Fermion masses and mixings

(Profile of a viable string theory)

G.G.Ross, KITP, Santa Barbara, Sept 2006

The Standard Model

- Gauge structure
  $SU(3)\times SU(2)\times U(1) \subset$ SU(5), SO(10)?
- Multiplet content
  $3(10+\bar{5}+1)+H(5?)$
- Fundamental parameters
  M_{Higgs} - SUSY?
  $g_i \subset g_5$
  quark and lepton masses and mixings
  CP violating phase
- Precision tests - no non-SM $(+\nu)$ phenomena

String phenomenology

- Can obtain gauge and multiplet structure
  + underlying GUT structure e.g. heterotic string
- Wilson line breaking at the compactification scale can elegantly solve the doublet triplet splitting problem
  $G \Rightarrow SU(3)\times SU(2)\times U(1)$
  $+ \; 3(10+\bar{5}+1) \; + \; H_u + H_d$ (MSSM)
- Nucleon stability : Z_2 matter parity? Z_3 baryon parity?
  $Z_2 \otimes Z_3$ baryon parity

- Many string possibilities - not necessarily with GUT(?) -
  possibly with a low scale of unification

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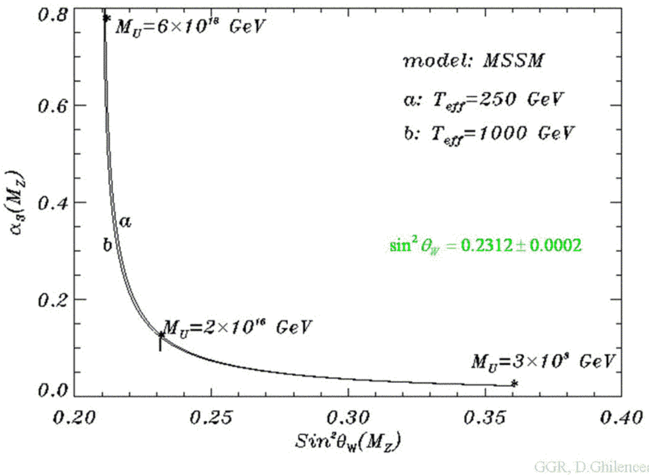
  $Z_2 \otimes Z_3$ baryon parity

How can we distinguish them?

Unification Hints - gauge couplings

SUSY UNIFICATION ✓



STRING UNIFICATION ✓

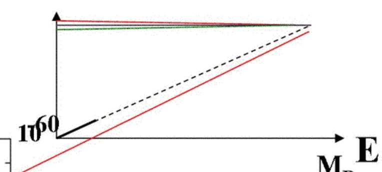
To preserve accuracy :

$$M_s R_c \le 2$$

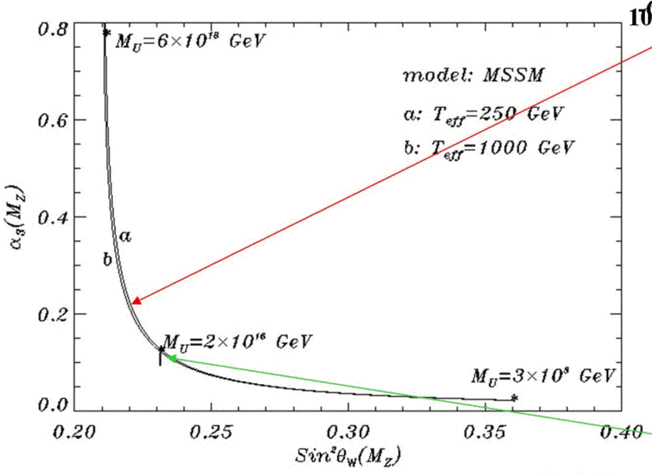
GGR

$$\sin^2\theta_W = 0.2334 \pm 0.0025 - 0.25(\alpha_s - 0.119) = 0.2312 \pm 0.0002 \quad (Expt)$$
$$\alpha_s = 0.134 \pm 0.01 - 4(\sin^2\theta_W - 0.2334) = 0.119 \pm 0.003(?) \quad (Expt)$$

Unification with gravity?



$$M_U^{WCHS} = 3.6\times10^{17}\,GeV\,?$$

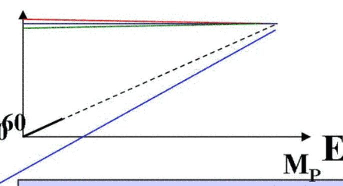


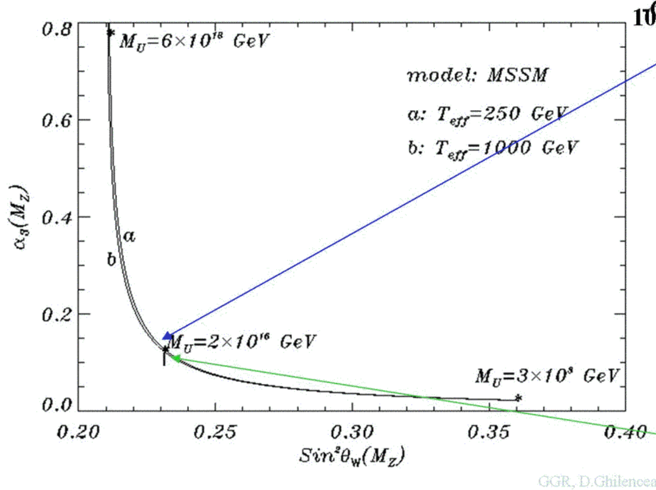
$$M_U = (2.5 \pm 2).10^{16}\,GeV$$

$$\sin^2\theta_W = 0.2334 \pm 0.0025 - 0.25(\alpha_s - 0.119) = 0.2312 \pm 0.0002 \quad (Expt)$$
$$\alpha_s = 0.134 \pm 0.01 - 4(\sin^2\theta_W - 0.2334) = 0.119 \pm 0.003(?) \quad (Expt)$$

Unification with gravity?

String unification with gravity





+ Wilson line breaking

$e.g.\quad Z_3 : SU(5) \to SM$

$M_U^{WCHS} = 6.10^{16} GeV,$

$\delta(\sin^2\theta_W) = -0.0018$

$\delta(\alpha_s) = -0.008$

$$M_X = (2.5 \pm 2).10^{16} GeV$$

$$\sin^2\theta_W = 0.2334 \pm 0.0025 - 0.25(\alpha_s - 0.119) \quad = 0.2312 \pm 0.0002 \quad (Expt)$$

$$\alpha_s = 0.134 \pm 0.01 - 4(\sin^2\theta_W - 0.2334) \quad = 0.119 \pm 0.003(?) \quad (Expt)$$

Fermion Masses

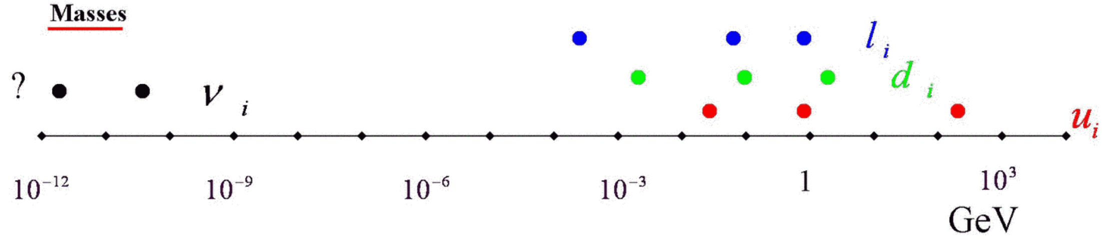
The Standard Model

$$L_{Yukawa} = Y_{ij}^u \; Q^i u^{c,j} H + Y_{ij}^d \; Q^i d^{c,j} \overline{H}$$

$$M^u{}_{ij} = Y_{ij}^{\;u} < H^0 > \qquad M^d{}_{ij} = Y_{ij}^{\;d} < \overline{H}^0 >$$

DATA :

Masses



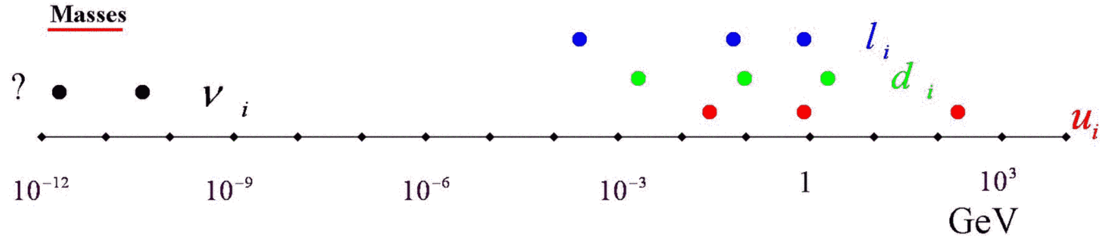
Mixing Quarks

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.218-0.224 & 0.002-0.005 \\ 0.218-0.224 & 1 & 0.032-0.048 \\ 0.004-0.015 & 0.03-0.048 & 1 \end{pmatrix}$$

$$M^{u} = V_L^{\dagger} \underline{M^{u}_{Diag}} V_R \qquad M^{d} = U_L^{\dagger} \underline{M^{d}_{Diag}} U_R \qquad \underline{V_{CKM}} = V_L^{\dagger} U_L$$

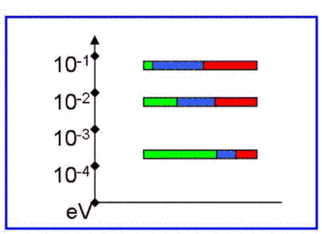
DATA :

Masses



Mixing Quarks Leptons

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.218-0.224 & 0.002-0.005 \\ 0.218-0.224 & 1 & 0.032-0.048 \\ 0.004-0.015 & 0.03-0.048 & 1 \end{pmatrix} \qquad V_{MNS} = \begin{pmatrix} 0.79-0.88 & 0.48-0.61 & <0.2 \\ 0.27-0.49 & 0.45-0.71 & 0.52-0.82 \\ 0.28-0.5 & 0.51-0.65 & 0.57-0.81 \end{pmatrix}$$



$$\approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \square\, 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Bi-Tri Maximal Mixing …
Non Abelian Structure?

- Data $\leftrightarrow$ Theory (Y_{ij})

...*underconstrained - need mixing angles but only* $\underline{V_{CKM}} = V_L^\dagger U_L$ *measured*

- Hierarchy $\leftrightarrow$ Democracy

$$\begin{pmatrix} a\varepsilon^2 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} \leftrightarrow \begin{pmatrix} 1+2\varepsilon+a\varepsilon^2 & 1-a\varepsilon^2 \\ 1-a\varepsilon^2 & 1-2\varepsilon+a\varepsilon^2 \end{pmatrix} / 2$$

$$\theta_C = \theta^u - \theta^d$$

Quark Textures

Hierarchical :

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix}$$

$$V_{23} \cong \frac{m_{23}}{m_{33}} + \frac{m_{32}}{m_{33}}\frac{m_s}{m_b}$$

$$V_{12} \cong \frac{m_{12}}{m_{22}} + \frac{m_{21}}{m_{22}}\frac{m_d}{m_s}$$

$$V_{13} \cong \frac{m_{13}}{m_{33}} + \frac{m_{31}}{m_{33}}\frac{m_d}{m_b}$$

Expansion parameter $\varepsilon = 0.15$

$$\frac{M^d}{m_b} = \begin{pmatrix} \leq \varepsilon^4 & \varepsilon^3 & \leq \varepsilon^3 \\ ? & \leq \varepsilon^2 & \varepsilon^2 \\ ? & ? & 1 \end{pmatrix}$$

m_d → ε^4; V_{us} → ε^3 (1,2); V_{ub} → ε^3 (1,3); V_{cb} → ε^2 (2,3); m_s → ε^2 (2,2)

Quark Textures

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Expansion parameter $\varepsilon = 0.15$

$$\frac{M^d}{m_b} = \begin{pmatrix} \le \varepsilon^4 & \varepsilon^3 & \le \varepsilon^3 \\ \le \varepsilon^3 & \le \varepsilon^2 & \varepsilon^2 \\ \le \varepsilon & \le 1 & 1 \end{pmatrix}$$

m_d, V_{us}, V_{ub}, V_{cb}, m_s, $\mathrm{Det}[M]$

Data ↔ Theory $(Y_{ij} \propto M_{ij})$

Symmetric fit

$$\frac{M^d}{m_b} = \begin{pmatrix} 0 & 1.5\varepsilon^3 & 0.4e^{i20}\varepsilon^3 \\ 1.5\varepsilon^3 & \varepsilon^2 & 1.3\varepsilon^2 \\ 0.4e^{i20}\varepsilon^3 & 1.3\varepsilon^2 & 1 \end{pmatrix} \qquad \varepsilon = 0.15$$

$$\frac{M^u}{m_t} = \begin{pmatrix} 0 & \varepsilon'^3 & ?\,\varepsilon'^3 \\ \varepsilon'^3 & \varepsilon'^2 & ?\,\varepsilon'^2 \\ ?\,\varepsilon'^3 & ?\,\varepsilon'^2 & 1 \end{pmatrix} \qquad \varepsilon' = 0.05$$

Roberts
Romanino
GGR
Velasco Sevilla

Asymmetric fit

$$\frac{M^d}{m_b} = \begin{pmatrix} 0 & 1.7\varepsilon^3 & 0 \\ 1.7\varepsilon^3 & 0 & 5\varepsilon^2 \\ 0 & 0.3 & 1 \end{pmatrix} \qquad \frac{M^u}{m_t} = \begin{pmatrix} 0 & 2\varepsilon'^3 & 0 \\ \varepsilon'^3 & 0 & 2\varepsilon' \\ 0 & 0.6\varepsilon' & 1 \end{pmatrix}$$

Texture zero

$$\frac{M^d}{m_b} = \begin{pmatrix} 0 & \varepsilon^3 & \le \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ ? & ? & 1 \end{pmatrix}$$

$\le \varepsilon^5$

symmetric

GATTO, SARTORI, TONIN

C$\not{P}$ SM phase

$$|V_{us}| = \left| \sqrt{\frac{m_d}{m_s}} - e^{i\delta} \sqrt{\frac{m_u}{m_c}} \right|$$

Fritzsch, Weinberg
Roberts, Romanino, GGR, Velasco

$0.217 - 0.222$ $c.f.$ $|(0.216 - 0.214) - (0.07 - 0.076)e^{i\delta}|$

$= 0.213 - 0.223, \ \delta = 90^0$

Origin of M_{quark} structure?

Symmetric fit

$$\frac{M^d}{m_b} = \begin{pmatrix} 0 & 1.5\varepsilon^3 & 0.4e^{i20}\varepsilon^3 \\ 1.5\varepsilon^3 & \varepsilon^2 & 1.3\varepsilon^2 \\ 0.4e^{i20}\varepsilon^3 & 1.3\varepsilon^2 & 1 \end{pmatrix} \qquad \varepsilon = 0.15$$

$$\frac{M^u}{m_t} = \begin{pmatrix} 0 & \varepsilon'^3 & ?\varepsilon'^3 \\ \varepsilon'^3 & \varepsilon'^2 & ?\varepsilon'^2 \\ ?\varepsilon'^3 & ?\varepsilon'^2 & 1 \end{pmatrix} \qquad \varepsilon' = 0.05$$

Roberts
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GGR
Velasco Sevilla

Asymmetric fit

$$\frac{M^d}{m_b} = \begin{pmatrix} 0 & 1.7\varepsilon^3 & 0 \\ 1.7\varepsilon^3 & 0 & 5\varepsilon^2 \\ 0 & 0.3 & 1 \end{pmatrix} \qquad \frac{M^u}{m_t} = \begin{pmatrix} 0 & 2\varepsilon'^3 & 0 \\ \varepsilon'^3 & 0 & 2\varepsilon' \\ 0 & 0.6\varepsilon' & 1 \end{pmatrix}$$

Origin of M_{quark} structure

- Third generation heavy $h_{t,b} \sim g$ OK (specific string calculations + IRFP)

  $h_b = h_\tau = (?) h_t$ (GUT?)

- Hierarchy :

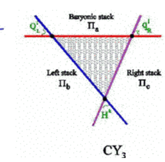
  ⇒ spontaneously broken family symmetry - mass matrix elements ordered by :

  … dimension of operator $\bar{\psi}_L \psi_R H \left(\frac{\langle\theta\rangle}{M}\right)^n$ ← 0.2 Froggatt-Nielsen

  … order of radiative corrections $\propto (h^2/16\pi^2)^n$

  ⇒ spatial separation

  $Y_{ijk} \sim h_{qu} \ldots d\, e^{-\frac{A_{ijk}}{2\pi\alpha'}} e^{2\pi i \ldots}$



Textures and flavour models

Symmetries Coherent picture of quark and lepton masses and mixing?

M^u (Family?)	← $GUT?$ →	M^ν (Family?)
$SU(2)_L \otimes SU(2)_R$? ↕		↕ $SU(2)_L \otimes SU(2)_R$?
M^d	← $GUT?$ →	M^l

Symmetries and textures

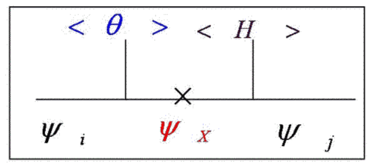
Hierarchical structure strongly suggests a broken symmetry

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \xrightarrow{<\theta> \neq 0} \begin{pmatrix} 0 & 0 & 0 \\ 0 & a\varepsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$a = O(1), \quad \varepsilon^2 = \frac{<\theta>}{M}$$

→ MESSENGER SECTOR?

$$m_{ij} = \frac{<\theta><H>}{M_X}$$



Froggatt, Nielsen

→ FAMILY SYMMETRY?

Abelian, Non-Abelian $\subset (U(3))^6$

Abelian Family symmetry

θ_{CKM} ✓

$$\frac{\overline{\psi}_R M^d \psi_L}{m_b} = \overset{\;\;-3\quad\; 2\quad\; 1}{(\bar{d}_L \quad \bar{s}_L \quad \bar{b}_L)} \begin{pmatrix} 0 & \varepsilon^3 & \varepsilon^4 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^4 & \varepsilon & 1 \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \begin{matrix} -3 \\ 2 \\ 1 \end{matrix}$$

$O(\varepsilon^8)$ ✓

$$V_{cb} = (40.4 \pm 1.8)10^{-3} = O\left(\tfrac{m_d}{m_s}\right)$$ ✗

$$Q_{Higgs} = -2, \qquad \varepsilon = \frac{\overset{1}{<\theta>}}{M_X} = \frac{\overset{-1}{<\bar{\theta}>}}{M_X}$$

Ibanez GGR

Non-Abelian Family symmetry?

$$\frac{\bar{\psi}_R M^d \psi_L}{m_b} = \begin{pmatrix} \bar{d}_L & \bar{s}_L & \bar{b}_L \end{pmatrix}^{\;-3\;\;2\;\;1} \begin{pmatrix} 0 & \varepsilon^3 & \varepsilon^4 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^4 & \varepsilon^2 & 1 \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \begin{matrix} -3 \\ 2 \\ 1 \end{matrix}$$

✓

$$V_{cb} = (40.4 \pm 1.8)10^{-3} = O\left(\frac{m_d}{m_s}\right)$$

$$Q_{Higgs} = -2, \qquad \varepsilon = \frac{\overset{1}{<\theta>}}{M_X} = \frac{\overset{-1}{<\bar{\theta}>}}{M_X}$$

Ibanez GGR

- **Extension to charged leptons – GUT?**

$$Det(M^l) = Det(M^d)|_{M_X}$$

$$\frac{M^l}{m_\tau} = \begin{pmatrix} 0 & \varepsilon^3 & ?\varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & ?\varepsilon^2 \\ ?\varepsilon^2 & ?\varepsilon^2 & 1 \end{pmatrix} \qquad ?$$

$$\frac{m_b}{m_\tau}(M_X) = 1$$

• Extension to charged leptons – GUT?

$Det(M^l) = Det(M^d)|_{M_X}$

$$\frac{M^l}{m_\tau} = \begin{pmatrix} 0 & \varepsilon^3 & ?\varepsilon^3 \\ \varepsilon^3 & 3\varepsilon^2 & ?\varepsilon^2 \\ ?\varepsilon^2 & ?\varepsilon^2 & 1 \end{pmatrix}$$

$\frac{m_s}{m_\mu}(M_X) = \frac{1}{3}$

$\frac{m_d}{m_e}(M_X) = 3$

Georgi Jarlskog

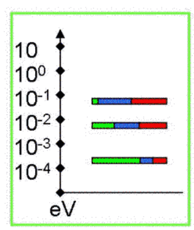
$\frac{m_b}{m_\tau}(M_X) = 1$

• Extension to neutrinos???

$$\mathcal{L}^\nu_{eff} = a\,\psi_i\theta^i_{23}\psi_j\theta^j_{23} + b\,\psi_i\theta^i_{123}\psi_j\theta^j_{123}$$

Tri-Bi-Maximal mixing

$\theta_{23} = \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}$ $\theta_{123} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$



$$\mathcal{L}^{l,q} = a\,\psi_i\theta^i_3\psi^c_j\theta^j_3 + \ldots$$

$\theta_3 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$

	θ_3	
q_i, l_i	$SU(3) \to SU(2) \to ..$	
	45^0	35^0
ν_i	$SU(3) \to SU(2)' \to ..$	
	θ_{23}	θ_{123}

??? Vacuum alignment+decoupling

…possible with "see-saw" plus non Abelian (discrete) family symmetry

- "See-saw" with sequential domination $M_\nu = M_D^\nu M_M^{-1} M_D^{\nu T}$ SRHD King

$$M_M \approx \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \qquad M_1 << M_2 << M_3 \qquad M_3 \text{ suppresses } \theta_3 \text{ contribution}$$

$$\mathcal{L}^{l,\nu}_{Dirac} = \alpha\, \psi_i \theta_3^i \psi_j^c \theta_3^j + \beta\, \psi_i \theta_{23}^i \psi^c{}_j \theta_{23}^j + \gamma\, \psi_i \theta_{123}^i \psi^c{}_j \theta_{123}^j \qquad \alpha > \beta > \gamma$$

small

$$\mathcal{L}^\nu_{eff} = \frac{\beta^2}{M_1} \psi_i \theta_{123}^i \psi_j \theta_{123}^j + \frac{\gamma^2}{M_2} \psi_i \theta_{23}^i \psi_j \theta_{23}^j + \frac{(\alpha+\beta+\gamma)^2}{M_3} \psi_i \theta_3^i \psi_j \theta_3^j$$

- (Discrete) Non-Abelian family symmetry

Vacuum alignment $\theta_3 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad \theta_{23} = \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \quad \theta_{123} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$

A complete model

$$SU(3) \otimes SU(2) \otimes U(1) \otimes G_f \otimes G \subset SO(10) \otimes G_f \otimes G$$

King, GGR, Varzielas

$G_f = \Delta(27)\ (\equiv Z_3 \ltimes Z_3') \subset SU(3)_f$ vacuum alignment readily obtained

$G = U(1) \otimes Z_2 \otimes R$

P_Y)($\frac{1}{M^2}\bar\theta_3 \psi_i \bar\theta_3 \psi_j H$ + $\frac{1}{M^3}\bar\theta_{23} \psi_i \bar\theta_{23} \psi_j H H_{45}$ + $\frac{1}{M^2}\bar\theta_{23} \psi_i \bar\theta_{123} \psi_j H$ + $\frac{1}{M^2}\bar\theta_{123} \psi_i \bar\theta_{23} \psi_j H$ + $\frac{1}{M^7}\bar\theta_{123} \psi_i \bar\theta_3 \psi_j H H_{45} \bar\theta_3 \bar\theta_{3k} \bar\theta_{23} \bar\theta_{3l}$

+ $\frac{1}{M^7}\bar\theta_3 \psi_i \bar\theta_{123} \psi_j H H_{45} \bar\theta_3 \bar\theta_{3k} \bar\theta_{23} \bar\theta_{3l}$ + $\frac{1}{M^6}\bar\theta_{123} \psi_i \bar\theta_{123} \psi_j H \bar\theta_3 \bar\theta_{3k} \bar\theta_3 \bar\theta_{3l}$

P_M)($\frac{1}{M}\theta \psi_i \theta \psi_j$ + $\frac{1}{M^5}\bar\theta_{23} \psi_i \bar\theta_{23} \psi_j \theta^k \bar\theta_{3k} \theta^l \bar\theta_{3l}$ + $\frac{1}{M^5}\bar\theta_{123} \psi_i \bar\theta_{123} \psi_j \theta^k \bar\theta_{3k} \theta^l \bar\theta_{3l}$

$\sin^2\theta_{12} = \frac{1}{3} \pm^{0.052}_{0.048}$
$\sin^2\theta_{23} = \frac{1}{2} \pm^{0.061}_{0.058}$
$\sin^2\theta_{13} = 0.0028$

From charged lepton mixing

$c.f. \sin^2\theta^{\exp t}_{13} < 0.025$

Strings and fermion masses

- Majorana masses — Occur in some string compactifications e.g. 3 generation Calabi Yau ✓

- Family symmetries?
  - Abelian symmetries $\Pi_i\, U(1)_i$ ✓
  - Non-Abelian symmetries $SU(3)_f$ ✗
  - $\Delta(27)...$ ✓

e.g. Calabi Yau manifold Z_3 □ Z_2 □ (Z_3 ◁ Z_3 ◁ .. (Tian Yau

$+n(f+\overline{f})$

(but 3 generation model R □ $R_0/$(Z_3 □ Z_3 (...)

also in small $\frac{R_c}{R_s}$ limit Yukawa coupling calculable : SU(2)^n symmetry

(a possible origin of the non Abelian structure?)

- **CP violation** SUSY CP problem - $\phi_A = Arg(Am^*_{1/2}), \quad \phi_B = Arg(Bm^*_{1/2}) < 10^{-2}$?

In string theory CP is a discrete gauge symmetry : Dine, Leigh, MacIntyre

⇨ CP conserved by compactification
- spontaneously broken on family symmetry breaking

⇨ CP violation from Yukawa sector ✓?

$$P = \left(\tfrac{\theta}{M}\right)^{\alpha(i,j)} Q_i q^c_j H_a + ..$$

$$A_{ij} Y_{ij} \tilde{Q}_i \tilde{q}^c_j H_a = (3+\alpha(i,j)) < P^* > Y_{ij} \tilde{Q}_i \tilde{q}^c_j H_a$$

Cannot align Yukawa and A terms

$$\frac{M^d}{m_b} = \begin{pmatrix} \le\varepsilon^4 & \varepsilon^3 & \le\varepsilon^3 \\ \le\varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \le\varepsilon^2 & \le\varepsilon^2 & 1 \end{pmatrix}$$

$(m_d, \Delta S \neq 0\, \Delta Q = 0)$ $\Delta S \neq 0\, \Delta Q = 0$ $(A_{\alpha\beta\gamma})$ CP $(A_{\alpha\beta\gamma})$ Vives, GGR

- OK with suitable family symmetry

$\mu \to e\gamma, \quad EDM$ close to experimental limits

String Profile

- Z_3 baryon parity or above
- $M_s R_c \leq 2$
- Wilson line breaking
- Non-Abelian (discrete) family symmetry
- Spontaneously broken CP symmetry

Phenomenological implications

- P-decay dimension 6 and above
- ? (High scale compactification)
- ? (Wilson line breaking)
- A new solution to the SUSY flavour problem - SUSY scalar spectrum

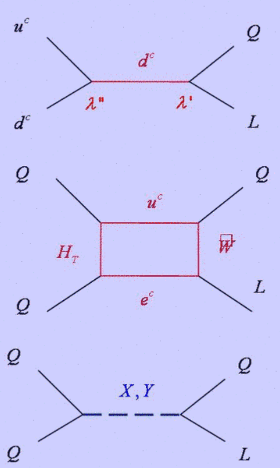
  n edm, $\mu \to e\gamma$ close to present limits

  Light Pseudo Goldstone familons
- Axion

Nucleon decay

$P_{D=4} = \lambda L L e^c + \lambda' L Q d^c + \lambda'' u^c d^c d^c$ — *R – parity violating*

$\Delta L=1$ $\Delta L=1$ $\Delta B=-1$ (forbidden in MSSM)



$D=4 \quad \propto \frac{1}{M_d^2}$ ×

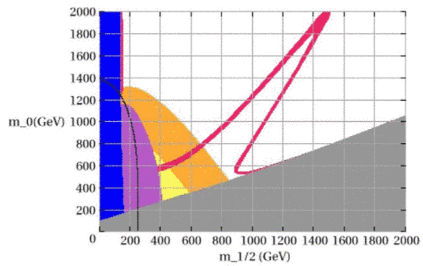
$D=5 \quad \propto \frac{1}{M_{H_T}}, \quad M_{H_T} > 10^{25}\,GeV$ ×

$D=6 \quad \propto \frac{1}{M_X}, \quad M_X > 10^{16}\,GeV$ ✓

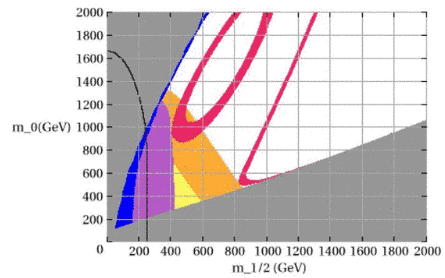
Baryon Parity : $\lambda''=0$ — $Z_3 : g(Q, u^c, d^c, L, e^c, H_1, H_2) = (1, \alpha^2, \alpha, \alpha^2, \alpha^2, \alpha, \alpha^2)$

(Anomaly free)

Ibanez, GGR ;
Allanach, Dedes, Dreiner



$$m_{Q_i} = m_{u_i^c} = m_{d_i^c} = m_H = m_0$$



$$m_{Q_{i\neq 3}} = m_{u_i^c} = m_{d_i^c} = m_H = m_0$$

$$m_{Q_3} = m_{Q i\neq 3}(1 \pm 0.2)$$

ϕ_3 family symmetry breaking

Ramage,GGR