From Flavour to SUSY Flavour

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Outline

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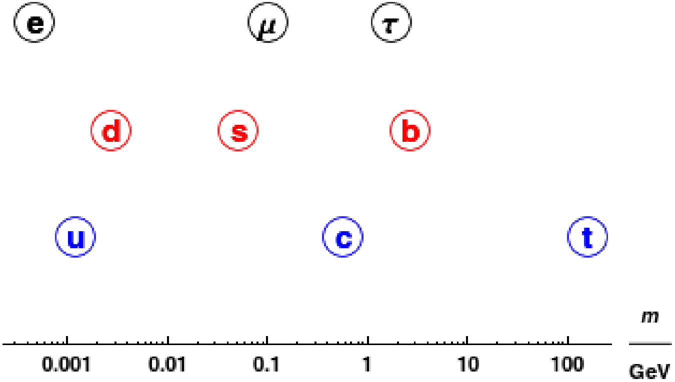
The Flavour Puzzle: Masses

Measurements reveal a peculiar pattern for fermion masses [PDG '08] :



The Flavour Puzzle: Mixing

Structure of mixing is even stranger [PDF '08 and Gonzalez-Garcia et al., '10] :

$$V_{CKM} = \begin{pmatrix} 0.9742 & 0.2257 & 0.0036 \\ 0.2256 & 0.9733 & 0.0415 \\ 0.0087 & 0.0407 & 0.9991 \end{pmatrix}$$

$$V_{PMNS} = \begin{pmatrix} 0.821 & 0.562 & < 0.10 \\ 0.469 & 0.568 & 0.676 \\ 0.325 & 0.601 & 0.730 \end{pmatrix}$$

How can one explain such a structure?

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Supersymmetry Transformation

$$\hat{\mathrm{Q}}|\text{fermion}\rangle = |\text{boson}\rangle$$
$$\hat{\mathrm{Q}}|\text{boson}\rangle = |\text{fermion}\rangle$$

Advantages:

- Hierarchy problem solved
- Gauge unification
- Natural CDM candidate
- Rich phenomenology

Soft SUSY Breaking

Soft Breaking Terms

$$\mathcal{L}_{soft} = \tilde{Q}^\dagger m^2_{\tilde{Q}}\, \tilde{Q} + \tilde{u}^{c\dagger} m^2_{\tilde{u}^c}\, \tilde{u}^c + \tilde{d}^{c\dagger} m^2_{\tilde{d}^c}\, \tilde{d}^c + \tilde{L}^\dagger m^2_{\tilde{L}}\, \tilde{L} + \tilde{e}^{c\dagger} m^2_{\tilde{e}^c}\, \tilde{e}^c$$
$$+ \tilde{Q}^T A_u\, \tilde{u}^c H_u + \tilde{Q}^T A_d\, \tilde{d}^c H_d + \tilde{L}^T A_e\, \tilde{e}^c H_d$$
$$+ \text{Gaugino and Higgs stuff}$$

$\Rightarrow$ 100+ new parameters

Constrained Breaking Terms

Usual Ansatz:

Constrained MSSM

$$m_f^2 = m_0^2 \; \mathbb{1} \quad \forall\, f = \tilde{Q}, \tilde{L}, \tilde{u}^c, \tilde{d}^c, \tilde{e}^c$$
$$A_f = A_0 \; Y_f \quad \forall\, f = u, d, e$$

$\Rightarrow$ 5 Parameters: $(m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}\;\mu)$

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Basics and Notation

Notation:

$$\begin{aligned} f &\rightarrow \text{fermion} \\ \tilde{f} &\rightarrow \text{scalar superpartner} \\ f &= Q, L \\ f^c &= u^c, d^c, e^c \\ H_f &= H_{u,d} \end{aligned}$$

Yukawa coupling in Lagrangian: $\mathcal{L}_{Yukawa} = f^T \; Y_f \; f^c \; H_f \Rightarrow m_f = Y_f \; v_f$

Flavons

Idea [Froggat, Nielsen '79]

Yukawa coupling $\leftrightarrow$ non-renormalisable coupling + "flavon" vev $\langle\phi\rangle$

$$(Y_f)_{ij} = \frac{\langle\phi_{ij}\rangle}{M}$$

$\Rightarrow$ Task: Constraining Y_f using symmetries and alignment

Symmetry - Example with $SO(3)$

Pathologic Case: $f, f^c \sim 3$

$f \cdot f^c$ invariant $\Rightarrow m_e \sim m_\tau$

We choose e.g. $f, \phi \sim 3, f^c \sim 1$

$$f^T \; Y_f \; f^c \; H_f = (f \cdot \vec{v}_1 \;\; f_1^c + f \cdot \vec{v}_2 \;\; f_2^c + f \cdot \vec{v}_3 \;\; f_3^c) H_f$$

$$\Rightarrow Y_f = \begin{pmatrix} \uparrow & \uparrow & \uparrow \\ \vec{v}_1 & \vec{v}_2 & \vec{v}_3 \\ \downarrow & \downarrow & \downarrow \end{pmatrix}$$

Alignment - Example with $SO(3)$

One choice

$$\vec{v}_{123} \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \vec{v}_{23} \propto \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}, \vec{v}_{3} \propto \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \tilde{v}_{23} \propto \begin{pmatrix} 0 \\ i \\ w \end{pmatrix}$$

Could yield:

$$Y_d = \begin{pmatrix} 0 & \epsilon_{23} & -\epsilon_{23} \\ \epsilon_{123} & \epsilon_{123} + i\,\tilde{\epsilon}_{23} & \epsilon_{123} + w\,\tilde{\epsilon}_{23} \\ 0 & 0 & \epsilon_{3} \end{pmatrix}$$

Original motivation:

$$Y_\nu = \begin{pmatrix} 0 & b \\ a & b \\ -a & b \end{pmatrix}, \quad M_N = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}, \quad Y_e \approx \text{diagonal}$$

$$\Rightarrow M_\nu = \frac{m_2}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \frac{m_3}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix}$$

$$\Rightarrow V_{PMNS} = V_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \end{pmatrix}$$

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SUSY breaking and F-Terms

Supersymmetry Breaking

$$\hat{\mathrm{Q}}|0\rangle \neq 0 \Leftrightarrow \hat{\mathrm{H}}|0\rangle \neq 0$$

Supersymmetric Scalar Potential

$$V = \sum_i |F_{\varphi_i}|^2 \text{ with } F_{\varphi_i} = F_{\varphi_i}(\varphi),\; F_{\varphi_i} \sim \varphi_i$$

$\Rightarrow \langle F_\varphi \rangle$ order parameters for SUSY breaking

Supergravity and F-Terms

Road to Supergravity (including SUSY breaking)

$$\text{SUSY} \rightarrow \text{SUGRA}$$
$$\text{global} \rightarrow \text{local}$$
$$F_\varphi \rightarrow F_\varphi + \tilde{m}\,\varphi$$
$$V \rightarrow V + \Delta V_{SUGRA}$$

$\Rightarrow$ Natural expectation: $\langle F_\varphi \rangle = c_\varphi\ \tilde{m}\ \langle \varphi \rangle$

Flavon F-terms also contribute to soft terms:

$$\tilde{f}^{c\dagger}\ m^2_{\tilde{f}^c}\ \tilde{f}^c = m_0^2\ \tilde{f}^{c\dagger}\tilde{f}^c$$

$$\begin{aligned}\tilde{f}^\dagger\ m^2_{\tilde{f}}\ \tilde{f} &= m_0^2\ \tilde{f}^\dagger\tilde{f} - \sum_{i,j}\tilde{f}^\dagger\cdot\frac{\langle F_{\phi_i}\rangle^*}{M}\ \frac{\langle F_{\phi_j}\rangle}{M}\cdot\tilde{f} = \\ &= m_0^2\ \tilde{f}^\dagger\tilde{f} - \sum_{i,j} c_i{}^* c_j\ \ m_0^2\ \ \tilde{f}^\dagger\cdot\vec{v}_i{}^*\ \vec{v}_j\cdot\tilde{f}\end{aligned}$$

$$\begin{aligned}\tilde{f}^T\ A_f\ \tilde{f}^c\ H_f &= A_0\ \tilde{f}^T\ \ Y_f\ \tilde{f}^c\ H_f + \tilde{f}^T\left(\frac{F_{\phi_1}}{M},\frac{F_{\phi_2}}{M},\frac{F_{\phi_3}}{M}\right)\tilde{f}^c H_f = \\ &= A_0\ \tilde{f}^T\ \ Y_f\ \tilde{f}^c\ H_f + A_0\ \tilde{f}^T\ \left(c_1\vec{v}_1, c_2\vec{v}_2, c_3\vec{v}_3\right)\ \tilde{f}^c\ H_f\end{aligned}$$

Comparing with Experiments: SCKM transformation

Super CKM Basis

$$f \rightarrow V_f \; f$$
$$\tilde{f} \rightarrow V_f \; \tilde{f}$$

$$f^c \rightarrow V_{f^c} \; f^c$$
$$\tilde{f}^c \rightarrow V_{f^c} \; \tilde{f}^c$$

$$Y_f \rightarrow V_f^T \, Y_f \, V_{f^c} = Y_f^{diag}$$
$$A_f \rightarrow V_f^T \, A_f \, V_{f^c}$$
$$m^2_{\tilde{f}} \rightarrow V_f^\dagger \, m^2_{\tilde{f}} \, V_f$$
$$m^2_{\tilde{f}^c} \rightarrow V_{f^c}^\dagger \, m^2_{\tilde{f}^c} \, V_{f^c}$$

Mass Insertion Approximation

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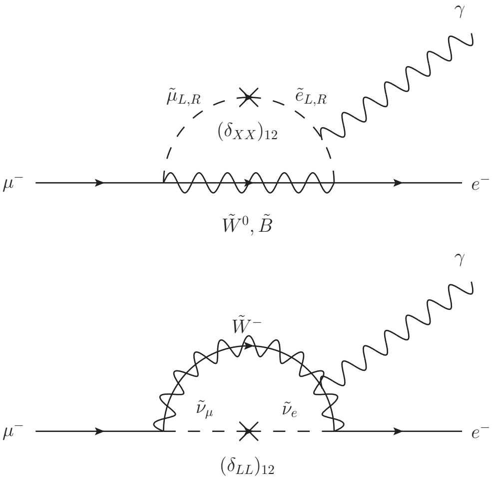
Define:

$$(\delta^f_{LL,RR})_{ij} = \frac{(m^2_{\tilde{f},\tilde{f}^c})_{ij}}{\overline{m^2_{\tilde{f},\tilde{f}^c}}}$$

$$(\delta^f_{LR})_{ij} = \frac{v_f (A_f)_{ij}}{\sqrt{\overline{m^2_{\tilde{f}}}\;\overline{m^2_{\tilde{f}^c}}}}$$

$$\delta^f_{RL} = \delta^{f\dagger}_{LR}$$

Example: $\mu \to e\gamma$



Bounds [Ciuchini et al., '07]	
$(\delta^e_{LL})_{12}$	$6 \cdot 10^{-4}$
$(\delta^e_{RR})_{12}$	-
$(\delta^e_{LR})_{12}$	$1 \cdot 10^{-5}$

Outline

Summary & Conclusions

- Yukawa matrices dynamically generated
- Deviations from CMSSM with definite structure
- Predictions for rare decays and CP violation

End of the talk

Thanks for your attention!

MIA Constraints from Observables

Observable	f, ij	LL	LR	RL	RR
$\mu \to e\gamma$, $\mu \to e$ in Ti	e, 12	x	x		
$\mu \to eee$	e, 12	x	x		x
$\tau \to eee$	e, 13	x	x		x
$\tau \to \mu ee$	e, 23	x	x		x
d_e	e, 11		x		
ΔM_K, ϵ, ϵ'/ϵ	d, 12	x	x	x	x
ΔM_{B_d}, $\sin 2\beta$, $\cos 2\beta$	d, 13	x	x	x	x
ΔM_{B_s}, $b \to s\gamma$, $b \to sl^+l^-$	d, 23	x	x	x	x
d_n, d_{Hg}	d, 11		x		
ΔM_D	u, 12	x	x		x
d_n, d_{Hg}	u, 11		x		

Soft Terms from Flavon F-Terms

$$\tilde{m}^2_{\bar{a}b} = m^2_{3/2}\tilde{K}_{\bar{a}b} - F_{\bar{m}}F_n\left(\partial_{\bar{m}}\partial_n\tilde{K}_{\bar{a}b}\right) + \dots$$

$$A = a_0 F_m\left(\left(\partial_m \frac{K_{hid}}{M^2_{Pl}}\right) Y + \partial_m Y\right) + \dots$$