Title: Irreducible flavour and CP violation in SUGRA flavour models

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Abstract: In SUGRA flavour models, a total sequestering is not possible and an irreducible amount of flavour and CP violation is essentially unavoidable, which renders many flavour models testable in the near future experiments.

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Irreducible SUSY flavour & CP violation in SUGRA flavour models

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Southampton, UK

In collaboration with S. Antusch, S.F. King & G.G.Ross

Outline

- Flavour & CP issue of the MSSM & SUGRA as a potential cure
- Irreducible flavour and CP violation in SUGRA models with family symmetries
- SU(3) family symmetry & SUGRA

G.G. Ross, O. Vives, Phys.Rev.D67 (2003)
S.Antusch, S.F.King, M.M. 2007
S.Antusch, S.F.King, M.M., G.G.Ross, in preparation

SUSY flavour and CP issue of the MSSM

MSSM flavour:

$$
\begin{aligned}
W_Y &\sim \varepsilon_{\alpha\beta}\left[\hat{H}_u^\alpha \hat{Q}^{\beta i} Y^u_{ij}\hat{u}^{cj} + \hat{H}_d^\alpha \hat{Q}^{\beta i} Y^d_{ij}\hat{d}^{cj} + \hat{H}_u^\alpha \hat{L}^{\beta i} Y^\nu_{ij}\hat{N}^{cj} + \hat{H}_d^\alpha \hat{L}^{\beta i} Y^e_{ij}\hat{e}^{cj}\right] + \hat{N}^{ci}(M_R)_{ij}\hat{N}^{cj} \\
\mathcal{L}_{\rm soft} &\sim \varepsilon_{\alpha\beta}\left[H_u^\alpha \tilde{Q}^{\beta i} A^u_{ij}\tilde{u}^{cj} + H_d^\alpha \tilde{Q}^{\beta i} A^d_{ij}\tilde{d}^{cj} + H_u^\alpha \tilde{L}^{\beta i} A^\nu_{ij}\tilde{N}^{cj} + H_d^\alpha \tilde{L}^{\beta i} A^e_{ij}\tilde{e}^{cj}\right] + \tilde{N}^{c*}_i (m^2_{\tilde{N}^c})^i_j \tilde{N}^{cj} \\
&+ \tilde{Q}^*_{i\alpha}(m^2_{\tilde{Q}})^i_j \tilde{Q}^{\alpha j} + \tilde{u}^{c*}_i (m^2_{\tilde{u}^c})^i_j \tilde{u}^{cj} + \tilde{d}^{c*}_i (m^2_{\tilde{d}^c})^i_j \tilde{d}^{cj} + \tilde{L}^*_{i\alpha}(m^2_{\tilde{L}})^i_j \tilde{L}^{\alpha j} + \tilde{e}^{c*}_i (m^2_{\tilde{e}^c})^i_j \tilde{e}^{cj}
\end{aligned}
$$

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Y^f = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \qquad M^2_{\tilde{f}} = \begin{pmatrix} m^{2f}_{LL} & m^{2f\dagger}_{LR} \\ m^{2f}_{LR} & m^{2f}_{RR} \end{pmatrix}
$$

$$
\begin{aligned}
m^{2f}_{LL} &\propto m^2_{\tilde{f}} + Y^\dagger_f Y_f v^2 + \Delta^f_L \mathbb{1} \\
m^{2f}_{RR} &\propto m^2_{\tilde{f}^c} + Y^\dagger_f Y_f v^2 + \Delta^f_R \mathbb{1} \\
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Convenience - the 'Super-CKM' basis:

Dugan, Grinstein, Hall, Nucl.Phys.B255(1985)

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V_L^{f\dagger} Y^f V_R^f = \begin{pmatrix} y_1^f & & \\ & y_2^f & \\ & & y_3^f \end{pmatrix}
$$

$$
M_f^2 \ni \begin{cases} V_L^{f\dagger} m^{2f}_{LL} V_L^f \propto V_L^{f\dagger} m_f^2 V_L^f + c_{LL} \mathbb{1} \\ V_R^{f\dagger} m^{2f}_{RR} V_R^f \propto V_R^{f\dagger} m_{f^c}^2 V_R^f + c_{RR} \mathbb{1} \\ V_L^{f\dagger} m^{2f}_{LR} V_R^f \propto V_L^{f\dagger} A^f V_R^f v + c_{LR} \mathbb{1} \end{cases}
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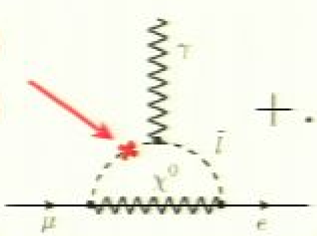
M^2_{\tilde f} \ni \left\{
\begin{aligned}
V^{f\dagger}_L m^{2f}_{LL} V^f_L &\propto V^{f\dagger}_L m^2_{\tilde f} V^f_L + c_{LL}\mathbb{1} \\
V^{f\dagger}_R m^{2f}_{RR} V^f_R &\propto V^{f\dagger}_R m^2_{\tilde f^c} V^f_R + c_{RR}\mathbb{1} \\
V^{f\dagger}_L m^{2f}_{LR} V^f_R &\propto V^{f\dagger}_L A^f V^f_R v + c_{LR}\mathbb{1}
\end{aligned}
\right.
$$

Example: SUSY FCNC

(δ^l_{LL})

(δ^l_{RR})

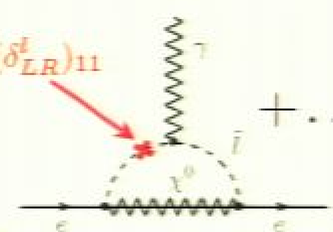


$+\ldots$

$$
(\delta^f_{XY})_{ij} \equiv \frac{(V^\dagger_X m^{2f}_{XY} V_Y)_{ij}}{\langle \tilde{m}^{2f} \rangle}
$$

SUSY CPV

$(\delta^l_{LR})_{11}$



$+\ldots$

Effective soft sector in SUGRA

Effective SUGRA soft terms:

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m^2_{soft} &= m^2_{3/2}\tilde{K}_{\overline{a}b} - \sum_{S,S'} F_{\overline{S'}} \left[\partial_{\overline{S'}}\partial_S \tilde{K}_{\overline{a}b} - \partial_{\overline{S'}}\tilde{K}_{\overline{a}c}(\tilde{K}^{-1})_{c\overline{d}}\partial_S \tilde{K}_{\overline{d}b}\right] F_S \\
A_{abc}Y_{abc} &\propto \sum_S F_S \left\{ \frac{1}{M^2_{Pl}}(\partial_S K_{hid.})Y_{abc} + \partial_S Y_{abc} - \left[(\tilde{K}^{-1})_{d\overline{e}}\partial_S \tilde{K}_{\overline{e}a} Y_{dbc} + cycl.\right]\right\}
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$$
K(\psi, X, \ldots) = \tilde{K}_{\overline{a}b}(X, \ldots)\psi^*_{\overline{a}}\psi_b + \ldots + K_{hid.}(X, \ldots) \qquad \langle F_X \rangle \neq 0
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Usual strategy:

- 'Sequestered' or clustered shape of a Kähler potential makes the soft masses universal ! (after canonical normalization of $\overline{\psi}_{\overline{a}}\tilde{K}_{\overline{a}b}D_\mu\gamma^\mu\psi_b$)
- If, moreover, the Yukawas do not feel X (or do in a flavour-blind way), the A-terms are aligned to Yukawas and CP and FV is essentially O.K.

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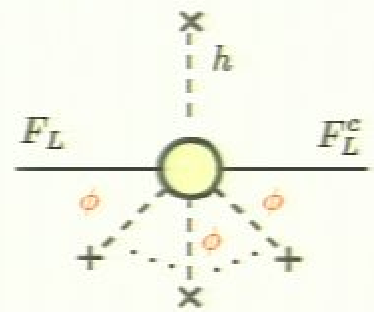
This is unlikely to work in models with spontaneously broken family symmetries...

Intermezzo: family symmetries & flavons

- Yukawa couplings protected by a family symmetry spontaneously broken by flavons

$$W \ni \frac{1}{M^n} F_L \phi^n F_L^c h$$



- Example: SU(3) family symmetry:
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  - coupled to flavons living in antitriplets

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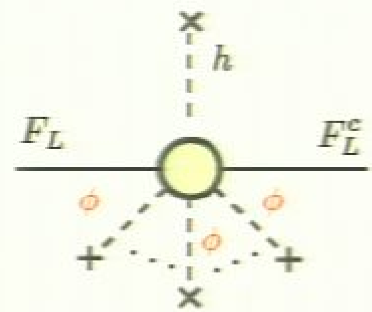

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Harrison, Perkins, Scott (2002)

- Breaking pattern constrained by SM fermion mixings and masses : $U_{\rm TB} \equiv \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$

$$Y^{\nu}_{LR} \sim \begin{pmatrix} 0 & b & . \\ a & b & . \\ -a & b & c \end{pmatrix} \qquad \frac{a^2}{M_1} \gg \frac{b^2}{M_2} \gg \frac{c^2}{M_3}$$

"sequential dominance" S.F.King (2000)

- Mixing driven by vacuum alignment : $\langle \phi_{23} \rangle = \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} a\,, \quad \langle \phi_{123} \rangle \sim \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} b\,, \quad \langle \phi_3 \rangle \propto \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} c$

- Hierarchies driven by expansion parameters : $\dfrac{|\langle \phi \rangle|}{M}$

Induced flavon F-terms

Generic SUGRA F-term:

$$F_I = -e^{K/2M_{Pl}^2}(K^{-1})_{I\bar{J}}\left(\frac{1}{M_{Pl}^2}W^* K_{\bar{J}} + W^*_{\bar{J}}\right) = -(K^{-1})_{I\bar{J}}\left(m_{3/2}K_{\bar{J}} - e^{K/2M_{Pl}^2}W^*_{\bar{J}}\right)$$

and thus

$$\langle F_\phi \rangle = -\left\langle \sum_{\phi'} (K^f)^{-1}_{\phi\bar{\phi}'}\left(m_{3/2}(K^f)_{\bar{\phi}'} - e^{K/2M_{Pl}^2}W^*_{\bar{\phi}'}\right)\right\rangle \sim m_{3/2}\langle\phi\rangle + \dots$$

G.G. Ross, O. Vives, Phys.Rev.D67 (2003)
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The pieces always present in the SUGRA soft masses and trilinears :

$$\begin{aligned} m^2_{soft} &= m^2_{3/2}\tilde{K}_{\bar{a}b} - \sum_{\phi,\phi'} F_{\bar{\phi}'}\left[\partial_{\bar{\phi}'}\partial_\phi \tilde{K}_{\bar{a}b} - \partial_{\bar{\phi}'}\tilde{K}_{\bar{a}c}(\tilde{K}^{-1})_{c\bar{d}}\partial_\phi \tilde{K}_{\bar{d}b}\right] F_\phi \\ A_{abc}Y_{abc} &= k\left\{\frac{F_X}{M^2_{Pl}}(\partial_X K_{hid.})Y_{abc} + \sum_\phi F_\phi \partial_\phi Y_{abc} - \sum_\phi F_\phi\left[(\tilde{K}^{-1})_{d\bar{e}}\partial_\phi \tilde{K}_{\bar{e}a}Y_{dbc} + cycl.\right]\right\} \end{aligned}$$

Magnitudes

Naively, the flavon F-terms can be shifted (i.e. suppressed) essentially at will...

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...but that is irrelevant !

1) Soft masses: $\tilde{K}_{\overline{a}b} \sim \delta_{\overline{a}b}\left(c_0 + d_0\frac{X^\dagger X}{M_{Pl}^2}\right) + \left(c_2 + d_2\frac{X^\dagger X}{M_{Pl}^2}\right)\frac{1}{M^2}(\phi\phi^*)_{\overline{a}b} + \ldots$

$$F_{\overline{X}}\left(\partial_{\overline{X}}\partial_X \tilde{K}_{\overline{a}b}\right)F_X \sim m_{3/2}^2\langle X^\dagger\rangle\left(\frac{d_0}{M_{Pl}^2} + \frac{d_2}{M_{Pl}^2}\frac{1}{M^2}\phi\phi^*\right)\langle X\rangle \sim m_{3/2}^2\left[\mathcal{O}(1) + \mathcal{O}\left(\frac{|\langle\phi\rangle|^2}{M^2}\right)\right]$$

$$F_{\overline{\phi}}\left(\partial_{\overline{\phi}}\partial_\phi \tilde{K}_{\overline{a}b}\right)F_\phi \sim m_{3/2}^2\langle\phi^*\rangle\left(c_2 + d_2\frac{X^\dagger X}{M_{Pl}^2}\right)\frac{1}{M^2}\langle\phi\rangle \sim m_{3/2}^2\mathcal{O}\left(\frac{|\langle\phi\rangle|^2}{M^2}\right)$$

subleading effect, but competitive !

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Exactly the flavour structure of SU(3)-like flavour models - SUGRA effects screened!

Example : SU(3) family symmetry

- Yukawa sector :

I. de Medeiros Varzielas,G.G. Ross, 2005

$$Y_{ij}^f = y_0^f \frac{\langle(\phi_3)_i(\phi_3)_j\rangle}{M_f^2} + y_1^f \frac{\langle(\phi_{123})_i(\phi_{23})_j\rangle}{M_f^2} + y_2^f \frac{\langle(\phi_{23})_i(\phi_{123})_j\rangle}{M_f^2} + y_\Sigma^f \frac{\langle(\phi_{23})_i(\phi_{23})_j\Sigma\rangle}{M_f^3} + \dots$$

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Example : SU(3) family symmetry

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I. de Medeiros Varzielas, G.G. Ross, 2005

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- If SUSY breaking scale is lower than the family symmetry brakdown, the same patterns govern the soft sector...

Example : electric dipole moments in SU(3)

- Soft sector :

$$(m^2_{f,f^c})^i_j = m_0^2 \left(b_0^{f,f^c} \delta^i_j + b_1^{f,f^c} \frac{\langle (\phi_{123})_j (\phi^*_{123})^i \rangle}{M^2_{f,f^c}} + b_2^{f,f^c} \frac{\langle (\phi_{23})_j (\phi^*_{23})^i \rangle}{M^2_{f,f^c}} + b_3^{f,f^c} \frac{\langle (\phi_3)_j (\phi^*_3)^i \rangle}{M^2_{f,f^c}} \right) + \ldots$$

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S.Antusch, S.F.King, M.M. 2007

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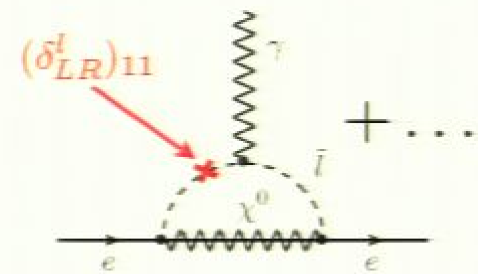
S.Antusch, S.F.King, M.M. 2007

- Electric dipole moments:
  - tightly constrained : $|\mathrm{Im}(\delta^{u,d}_{11})_{LR}| \lesssim 10^{-6}, \quad |\mathrm{Im}(\delta^{l}_{11})_{LR}| \lesssim 10^{-7}$

$$\langle \tilde{m}_q \rangle \sim 500\,\mathrm{GeV}, \quad \langle \tilde{m}_l \rangle \sim 100\,\mathrm{GeV}$$



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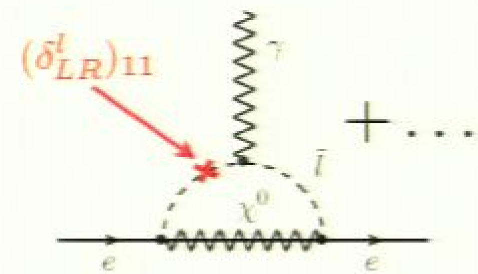

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$$|\mathrm{Im}(\delta^{d,l}_{LR})_{11}| \;\sim\; 5\times10^{-6}\frac{A_0}{\langle\tilde m_{d,l}\rangle}\left(\frac{500\,\mathrm{GeV}}{\langle\tilde m_{d,l}\rangle}\right)\left(\frac{10}{\tan\beta}\right)\left|(a_1^{d,l}+a_2^{d,l})-\frac{a^{d,l}_\Sigma}{y^{d,l}_\Sigma}(y_1^{d,l}+y_2^{d,l})\right|\sin\phi_1$$

Example: SU(3) family symmetry & SUGRA

SUGRA estimate of effective coefficients :

$$A_{ij} \sim \sum_{\Phi} F_{\Phi} \partial_{\Phi} Y_{ij} \qquad \Phi \equiv \phi_{23},\, \phi_{123},\, \Sigma$$

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Typically $a_\Phi \sim \dim \mathcal{O}_\Phi \times y_\Phi$ (for the naive estimate $F_\phi \sim m_{3/2}\langle\phi\rangle$)

$$\left|(a_1 + a_2) - \frac{a_\Sigma}{y_\Sigma}(y_1 + y_2)\right| \to |y_1 + y_2| \sim \mathcal{O}(1)$$

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Unless something nontrivial happens, SUGRA does not provide a relief !

Work in progress...

Conclusions

- SUSY flavour and CP puzzles challenge the models with family symmetries
- Irreducible SUGRA flavour & CP violation due to flavon F_ϕ-terms omnipresent
- Looks like SU(3) as good/bad as SU(3) + SUGRA
- Could flavon dynamics provide a relief ? Work in progress...