Horizontal Theories and Soft Breaking

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Flavour Physics

- 3 fermionic families with identical gauge numbers ?

- Origin of the mass hierarchy ?

- Intergenerational mixing ?

SM

12 masses

10 mixing angles

and phases . . .

MSSM

fermion + sfermion

masses + mixings

= 124 !!!!

Flavour and CP Problems

- Yukawa couplings in Superpotential and soft breaking masses different origins.
- In general, not simultaneously diagonalizable
- New complex parameters in W and soft breaking terms.

$\Downarrow$

Too large Flavour Changing and CP violating contributions

Stringent bounds on sfermion mass matrices and SUSY phases at M_W.

Solutions:

Universality, Alignment ...

Minimal Supergravity

Canonical Kähler potential for chiral Superfields $K = \sum_i |\phi^i|^2$ and Superpotential

$$W = W^{hid}(\chi_k) + \left(\frac{\theta}{M}\right)^{\alpha(i,j)} H_a Q_{Li} q^c_{Rj} + \dots$$

with (perhaps several) θ/M generate Yukawa structure.

Scalar potential (F-terms):

$$V = e^K \left[\sum_i \left| \frac{\partial W}{\partial \phi_i} + \phi^{i*} W \right|^2 - 3|W|^2 \right]$$

with $F_{\phi_i} = -e^{K/2}\,(W_i^* + \phi_i W^*)$.

SUSY breaking in hidden sector $\langle W \rangle \simeq m_{3/2}$, we obtain Soft Breaking terms.

Cannonical Kähler potential $\rightarrow$ Universal scalar masses

$$m^2_{\phi_i}\ \phi_i \phi^{i*} = |\langle W \rangle|^2\ \phi_i \phi^{i*}$$

However trilinear couplings:

$$A_{ij}\ Y_{ij}\ H_a \tilde{Q}_{Li} \tilde{q}^c_{Rj} =$$

$$\left(\frac{\partial W}{\partial H_a} H_a + \frac{\partial W}{\partial \tilde{Q}_{Li}} \tilde{Q}_{Li} + \frac{\partial W}{\partial \tilde{q}^c_{Rj}} \tilde{q}^c_{Rj} \right) \langle W^* \rangle +$$

$$\frac{\partial W}{\partial \theta} \theta\ \langle W^* \rangle = (3 + \alpha(i,j)) \langle W^* \rangle\ Y_{ij}\ H_a \tilde{Q}_{Li} \tilde{q}^c_{Rj}$$

Yukawa matrices as effective operators as powers of scalar vevs. Irrespective of the source of SUSY breaking

$\Downarrow$

Nonuniversal trilinear terms !!

Universality and Alignment not possible in this framework.

$\Downarrow$

New sources of FCNC

Yukawa Textures and Soft breaking

- Explain fermion masses and mixings in terms of a few fundamental parameters
- Off-diagonal entries small relative on-diagonal
- Approximate texture zeros: mixings in terms of masses

Textures fitting the experimental data:

R. G. Roberts, A. Romanino, G. G. Ross and L. Velasco-Sevilla, Nucl. Phys. B **615** (2001) 358

Symmetric Texture

$$\frac{M_u}{m_t} = \begin{pmatrix} 0 & b'\epsilon^3 & c'\epsilon^4 \\ b'\epsilon^3 & \epsilon^2 & a'\epsilon^2 \\ c'\epsilon^4 & a'\epsilon^2 & 1 \end{pmatrix} \quad \frac{M_d}{m_b} = \begin{pmatrix} 0 & b\bar{\epsilon}^3 & c\bar{\epsilon}^4 \\ b\bar{\epsilon}^3 & \bar{\epsilon}^2 & a\bar{\epsilon}^2 \\ c\bar{\epsilon}^4 & a\bar{\epsilon}^2 & 1 \end{pmatrix}$$

with $\epsilon \simeq 0.05$ and $\bar{\epsilon} \simeq 0.15$

if $\epsilon = \langle\theta\rangle/M$ and $\bar{\epsilon} = \langle\bar{\theta}\rangle/M$ we obtain as trilinear

$$(Y^A)_{ij} \equiv Y_{ij}A_{ij} = h_3 m_{3/2} \begin{pmatrix} 0 & 6b'\epsilon^3 & 7c'\epsilon^4 \\ 6b'\epsilon^3 & 5\epsilon^2 & 5a'\epsilon^2 \\ 7c'\epsilon^4 & 5a'\epsilon^2 & 3 \end{pmatrix}$$

Asymmetric Texture

$$\frac{M_u}{m_t} = \begin{pmatrix} 0 & c\epsilon\epsilon' & 0 \\ c\epsilon\epsilon' & \beta\epsilon^2 & b\epsilon \\ 0 & a\epsilon & 1 \end{pmatrix} \quad \frac{M_d}{m_b} = \begin{pmatrix} 0 & \epsilon' & 0 \\ \epsilon' & \alpha\epsilon & \epsilon \\ 0 & t & 1 \end{pmatrix}$$

with $\epsilon \simeq 0.08$, $\epsilon' \simeq 0.006$ and $t \simeq 0.3.$

if $\epsilon = \langle\theta\rangle/M$, $\bar{\epsilon}' = \langle\bar{\theta}'\rangle/M$ and $t = \langle\bar{\theta}_t\rangle/M$

$$(Y_u^A)_{ij} = h_t m_{3/2} \begin{pmatrix} 0 & 5c\epsilon\epsilon' & 0 \\ 5c\epsilon\epsilon' & 5\beta\epsilon^2 & 4b\epsilon \\ 0 & 4a\epsilon & 3 \end{pmatrix}$$

$$(Y_b^A)_{ij} = h_b m_{3/2} \begin{pmatrix} 0 & 4\epsilon' & 0 \\ 4\epsilon' & 4\alpha\epsilon & 4\epsilon \\ 0 & 4t & 3 \end{pmatrix}$$

Non diagonal Trilinear couplings $\Rightarrow$ Left-Right FCNC

FCNC and CP Phenomenology

- Soft breaking terms at high scale $\sim M_{GUT}$
- RGE evolution to electroweak scale.

1.- Diagonal elements receive large gaugino contribution

$$(m^2_{\tilde{f}})_{ii}(M_W) \simeq 6\ m^2_{1/2} + (m^2_{\tilde{f}})_{ii}(M_{Pl})$$

2.- Trilinear couplings align with gaugino

$$A_t(M_W) \simeq 0.25\ A_t^0 - 2\ m_{1/2}$$

$$A_u(M_W) \simeq 0.6\ A_u^0 - 2.9\ m_{1/2}$$

$$A_d(M_W) \simeq 1\ A_d^0 - 3.6\ m_{1/2}$$

small $\tan\beta \simeq 5$:

$$A_b(M_W) \simeq 1\ A_b^0 - 3.4\ m_{1/2}$$

large $\tan\beta \simeq 30$:

$$A_b(M_W) \simeq 0.74\ A_b^0 - 2.9\ m_{1/2}$$

$$\Downarrow$$

"String CP problem" and MI bounds

"String CP problem"

S. Abel, S. Khalil and O. Lebedev, hep-ph/0112260.

- Yukawa matrices contain $\mathcal{O}(1)$ CP violating phases (δ_{CKM})
- If nonuniversal, even real A can overproduce EDMs

Super CKM basis

$$V_{qL}^{\dagger} Y_q V_{qR} = \mathrm{Diag}(h_1, h_2, h_3) \qquad \tilde{Y}_q^A = V_{qL}^{\dagger} Y_q^A V_{qR}$$

Can we have $(\tilde{Y}_u^A)_{11} \propto \epsilon\, m_t\, e^{i\phi}$??

Abel et al., assume nonuniversal A terms and $(V_{L,R})_{ij} \sim V_{ij}^{CKM}$, both in up and down sector

However

- Before diagonalizing Yukawas, with real trilinear terms $\arg(Y_q^A)_{ij} = \arg(Y_q)_{ij}$.

$$h_u = (V_L)^*_{i1} (Y_u)_{ij} (V_R)_{j1} \simeq \epsilon^4$$

$$(\tilde{Y}_u^A)_{11} = (V_L)^*_{i1} (\tilde{Y}_u^A)_{ij} (V_R)_{j1}$$

If there is a single leading contribution $h^u \simeq (V_L)^*_{21} (Y_u)_{21}$ then $(\tilde{Y}_u^A)_{11}$ is also real .

If several terms of the same order contribute to the up mass,

$$h^u \simeq (V_L)^*_{21}(Y_u)_{21} + (V_L)^*_{21}(Y_u)_{22}(V_R)_{21} + \dots$$
$$= ae^{\phi_a}\epsilon^4 + be^{\phi_b}\epsilon^4 + \dots$$
$$(\tilde{Y}^A_u)_{11} = \alpha(1,2)ae^{\phi_a}\epsilon^4 + \alpha(2,2)be^{\phi_b}\epsilon^4 + \dots$$

which is not real in general... EDMs constrain this element to have a phase $\lesssim 10^{-2}$

$\Rightarrow$ "String CP problem".

However, freedom to rotate away 6 phases from Yukawa $\Rightarrow$ observable effects must involve all three generations .

Possible solutions:

- Hermitian Yukawa (and trilinear)
- single contribution to h_u
- Higher order 3^{rd} generation contrib. to Y^A_{11}

Important constraints on the structure of the Yukawas $\Rightarrow$ Talk by G. G. Ross tomorrow

Mass Insertion limits

Mass Insertions

$$(\delta^d_A)_{ij} = \frac{(m^2_{\tilde{D}_A})_{ij}}{m^2_{\tilde{q}}}$$

$$(\delta^q_{LR})_{i\neq j} = \frac{v_q(\tilde{Y}^A_q)_{ij}}{6\ m^2_{1/2} + m^2_0}$$

$$\tilde{Y}^A_q \simeq \sqrt{3}\, m_{3/2}\ M_q/v_q + \frac{m_{3/2}}{\sqrt{3}} V^\dagger_L(\alpha(i,j)Y_{ij})V_R$$

Symmetric Texture

$$(\delta^d_{LR})_{21} \simeq \frac{m_{3/2} m_b \bar{\epsilon}^3}{6\ m^2_{1/2} + m^2_0} \simeq \frac{m_b \bar{\epsilon}^3}{18 m_{3/2}} \simeq 8 \times 10^{-6}$$

$$(\delta^d_{LR})_{32} \simeq \frac{2\ m_{3/2}\ m_b\ \bar{\epsilon}^2}{6\ m^2_{1/2} + m^2_0} \simeq \frac{m_b\ \bar{\epsilon}^2}{9\ m_{3/2}} \simeq 1 \times 10^{-4}$$

using $m_{\tilde{q}} \simeq 500$ GeV $\Rightarrow m_{3/2} \simeq 120$ GeV with $m_{1/2} = \sqrt{3} m_{3/2}$.

Asymmetric Texture

$$(\delta^d_{LR})_{32} \simeq \frac{m_{3/2} m_b t}{6\ m^2_{1/2} + m^2_0} \simeq \frac{m_b t}{18\ m_{3/2}} \simeq 4 \times 10^{-4}$$

$$(\delta^u_{LR})_{32} \simeq \frac{m_{3/2} m_t \epsilon}{6\ m^2_{1/2} + m^2_0} \simeq \frac{m_t \epsilon}{18\ m_{3/2}} \simeq 7 \times 10^{-3}$$

minimal suppression in down
$m_b/(6m_{3/2}) \lesssim 5 \times 10^{-3}$, no suppression a priori in up sector.

However, in the leptonic sector, even symmetric texture

$$(\delta^e_{LR})_{12} \simeq \frac{m_{3/2}\ m_\tau\ \bar{\epsilon}^3}{1.5\ m^2_{1/2} + m^2_0} \simeq \frac{m_\tau\ \bar{\epsilon}^3}{5.5\ m_{3/2}} \simeq 1.3 \times 10^{-5}$$

with $m_{\tilde{l}} = 280$ GeV, while the phenomenological bound with photino...
$(\delta^l_{LR})_{12} \lesssim 6.6 \times 10^{-6}$

Requires larger sfermion masses: OK for $m_{3/2} = 170$ GeV.

MI limits

x	$\sqrt{\left\|\mathrm{Im}\left(\delta^d_L\right)^2_{12}\right\|}$	$\sqrt{\left\|\mathrm{Im}\left(\delta^d_{LR}\right)^2_{12}\right\|}$	$\sqrt{\left\|\mathrm{Im}\left(\delta^d_L\right)_{12}\left(\delta^d_R\right)_{12}\right\|}$
0.3	2.9×10^{-3}	1.1×10^{-5}	1.1×10^{-4}
1.0	6.1×10^{-3}	2.0×10^{-5}	1.3×10^{-4}
4.0	1.4×10^{-2}	6.3×10^{-5}	1.8×10^{-4}

x	$\sqrt{\left\|\mathrm{Re}\left(\delta^d_{13}\right)^2_{LL}\right\|}$	$\sqrt{\left\|\mathrm{Re}\left(\delta^d_{13}\right)^2_{LR}\right\|}$	$\sqrt{\left\|\mathrm{Re}\left(\delta^d_{13}\right)_{LL}\left(\delta^d_{13}\right)_{RR}\right\|}$
0.3	4.6×10^{-2}	5.6×10^{-2}	1.6×10^{-2}
1.0	9.8×10^{-2}	3.3×10^{-2}	1.8×10^{-2}
4.0	2.3×10^{-1}	3.6×10^{-2}	2.5×10^{-2}