ x $SU(3)_R$ Quartification



Moose diagram of $[SU(3)]^4$ quartification

$$q \sim (3, 3^*, 1, 1) \qquad q^c \sim (3^*, 1, 1, 3)$$

$$l \sim (1, 3, 3^*, 1) \qquad l^c \sim (1, 1, 3, 3^*)$$

$$q \sim \begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} \qquad q^c \sim \begin{pmatrix} d^c & d^c & d^c \\ u^c & u^c & u^c \\ h^c & h^c & h^c \end{pmatrix}$$

$$l \sim \begin{pmatrix} x_1 & x_2 & \nu \\ y_1 & y_2 & e \\ z_1 & z_2 & N \end{pmatrix} \qquad l^c \sim \begin{pmatrix} x_1^c & y_1^c & z_1^c \\ x_2^c & y_2^c & z_2^c \\ \nu^c & e^c & N^c \end{pmatrix}$$

Surviving symmetry: $SU(3)_C$ x $SU(2)_L$ x $U(1)$ x $SU(3)_l$

Structure of Matter Multiplets

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = (u_1^c \quad u_2^c \quad u_3^c) \sim (\overline{3}, 1, \frac{-2}{3})$$

$$d^c = (d_1^c \quad d_2^c \quad d_3^c) \sim (\overline{3}, 1, \frac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

$$e^c \sim (1, 1, +1)$$

$$\nu^c \sim (1, 1, 0)$$

Matter Unification in 16 of SO(10)

u_1	:	$\vert\uparrow\downarrow\uparrow\uparrow\downarrow>$
u_2	:	$\vert\uparrow\downarrow\uparrow\downarrow\uparrow>$
u_3	:	$\vert\uparrow\downarrow\downarrow\uparrow\uparrow>$
d_1	:	$\vert\downarrow\uparrow\uparrow\uparrow\downarrow>$
d_2	:	$\vert\downarrow\uparrow\uparrow\downarrow\uparrow>$
d_3	:	$\vert\downarrow\uparrow\downarrow\uparrow\uparrow>$
u_1^c	:	$\vert\downarrow\downarrow\uparrow\downarrow\downarrow>$
u_2^c	:	$\vert\downarrow\downarrow\downarrow\uparrow\downarrow>$
u_3^c	:	$\vert\downarrow\downarrow\downarrow\downarrow\uparrow>$
d_1^c	:	$\vert\uparrow\uparrow\uparrow\downarrow\downarrow>$
d_2^c	:	$\vert\uparrow\uparrow\downarrow\uparrow\downarrow>$
d_3^c	:	$\vert\uparrow\uparrow\downarrow\downarrow\uparrow>$
ν	:	$\vert\uparrow\downarrow\downarrow\downarrow\downarrow>$
e	:	$\vert\downarrow\uparrow\downarrow\downarrow\downarrow>$
e^c	:	$\vert\downarrow\downarrow\uparrow\uparrow\uparrow>$
ν^c	:	$\vert\uparrow\uparrow\uparrow\uparrow\uparrow>$

Neutrino Masses and the Scale of New Physics

$$\mathcal{L} = \frac{LLHH}{M_R}$$

$$\langle H \rangle \sim 246 \text{ GeV and } m_{\nu_3} \sim 0.05 \text{ eV}$$

from atmospheric neutrino oscillation data

$$\Rightarrow \qquad m_R \sim 10^{14} - 10^{15} \text{GeV}$$

Very Close to the GUT scale.

Leptogenesis via ν_R decay explains cosmological baryon asymmetry

Other Evidences

- **Anomaly freedom automatic in many GUTs**
- **Electric charge quantization**
- **Nonzero neutrino masses required in many GUTs**
- **Baryon number violation natural in GUTs – needed for generating cosmological baryon asymmetry**
- $M_d = M_\ell^T$ **works well for 3rd family** $(m_b = m_\tau)$

GUT Gauge Groups

- SU(5)
- SO(10)
- E_6
- E_8
- …

- $[SU(3)]^3$
- $[SU(5)]^2$
- $[SU(3)]^4$
- …

SU(5) GUT

Matter multiplets: $\{\mathbf{10}+\bar{\mathbf{5}}+\mathbf{1}\}$

$$\mathbf{10}:\begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}$$

$$\bar{\mathbf{5}}:(d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

$$\mathbf{1}:\nu^c$$

Higgs: $\mathbf{24}_H, \quad \{\mathbf{5}_H, \quad \bar{\mathbf{5}}_H\}$ ⇨ Contain color triplets $\{H_C, \ \bar{H}_C\}$

Yukawa Couplings $Y_u^{ij}\mathbf{10}_i\mathbf{10}_j\mathbf{5}_H + Y_d^{ij}\mathbf{10}_i\bar{\mathbf{5}}_j\bar{\mathbf{5}}_H$

$$M_\ell = M_d^T \Rightarrow m_b = m_\tau, m_s = m_\mu, m_d = m_e$$

MSSM Higgs doublets have color triplet partners in GUTs.

$$H(1,2,1/2) \oplus H_c(3,1,-1/3) = \mathbf{5} \text{ of } SU(5)$$

$$\bar{H}(1,2,-1/2) \oplus \bar{H}_c(\bar{3},1,1/3) = \bar{\mathbf{5}}$$

$H,\ \bar{H}$ **must remain light**

$H_c, \bar{H}_c$ **must have GUT scale mass to prevent rapid proton decay**

Doublet-triplet splitting

Even if color triplets have GUT scale mass, d=5 proton decay is problematic.

Symmetry Breaking

Doublet-triplet splitting in SU(5)

$$W_{D-T} = \bar{\mathbf{5}}_H(\lambda \mathbf{24}_H + M)\mathbf{5}_H$$

$$< 24_H >= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -3/2 & 0 \\ 0 & 0 & 0 & 0 & -3/2 \end{pmatrix} V$$

FINE-TUNED TO $O(M_W)$

$$M_{H_c} = \lambda V + M \sim O(M_{GUT}) \quad M_H = -\frac{3}{2}\lambda V + M$$

The GOOD

(1) Predicts unification of couplings

(2) Uses economic Higgs sector

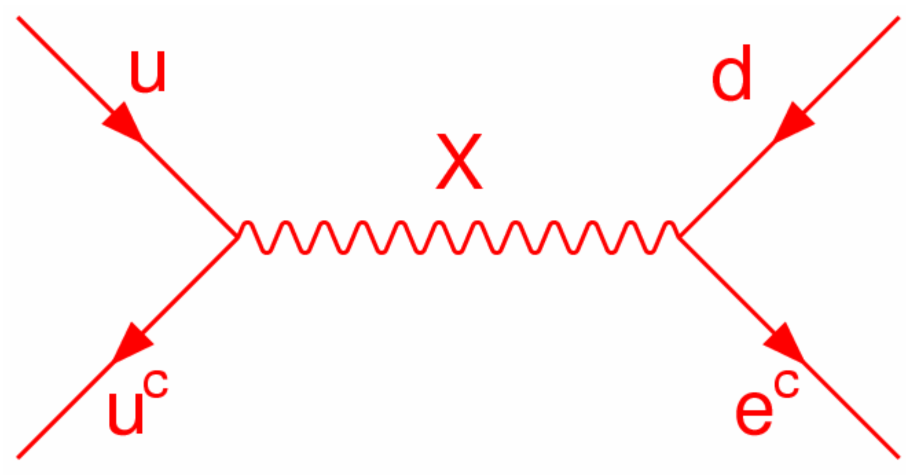
The BAD

(1) Unnatural fine tuning

(2) Large proton decay rate

Nucleon Decay in SUSY GUTs

Gauge boson Exchange

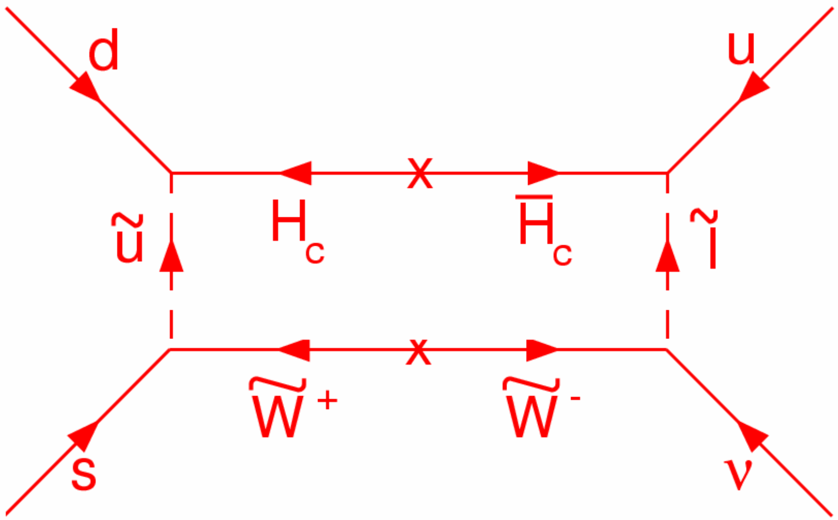


$$p \to e^+\pi^0,\ \tau_p^{-1} \approx \left[\frac{g^2}{M_X^2}\right]^2 m_p^5 \approx [10^{36\pm1} yr]^{-1}$$

Higgsino Exchange

Sakai, Yanagida (1982)

Weinberg (1982)



$$p \rightarrow \bar{\nu} K^{+}$$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{32} yr]^{-1}$$

SO(10) GUT

- Quarks and leptons ~{16_i}
- Contains ν_R and Seesaw mechanism

Model with Non-renormalizable Yukawa Couplings

Higgs: $\{45_H + 10_H + 16_H + \overline{16}_H\}$

$$\mathcal{L}_{\text{Yukawa}} = f_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H + h_{ij}16_i16_j\overline{16}_H\overline{16}_H/M_{Pl}$$

$$\Rightarrow \quad m^D_{\nu_\tau} \simeq m_t;\ m^M_{\nu_{\tau_R}} \simeq h_{33}\frac{M^2_{GUT}}{M_{Pl}}$$

$$m_{\nu_\tau} = \frac{m_t^2}{m_{\nu_{\tau_R}}} \simeq 0.05\ \text{eV},\ h_{33} \sim 1$$

Fits the atmospheric neutrino data well

- Small Higgs rep $\Rightarrow$ small threshold corrections for gauge couplings
- R-parity not automatic (needs a Z_2 symmetry)

Matter Unification in 16 of SO(10)

$$
\begin{array}{rcl}
u_1 & : & |\uparrow\downarrow\uparrow\uparrow\downarrow> \\
u_2 & : & |\uparrow\downarrow\uparrow\downarrow\uparrow> \\
u_3 & : & |\uparrow\downarrow\downarrow\uparrow\uparrow> \\
d_1 & : & |\downarrow\uparrow\uparrow\uparrow\downarrow> \\
d_2 & : & |\downarrow\uparrow\uparrow\downarrow\uparrow> \\
d_3 & : & |\downarrow\uparrow\downarrow\uparrow\uparrow> \\
u^c_1 & : & |\downarrow\downarrow\uparrow\downarrow\downarrow> \\
u^c_2 & : & |\downarrow\downarrow\downarrow\uparrow\downarrow> \\
u^c_3 & : & |\downarrow\downarrow\downarrow\downarrow\uparrow> \\
d^c_1 & : & |\uparrow\uparrow\uparrow\downarrow\downarrow> \\
d^c_2 & : & |\uparrow\uparrow\downarrow\uparrow\downarrow> \\
d^c_3 & : & |\uparrow\uparrow\downarrow\downarrow\uparrow> \\
\nu & : & |\uparrow\downarrow\downarrow\downarrow\downarrow> \\
e & : & |\downarrow\uparrow\downarrow\downarrow\downarrow> \\
e^c & : & |\downarrow\downarrow\uparrow\uparrow\uparrow> \\
\nu^c & : & |\uparrow\uparrow\uparrow\uparrow\uparrow>
\end{array}
$$

Renormalizable Yukawa Coupling Model

Higgs: $\{210_H + \overline{126}_H + 10_H\}$

Automatic R-parity

$$\mathcal{L}_{\text{Yukawa}} = f_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H + h_{ij}16_i16_j\overline{126}_H$$

Under $SU(2)_L \times SU(2)_R \times SU(4)_C$

$$\overline{126} = (1,3,\overline{10}) + (3,1,10) + (1,1,6) + (2,2,15)$$

contains $(1,1,0)$ of SM

contains $(1,2,1/2)$ of SM

$$M_u = A + B \qquad M_{\nu_D} = A - 3B$$

$$M_d = \alpha A + \beta B \qquad M_\ell = \alpha A - 3\beta B$$

$$M_{\nu_M} \propto B$$

Model has only 11 real parameters plus 7 phases

K.S. Babu and R. Mohapatra, Phys. Rev. Lett.70, 2845 (1993)

Quark, Lepton & Neutrino Masses & Mixings in Minimal SO(10)

Fit

Input at GUT scale

$$\tan\beta = 55$$

$$m_u = 0.85 \text{ } MeV \qquad m_d = 1.08 \text{ MeV}$$

$$m_c = 222.3 \text{ } MeV \qquad m_s = 34.3 \text{ MeV}$$

$$m_t = 85.5 \text{ } GeV \qquad m_b = 1.549 \text{ GeV}$$

$$\delta_{CKM} = 1.508$$

$$V_{us} = 0.22 \quad V_{ub} = 0.0027 \quad V_{cb} = 0.036$$

Output: Type II Seesaw

$$\sin^2 2\theta_{\odot} = 0.635$$

$$\sin^2 2\theta_{e3} = 0.08$$

$$\sin^2 2\theta_{\mathrm{atm}} = 0.892$$

$$\frac{\Delta m^2_{\mathrm{atm}}}{\Delta m^2_{\odot}} = 15.2$$

$$\epsilon_1 = 1.0 \times 10^{-6} \Rightarrow Y_B \sim 10^{-10}$$

KSB, C. Macesanu (2003)

Minimal SO(10) GUT Prediction for Neutrino Mixings

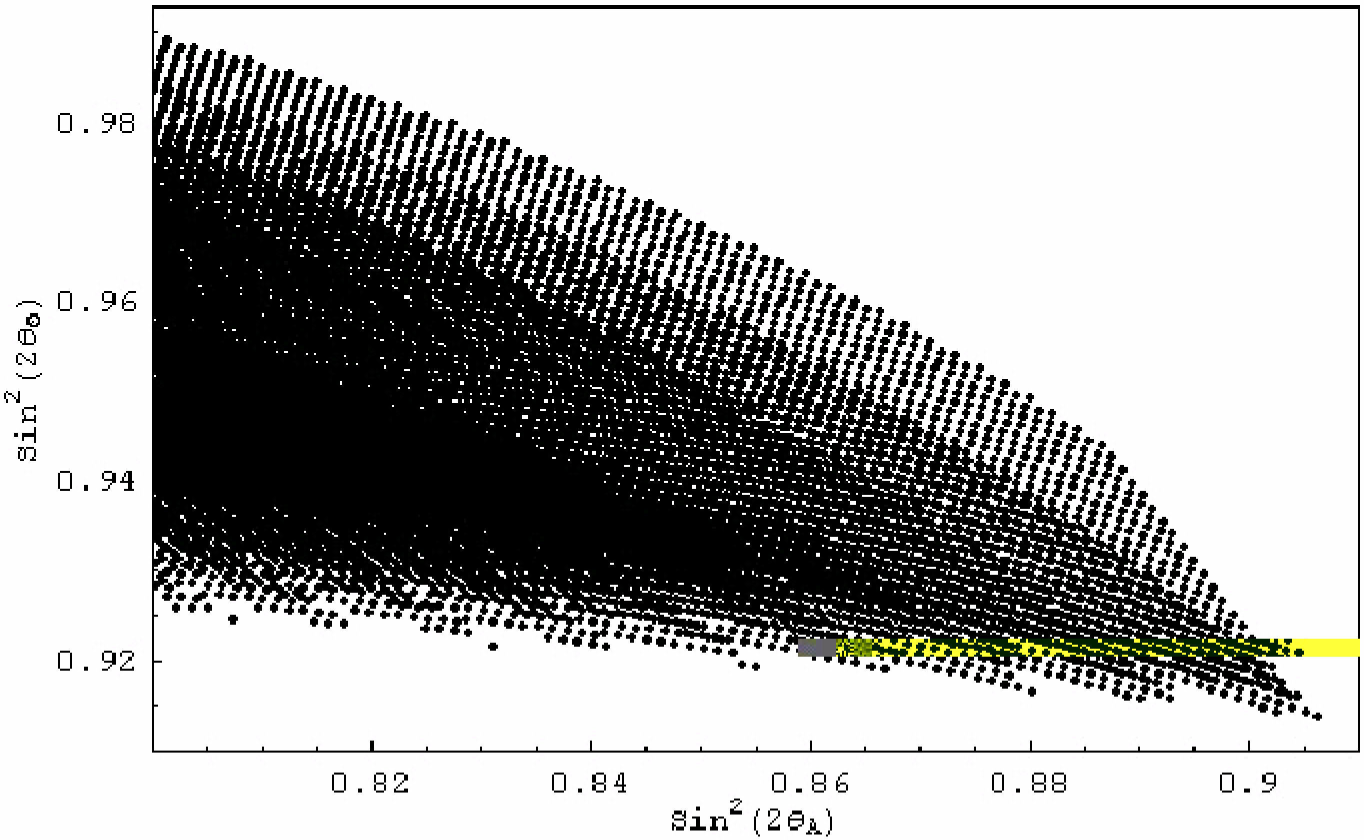


FIG. 1. The figure shows the range of predictions for $\sin^2 2\theta_\odot$ and $\sin^2 2\theta_A$ for the range of quark masses in table I that fit the charged lepton spectrum and where all CP phases are set to zero. We required that the ratio $\Delta m^2_\odot/\Delta m^2_A \leq 0.05$. Note that $\sin^2 2\theta_\odot \geq 0.9$ and $\sin^2 2\theta_A \leq 0.9$.

H.S. Goh, R.N. Mohapatra, Siew-Phang Ng, hep-ph/0308197

See also: Fukuyama, Okada, 2002; Aulakh et. al., 2003; Goh, Mohapatra, Ng, 2003

SUSY SO(10)

$$W_{D-T} = \lambda(\bar{\mathbf{10}}_H \mathbf{45}_H \mathbf{10}'_H) + \ldots$$

$$< 45_H >= \begin{pmatrix} a & 0 & 0 & 0 & 0 \\ 0 & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \otimes i\tau_2 \quad \propto B - L$$

- B-L VEV gives mass to triplets only (DIMOPOULOS-WILCZEK)
- If 10_H only couples to fermions, no d=5 proton decay
- Doublets from 10_H and $10'_H$ light

4 doublets, unification upset

Add mass term for *$10'_H$*

$$W_{D-T} = \lambda(\bar{\mathbf{10}}_H \mathbf{45}_H \mathbf{10}'_H) + M\mathbf{10}'_H\mathbf{10}'_H$$

Realistic SO(10) Model

Pati, Wilczek, KB (1998)

$$U = \begin{pmatrix} 0 & \epsilon' & 0 \\ -\epsilon' & 0 & \epsilon+\sigma \\ 0 & -\epsilon+\sigma & 1 \end{pmatrix} m_U, \quad D = \begin{pmatrix} 0 & \epsilon'+\eta' & 0 \\ -\epsilon'+\eta' & 0 & \epsilon+\eta \\ 0 & -\epsilon+\eta & 1 \end{pmatrix} m_D,$$

$$N = \begin{pmatrix} 0 & -3\epsilon' & 0 \\ 3\epsilon' & 0 & -3\epsilon+\sigma \\ 0 & 3\epsilon+\sigma & 1 \end{pmatrix} m_U, \quad L = \begin{pmatrix} 0 & -3\epsilon'+\eta' & 0 \\ 3\epsilon'+\eta' & 0 & -3\epsilon+\eta \\ 0 & 3\epsilon+\eta & 1 \end{pmatrix} m_D$$

$$M_\nu^R = \begin{pmatrix} x & 0 & z \\ 0 & 0 & y \\ z & y & 1 \end{pmatrix} M_R$$

$$\begin{aligned} "1" &: \; 16_3 16_3 10_H \\ "\epsilon" &: \; 16_2 16_3 (10_H \times 45_H)/M \\ "\sigma" &: \; 16_2 16_3 (10_H \times 1_H)/M \\ "\eta" &: \; 16_2 16_3 16_H 16_H/M \end{aligned}$$

$$\langle 45_H \rangle \propto (B-L)$$

Predictions

$$
\begin{aligned}
m_b^0 &\approx m_\tau^0 \\
m_s(1\ GeV) &\approx 116\ MeV \\
V_{cb} &\approx 0.043 \\
\sin^2 2\theta_{\mu\tau} &= (0.96,\ 0.91,\ 0.86,\ 0.83\ ,0.81) \\
\frac{m_{\nu_\mu}}{m_{\nu_\tau}} &= (1/10,\ 1/15,\ 1/20,\ 1/25,\ 1/30)
\end{aligned}
$$

$$
\begin{aligned}
m_d(1\ GeV) &\approx 8\ MeV \\
\theta_c &\approx |\sqrt{m_d/m_s} - e^{i\phi}\sqrt{m_u/m_c}| \\
\left|\frac{V_{us}}{V_{cs}}\right| &\approx \sqrt{\frac{m_u}{m_c}} \approx 0.07
\end{aligned}
$$

$$
\tau(p \to \bar{\nu} K^+) \lesssim 10^{34}\ \text{yr}
$$

$$
Br(p \to \mu^+ K^0) \sim 10\%
$$

Large Neutrino Mixing with Lopsided Mass Matrices

Quark and Lepton Mass hierarchy:

$$m_d : m_s : m_b \sim m_e : m_\mu : m_\tau \sim \epsilon_1 : \epsilon_2 : \epsilon_3$$
$$m_u : m_c : m_t \sim \epsilon_1^2 : \epsilon_2^2 : \epsilon_3^2$$

This motivates:

$$\begin{aligned} U &= H^T U_0 H \\ D &= D_0 H \\ L &= H^T L_0 \\ N &= N_0 \end{aligned}$$

$H = \text{Diag}(\epsilon_1,\ \epsilon_2,\ \epsilon_3)$ $\qquad$ $\epsilon_1 << \epsilon_2 << \epsilon_3$

10_i of $SU(5)$ carry flavor charge, $\bar{5}_i$ do not.
Leads to large left-handed charged lepton mixing and large right-handed down quark mixing.

KSB and S. Barr, 1995

Albright, KSB and Barr, 1998

Sato and Yanagida, 1998

Irges, Lavignac, Ramond, 1998

Altarelli, Feruglio, 1998

Example of Lopsided Mass Matrices

Gogoladze, Wang, KSB, 2003

$$U_{ij} = \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} H_u, \qquad D_{ij} = \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & 1 \end{pmatrix} \epsilon^p H_d,$$

$$L_{ij} = \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon \\ \epsilon^3 & \epsilon^2 & 1 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \epsilon^p H_d, \qquad \nu^D_{ij} = \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \epsilon^{a_1} H_u$$

$$\nu^M_{ij} = \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \epsilon^{a_2} \qquad \sim \mathrm{M}^{\nu}_{\mathrm{light}}$$

$\epsilon \sim 0.2$

Structure enforced by Anomalous U(1) Symmetry or Discrete Z_N Gauge Symmetry via Froggatt-Nielsen Mechansim

Lopsided Mass Matrix Model in SO(10)

S.Barr and KSB,2002

$$L = \begin{pmatrix} 0 & 0 & \delta' \\ 0 & \delta & -\epsilon' \\ \rho' & \rho - \epsilon & 1 \end{pmatrix} m_D, \qquad D = \begin{pmatrix} 0 & 0 & \rho' \\ 0 & \delta & \rho - \epsilon' \\ \delta' & -\epsilon & 1 \end{pmatrix} m_D,$$

$$N = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \epsilon' \\ 0 & \epsilon & 1 \end{pmatrix} m_U, \qquad U = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \epsilon' \\ 0 & \epsilon & 1 \end{pmatrix} m_U$$

$$\begin{aligned} W_{\mathrm{Yuk}} \quad = \quad & 16_3 16_3 10_H + 16_2 16_3 10_H 45_H/M + \\ & 16_2 16_3 16_H 16'_H/M + 16_1 16_3 16_H 16'_H/M + \\ & 16_2 16_3 16_H 16'_H/M \end{aligned}$$

10 Parameters vs. 20 Observables $\Rightarrow$ **PREDICTIONS**

Predictions

$$1, \rho, \rho' \gg \epsilon, \epsilon' \gg \delta, \delta'$$

$$m_b \simeq m_\tau = \sqrt{1+\sigma^2} m_D$$

Buras, et al

$$\frac{m_s}{m_b} \simeq \frac{|\sigma\epsilon + \delta\rho/\sigma|}{1+\sigma^2}$$

$$\frac{m_\mu}{m_\tau} \simeq \frac{|\sigma\epsilon' + \delta\rho/\sigma|}{1+\sigma^2}$$

$$m_d m_s m_b \simeq m_e m_\mu m_\tau$$

Georgi-Jarlskog

$$\frac{m_c}{m_t} \simeq \epsilon\epsilon' \qquad \frac{m_u}{m_t} \simeq 0 \qquad m_\mu \neq m_s$$

$$|V_{us}| \simeq \frac{\delta'}{\epsilon + \delta\rho/\sigma^2} \qquad |V_{ub}| \simeq \frac{\delta'}{1+\sigma^2}$$

$$|V_{cb}| \simeq \frac{|\epsilon(2+\sigma^2) - \delta\rho|}{1+\sigma^2} \qquad \eta_{\mathrm{CP}} \simeq \frac{2\epsilon\rho Im(\delta)}{\sigma^2(1+\sigma^2)|V_{cb}|^2}$$

$$\tan\theta_{\mathrm{atm}} \simeq \frac{m_s}{m_b}\left|\frac{V_{us}}{V_{ub}}\right|$$

$$\tan\theta_\odot \simeq (0.4 - 0.6)$$

$$|U_{e3}| \simeq 0.06$$

Lepton Flavor Violation and Neutrino Mass

Seesaw mechanism naturally explains small n - mass.

$$\mathcal{L} = \bar{\nu}_L M_D \nu_R + \frac{1}{2} {\nu_R}^T M_R \nu_R + h.c.$$

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

Current neutrino-oscillation data suggests

$$M_R \sim (10^{12} - 10^{15})\ \mathrm{GeV}$$

Flavor change in neutrino-sector

Flavor change in charged leptons

In standard model with Seesaw, leptonic flavor changing is very tiny.

$$Br(\mu \to e\gamma) \propto \frac{1}{M_{Pl}^4} \sim 10^{-50}$$

In Supersymmetric Standard model

$$Br(\mu \to e\gamma) \propto \frac{1}{M_{SUSY}^4} \sim 10^{-10}$$

For $M_R \leq \mu \leq M_{Pl}$ n_R **active**

flavor violation in neutrino sector Transmitted to Sleptons

Borzumati, Masiero (1986)

Hall, Kostelecky, Raby (1986)

Hisano et. al., (1995)

SUSY Seesaw Mechanism

$$\mathcal{W} = f\nu^c\nu^c\Delta + Y_\nu \nu^c L H_u$$

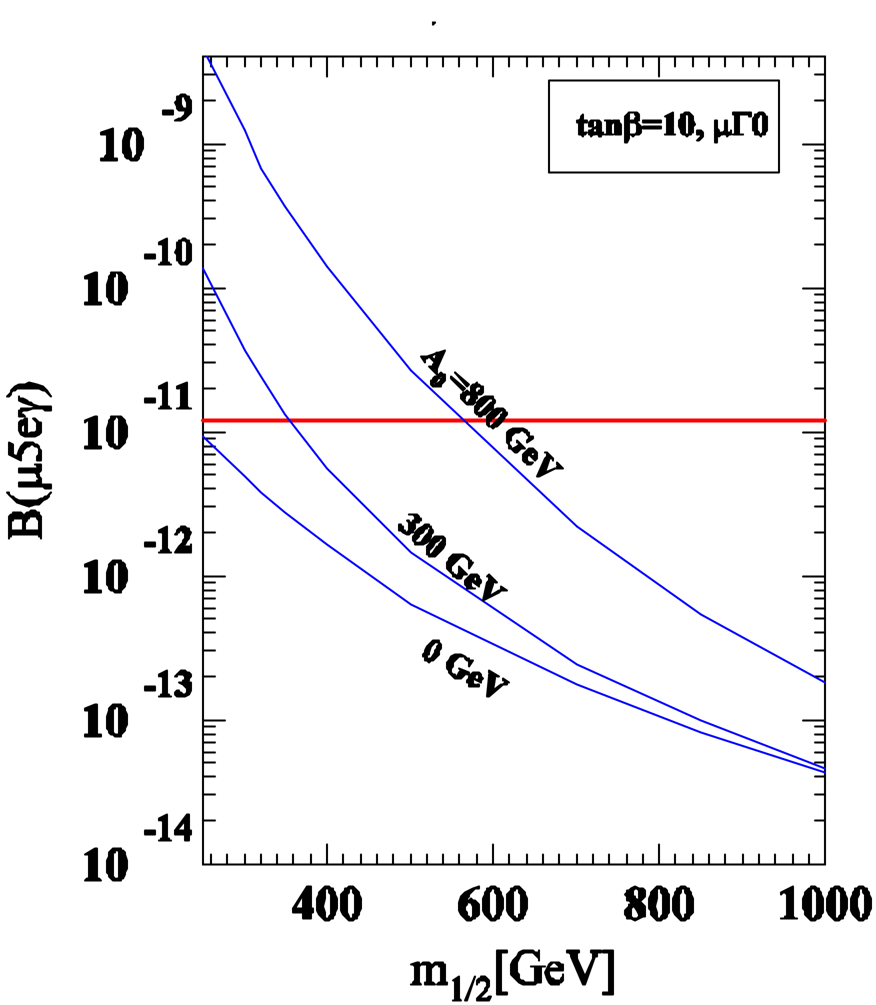
$$M_D = Y_\nu v_u \ ; \ M_R = f v_{B-L}$$

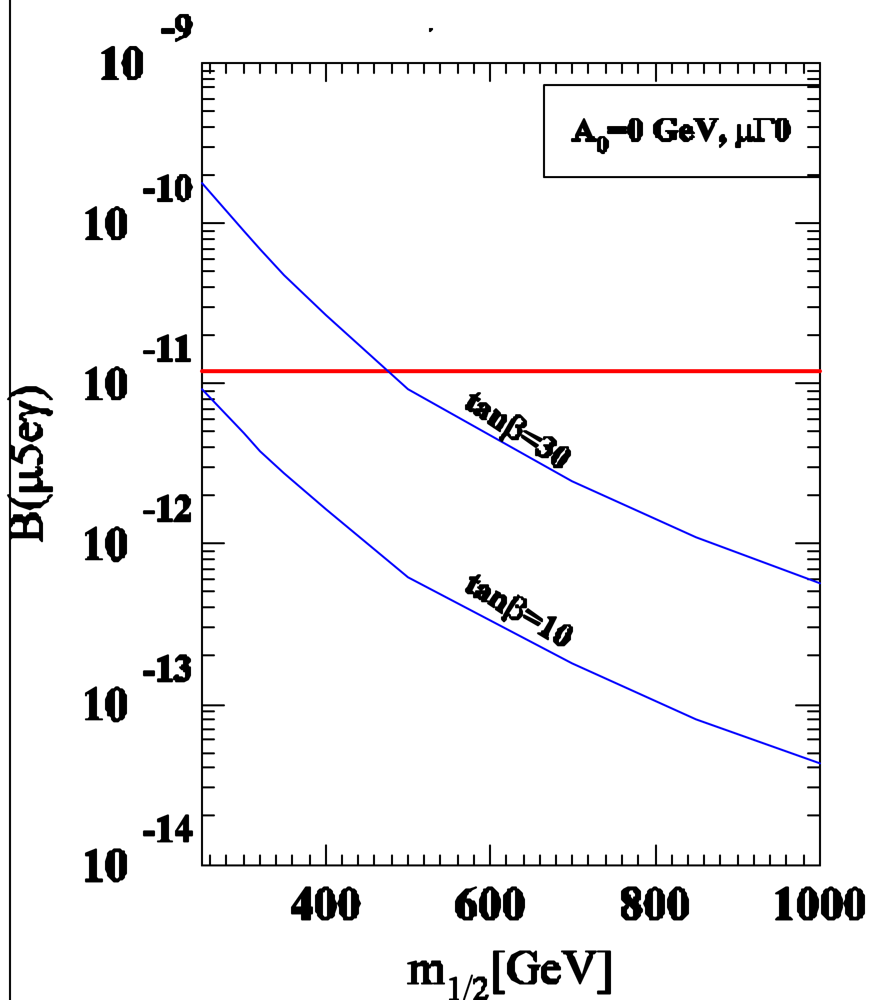
If *B*-*L* is gauged, M_R must arise through Yukawa couplings.

Flavor violation may reside entirely in f or entirely in Y_n

$\mu \rightarrow e\gamma$

Majorana LFV





Dutta, Mohapatra, KB (2002)

Conclusions

- **Grand Unification motivated on various grounds**
- **Challenges in GUT-model Building:**

  Doublet-triplet Splitting

  Realistic Quark and Lepton Masses

  Proton Decay

- **Promises of GUT models:**

  Predictive Quark-Lepton Spectrum

  Naturally Small Neutrino Masses

  Baryon Asymmetry Generation

  Proton Decay in Observable Range