Effective Theories of Flavour and the Non-Universal MSSM

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Phys. Rev. D 95, 035001 & JHEP 1711 (2017) 162

Outline

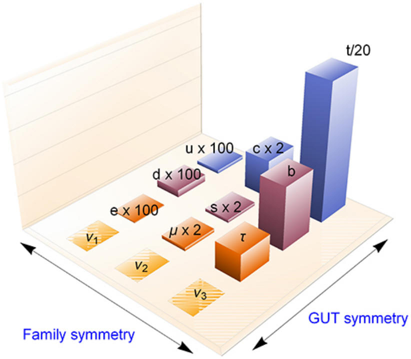
1. Why Flavour Symmetries?
2. Flavour Symmetries within the MSSM
3. Some Examples: $U(1)_f$, $SU(3)_f$
4. Conclusions

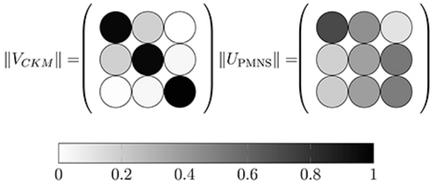
Motivation

Fundamental flavour problem of the SM

Masses of SM fermions differ by 11 orders of magnitude

why three families? why a CP phase? why these peculiar masses and mixings?



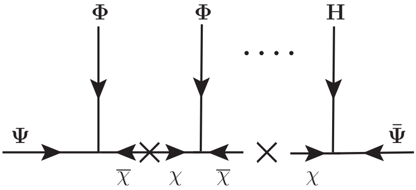


Nice solution

Froggatt-Nielsen Mechanism

[Nucl.Phys.B, 147, 222-298]

A flavour symmetry spontaneously broken by the VEVs of some new scalars, $\langle \Phi \rangle = v_\Phi$, to effectively generate the Yukawa couplings.



$$\mathcal{L}_\mathrm{Y} = Y_{ij}\,\bar{\Psi}\,\Psi\,H$$

$$Y_{ij} \sim \left(\frac{\langle \Phi \rangle}{M}\right)^{n_{ij}} \equiv \varepsilon^{n_{ij}} \ll 1$$

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How can these models be tested?

Excellent postdictions, but... how distinguish among them?

A Review of the Mechanism

Flavour Symmetries in SUSY

Two scales at work

Λ_{SUSY} *(SUSY breaking)* + Λ_f *(flavour breaking)*

$\Lambda_f \ll \Lambda_{SUSY}$

- Soft terms present below Λ_{SUSY}
- Invariant under G_f
- Flavour opportunities! New flavour effects.

Ex.: supergravity

$\Lambda_f \gg \Lambda_{SUSY}$

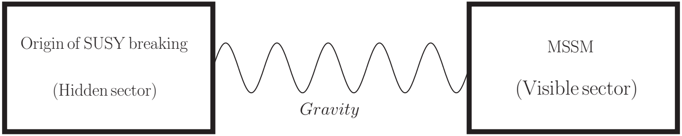
- Soft terms generated after flavour breaking
- Only Yukawas as flavour remnant below Λ_f
- Only masses and CKM, PMNS observable.

Ex.: gauge-mediated

Gravity-mediated SUSY breaking

Supergravity

$$\Lambda_f \ll \Lambda_{SUSY} \simeq M_{Planck}$$



SUSY breaking communicated through non-renormalizable (gravitational) interactions.

Gravity-mediated SUSY breaking

- Simplest case: a single universal spurion field $\langle X \rangle = F_X$

$$
\begin{aligned}
\mathrm{W} &= \mathrm{W}_{\mathrm{MSSM}} - \frac{X}{M_{\mathrm{Pl}}} \left(\frac{1}{6} \alpha y^{ijk} \Phi_i \Phi_j \Phi_k + \frac{1}{2} \beta \mu^{ij} X \Phi_i \Phi_j \right) + \ldots \\
K &= \Phi^{*i} \Phi_i + \frac{X X^*}{M_{\mathrm{Pl}}^2} k \delta_i^j \Phi^{*i} \Phi_j + \ldots \\
\mathrm{f}_{ab} &= \frac{\delta_{ab}}{g_a^2} \left(1 - \frac{2X}{M_{\mathrm{Pl}}} f_a + \ldots \right)
\end{aligned}
$$

- Soft terms:

$$
\begin{aligned}
\mathcal{L}_{\mathrm{soft}} &= -\frac{1}{2M_{\mathrm{Pl}}} f_a \lambda^a \lambda^a - \frac{F_X}{6M_{\mathrm{Pl}}} \alpha\, y^{ijk} \phi_i \phi_j \phi_k - \frac{F_X}{2M_{\mathrm{Pl}}} \beta\, \mu^{ij} \phi_i \phi_j + \mathrm{c.c.} \\
&\quad - \frac{|F_X|^2}{M_{\mathrm{Pl}}^2} k\, \phi^{*i} \phi_i
\end{aligned}
$$

- Introducing a flavour symmetry: breaking of universality!

Effective Yukawas

[JHEP 11 (2017) 162]

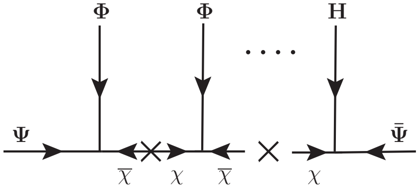
Symmetry associated with the flavour group G_f

→ Yukawa couplings forbidden by the flavour symmetry.

→ Integrating heavy messengers, corrections from non-renormalizable operators:

$$\mathrm{W}_{\mathrm{MSSM}} = \mathrm{W}_{\mathrm{ren}} + \Psi\,\bar{\Psi}\,\mathrm{H} \sum_{n=1}^{\infty} x_n \left(\frac{\Phi}{M}\right)^n$$

→ There corrections can be studied in terms of supergraphs:



Effective Trilinears

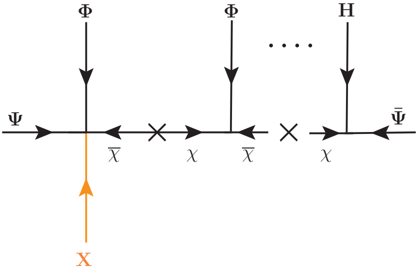
[JHEP 11 (2017) 162]

Symmetry associated with the flavour group G_f

→ Trilinear couplings generated by similar corrections:

$$\mathcal{L}_{\rm soft} \supseteq \frac{\mathsf{F_X}}{M_{\rm Pl}} \times \mathsf{W}_{\rm MSSM} \equiv m_{3/2}\,\mathsf{W}_{\rm MSSM}$$

→ In terms of supergraphs:



$$A_{ij} = (2N_{\rm in} + 1)\, a_0\, Y_{ij}$$

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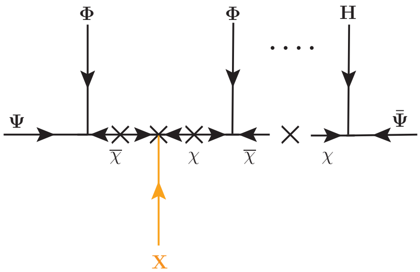

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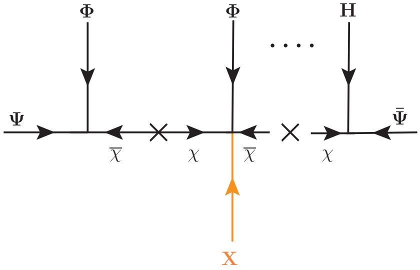

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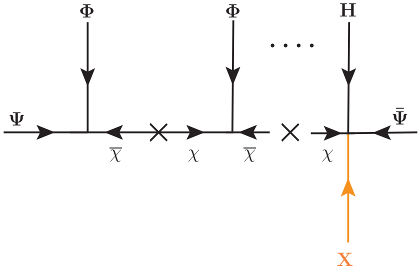


$$A_{ij} = (2N_{\rm in}+1)\, a_0\, Y_{ij}$$

Kähler Metric

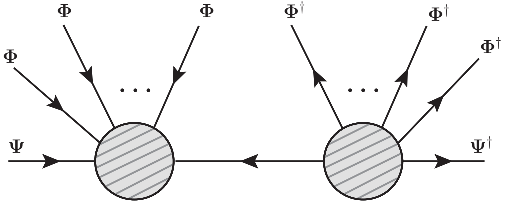
Symmetry associated with the flavour group G_f

→ Similar considerations for Kähler potential: corrections when heavy mediators are integrated over.

⇝ Abelian: $(K_\Psi)_{ij} = \Psi_i \Psi_j^\dagger \left(\delta_{ij} + \sum_{n,m} c_{ij}^{n,m} \left(\frac{\Phi}{M}\right)^n \left(\frac{\Phi^\dagger}{M}\right)^m \right)$

⇝ Non-Abelian: $(K_\Psi)_{ij} = \Psi_i \Psi_j^\dagger \left(\delta_{ij} + \sum_{r,n} c_{ij}^{r,n} \left(\frac{\Phi_r\, \Phi_r^\dagger}{M^2}\right)^n \right)$

→ Leading-order supergraphs:



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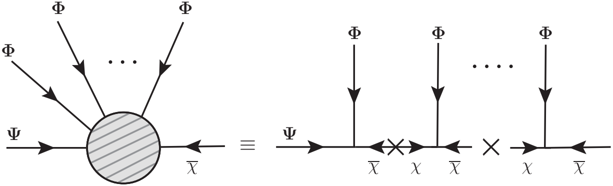

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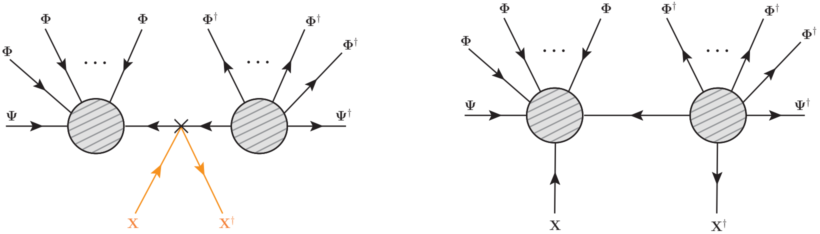
→ Similar corrections for soft masses:

$$\mathcal{L}_{\rm soft} \supseteq \frac{|F_X|^2}{M_{\rm Pl}^2} \times K_\Psi \equiv m_{\rm soft}^2 \, K_\Psi$$

→ In terms of supergraphs:



$$(m_\Psi)_{ij} = f_N \, m_{\rm soft}^2 \, (K_\Psi)_{ij} \, , \quad f_N = 1 + (2N_{\rm in} - 1)(2N_{\rm out} - 1)$$

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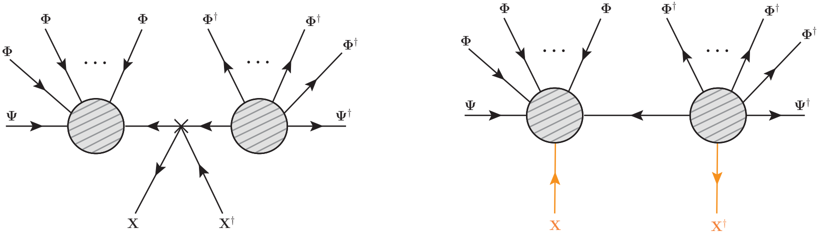

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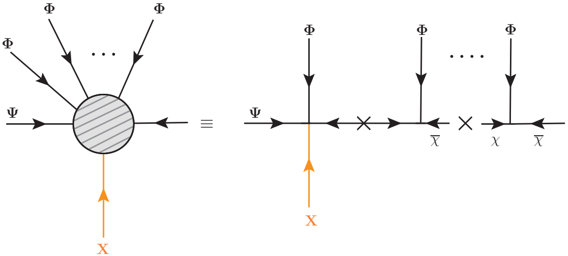

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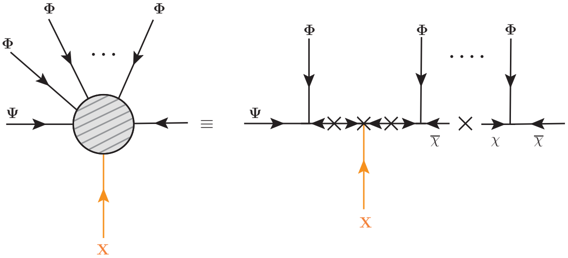

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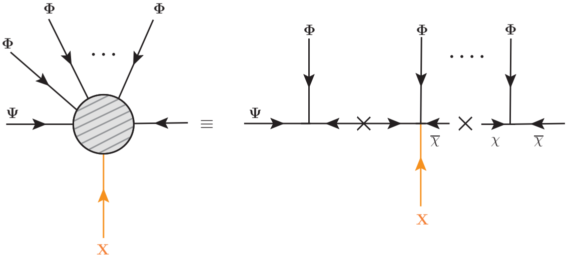

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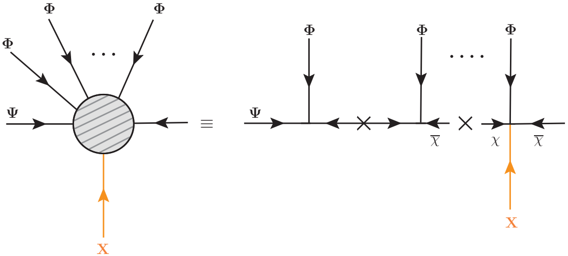

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Why is this important?

$\rightarrow$ Trilinear and soft-mass matrices are not directly proportional to Yukawas and Kähler metric.

$\rightarrow$ Going to the canonical basis (normalized Kähler) and mass basis (diagonal Yukawas) $\Longrightarrow$ Flavour Violation.

$\rightarrow$ Even having a single universal source of SUSY breaking, non-universal flavour structures arise for soft terms.

Quark Sector:

1.- Toy $U(1)_f$ model

Toy $U(1)_f$ model

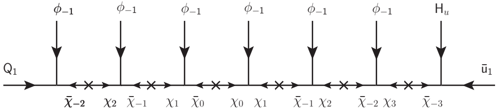
[Phys.Rev.D 95, 035001]

Particle Content

	Q_3	Q_2	Q_1	$\bar{u}_3$	$\bar{u}_2$	$\bar{u}_1$	$\bar{d}_3$	$\bar{d}_2$	$\bar{d}_1$	ϕ	$\bar{\phi}$	χ_q	$\bar{\chi}_{-q}$
$U(1)_f$	0	2	3	0	2	3	0	0	1	-1	1	q	$-q$

Yukawa Couplings

$$Y_{ij} \sim \varepsilon^{n_{ij}}$$



$$n_{ij} = q_i + q_j$$

$$Y_u \sim y_t \begin{pmatrix} e\varepsilon^6 & \varepsilon^5 & \varepsilon^3 \\ \varepsilon^5 & d\varepsilon^4 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix} \qquad Y_d \sim y_b \begin{pmatrix} e'\varepsilon^4 & f'\varepsilon^3 & f\varepsilon^3 \\ \varepsilon^3 & d'\varepsilon^2 & h\varepsilon^2 \\ \varepsilon & k' & k \end{pmatrix}$$

Toy $U(1)_f$ model

[Phys.Rev.D 95, 035001]

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Trilinears Couplings

$$A_{ij} \propto m_{3/2}(2n_{ij}+1)Y_{ij}$$

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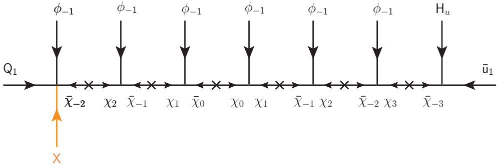

$$Y_u \sim y_t \begin{pmatrix} e\varepsilon^6 & \varepsilon^5 & \varepsilon^3 \\ \varepsilon^5 & d\varepsilon^4 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix} \qquad A_u \sim m_{3/2}\, y_t \begin{pmatrix} 13e\varepsilon^6 & 11\varepsilon^5 & 7\varepsilon^3 \\ 11\varepsilon^5 & 9d\varepsilon^4 & 5\varepsilon^2 \\ 7\varepsilon^3 & 5\varepsilon^2 & 1 \end{pmatrix}$$

Toy $U(1)_f$ model

[Phys.Rev.D 95, 035001]

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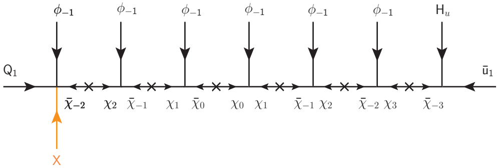

$$n_{ij} = q_i + q_j$$

$$Y_d \sim y_b \begin{pmatrix} e'\varepsilon^4 & f'\varepsilon^3 & f\varepsilon^3 \\ \varepsilon^3 & d'\varepsilon^2 & h\varepsilon^2 \\ \varepsilon & k' & k \end{pmatrix} \qquad A_d \sim m_{3/2}\, y_b \begin{pmatrix} 9e'\varepsilon^4 & 7f'\varepsilon^3 & 7f\varepsilon^3 \\ 7\varepsilon^3 & 5d'\varepsilon^2 & 5h\varepsilon^2 \\ 3\varepsilon & k' & k \end{pmatrix}$$

Toy $U(1)_f$ model

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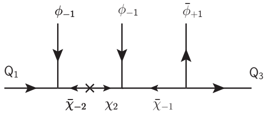
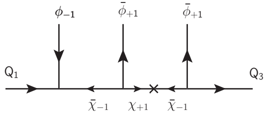
Kähler Potential

$$K_\psi = \psi_i^\dagger \psi_j \left(\delta_{ij} + c_{ij}\right)$$





$$q_{ij} = |q_i - q_j|$$

$$c_{ij} \sim \begin{cases} (q_{ij} - 1)\varepsilon^{q_{ij}} & \text{for } q_{ij} \geq 2 \\ 2\varepsilon^3 & \text{for } q_{ij} = 1 \\ \varepsilon^2 & \text{for } q_{ij} = 0 \end{cases}$$

$$c_{ij}^{(Q,\overline{u},\overline{d})} = \begin{pmatrix} \varepsilon^2 & 2\varepsilon^3 & 2\varepsilon^3 \\ 2\varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ 2\varepsilon^3 & \varepsilon^2 & \varepsilon^2 \end{pmatrix}$$

Toy $U(1)_f$ model

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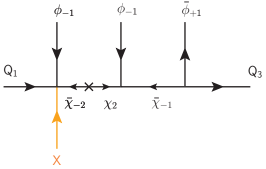
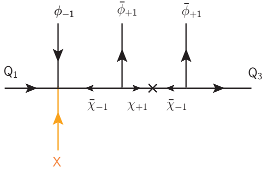
Soft Masses

$$\left(m^2_{\text{soft}}\right)_{ij} \propto m^2_{3/2}\left(\delta_{ij} + b_{ij}\right)$$

$$q_{ij} = |q_i - q_j|$$





$$b_{ij} = N\, c_{ij}$$

$$c_{ij}^{(Q,\overline{u},\overline{d})} = \begin{pmatrix} \varepsilon^2 & 2\varepsilon^3 & 2\varepsilon^3 \\ 2\varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ 2\varepsilon^3 & \varepsilon^2 & \varepsilon^2 \end{pmatrix} \quad N = \begin{cases} q_{ij} & \text{for } q_{ij} \geq 2 \\ 3 & \text{for } q_{ij} = 1 \\ 2 & \text{for } q_{ij} = 0 \end{cases} \quad b_{ij}^{(Q,\overline{u},\overline{d})} = \begin{pmatrix} 2\varepsilon^2 & 6\varepsilon^3 & 6\varepsilon^3 \\ 6\varepsilon^3 & 2\varepsilon^2 & 2\varepsilon^2 \\ 6\varepsilon^3 & 2\varepsilon^2 & 2\varepsilon^2 \end{pmatrix}$$

Toy $U(1)_f$ model

[Phys.Rev.D 95, 035001]

After canonical normalization & SCKM basis

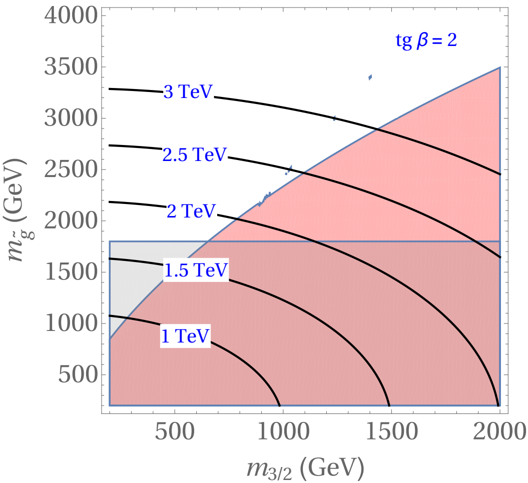
$$A_u \to U_u A_u V_u^\dagger \approx m_{3/2}\, y_t \begin{pmatrix} 14.6\varepsilon^6 & 10.9\varepsilon^5 & 7\varepsilon^3 \\ 10.9\varepsilon^5 & 35.9\varepsilon^4 & 4.9\varepsilon^2 \\ 7\varepsilon^3 & 4.9\varepsilon^2 & 1 \end{pmatrix}$$

$$A_d \to U_d A_d V_d^\dagger \approx m_{3/2}\, y_b \begin{pmatrix} 11.3\varepsilon^4 & 4\varepsilon^3 & 6.5\varepsilon^3 \\ 4.9\varepsilon^3 & 3.2\varepsilon^2 & 4.3\varepsilon^2 \\ 2.1\varepsilon & 0.86 & 0.49 \end{pmatrix}$$

$$(T^{-1})^\dagger (m^2_{\rm soft})_{ij} T^{-1} \sim m^2_{3/2} \begin{pmatrix} 1+\varepsilon^2-\frac{7}{4}\varepsilon^4 & 4\varepsilon^3 & 4\varepsilon^3 \\ 4\varepsilon^3 & 1+\varepsilon^2-\frac{7}{4}\varepsilon^4 & \varepsilon^2-\frac{7}{4}\varepsilon^4 \\ 4\varepsilon^3 & \varepsilon^2-\frac{7}{4}\varepsilon^4 & 1+\varepsilon^2-\frac{19}{4}\varepsilon^4 \end{pmatrix}$$

[Phys.Rev.D 95, 035001]

Phenomenological Analysis



Red area: excluded by ΔM_K

Gray rectangle: LHC direct limits

Black solid lines: average squark mass

Quark Sector:

2.- A $SU(3)_f$ model

$SU(3)_f$ model

[Phys.Rev.D 95, 035001]

Particle Content

Field	ψ	$\bar{\psi}$	H	Σ	$\bar{\phi}_3$	$\bar{\phi}_{23}$	$\bar{\phi}_{123}$
R	1	1	0	0	0	0	0
U(1)	0	0	-4	2	2	1	3
$SU(3)_f$	**3**	**3**	**1**	**1**	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$

[Medeiros, Ross: hep-ph/0507176]

The symmetry is spontaneously broken by the minima of the scalar potential where the flavons take the VEVs:

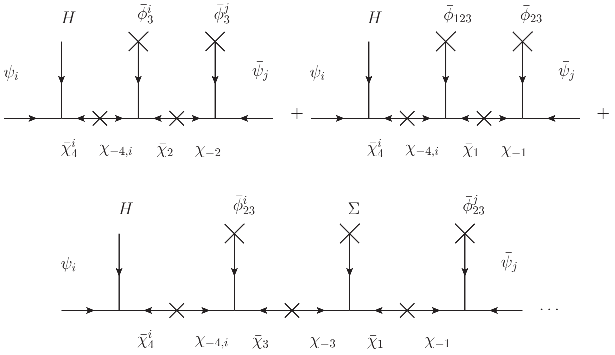
$$\langle \bar{\phi}_{123} \rangle = \begin{pmatrix} \gamma & \gamma & \gamma \end{pmatrix} \qquad \langle \bar{\phi}_{23} \rangle = \begin{pmatrix} 0 & \beta & -\beta \end{pmatrix}$$

$$\langle \bar{\phi}_3 \rangle = \begin{pmatrix} 0 & 0 & 1 \end{pmatrix} \otimes \begin{pmatrix} \alpha_u & 0 \\ 0 & \alpha_d \end{pmatrix}$$

$$\alpha \equiv \frac{\alpha_u}{M_u} \simeq \frac{\alpha_d}{M_d} \gg \varepsilon_f \equiv \frac{\beta}{M_f} \gg \varepsilon_d^2 = \frac{\gamma}{M_d}$$

[Phys.Rev.D 95, 035001]

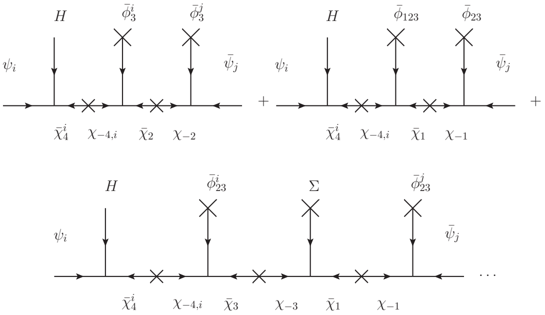
Yukawas



$$\mathbf{Y_u} \sim y_t \begin{pmatrix} 0 & f\ \varepsilon_u^2\,\varepsilon_d & -f'\ \varepsilon_u^2\,\varepsilon_d \\ f\ \varepsilon_u^2\,\varepsilon_d & -\frac{2}{3}\ d\,\varepsilon_u^2 & \frac{2}{3}\ e\,\varepsilon_u^2 \\ -f'\ \varepsilon_u^2\,\varepsilon_d & \frac{2}{3}\ e\,\varepsilon_u^2 & 1 \end{pmatrix} \qquad \mathbf{Y_d} \sim y_b \begin{pmatrix} 0 & h\ \varepsilon_d^3 & -k\ \varepsilon_d^3 \\ h\ \varepsilon_d^3 & l\ \varepsilon_d^2 & -k'\ \varepsilon_d^2 \\ -k\ \varepsilon_d^3 & -k'\ \varepsilon_d^2 & 1 \end{pmatrix}$$

Trilinears

[Phys.Rev.D 95, 035001]



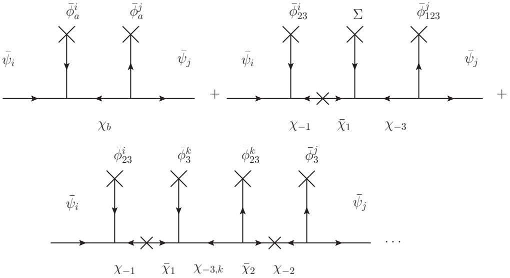
$$\mathbf{A}_u \sim m_{3/2}\, y_t \begin{pmatrix} 0 & 5\, f\, \varepsilon_u^2\, \varepsilon_d & -5\, f'\, \varepsilon_u^2\, \varepsilon_d \\ 5\, f\, \varepsilon_u^2\, \varepsilon_d & -\frac{14}{3}\, d\, \varepsilon_u^2 & \frac{14}{3}\, e\, \varepsilon_u^2 \\ -5\, f'\, \varepsilon_u^2\, \varepsilon_d & \frac{14}{3}\, e\, \varepsilon_u^2 & 5 \end{pmatrix}$$

$$\mathbf{A}_d \sim m_{3/2}\, y_b \begin{pmatrix} 0 & 5\, h\, \varepsilon_d^3 & -5\, k\, \varepsilon_d^3 \\ 5\, h\, \varepsilon_d^3 & 7\, l\, \varepsilon_d^2 & -7\, k'\, \varepsilon_d^2 \\ -5\, k\, \varepsilon_d^3 & -7\, k'\, \varepsilon_d^2 & 5 \end{pmatrix}$$

[Phys.Rev.D 95, 035001]

Kähler & Soft Masses

$$K \;=\; \psi_i^\dagger \psi_j \left(\delta_{ij} + c_{ij} + (\delta_{ij} + b_{ij}) \frac{|F_X|^2}{M_{\rm Pl}^2} \right)$$

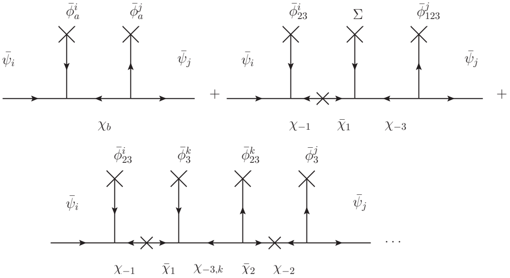


$$c_{ij}^u \simeq y_t \begin{pmatrix} \varepsilon_u^2\,\varepsilon_d^2 & -2\varepsilon_u^3 & 2\varepsilon_u^3 \\ -2\varepsilon_u^3 & \varepsilon_u^2 & -\varepsilon_u^2 \\ 2\varepsilon_u^3 & -\varepsilon_u^2 & 1 \end{pmatrix} \qquad b_{ij}^u \simeq y_t \begin{pmatrix} 2\varepsilon_u^2\,\varepsilon_d^2 & -8\varepsilon_u^3 & 8\varepsilon_u^3 \\ -8\varepsilon_u^3 & 2\varepsilon_u^2 & -2\varepsilon_u^2 \\ 8\varepsilon_u^3 & -2\varepsilon_u^2 & 2 \end{pmatrix}$$

[Phys.Rev.D 95, 035001]

Kähler & Soft Masses

$$K = \psi_i^\dagger \psi_j \left(\delta_{ij} + c_{ij} + (\delta_{ij} + b_{ij}) \frac{|F_X|^2}{M_{\rm Pl}^2} \right)$$



$$c_{ij}^d \simeq y_b \begin{pmatrix} \varepsilon_d^4 & \varepsilon_d^3 & -\varepsilon_d^3 \\ \varepsilon_d^3 & \varepsilon_d^2 & -\varepsilon_d^2 \\ -\varepsilon_d^3 & -\varepsilon_d^2 & 1 \end{pmatrix} \qquad b_{ij}^d \simeq y_b \begin{pmatrix} 2\varepsilon_d^4 & 4\varepsilon_d^3 & -4\varepsilon_d^3 \\ 4\varepsilon_d^3 & 2\varepsilon_d^2 & -2\varepsilon_d^2 \\ -4\varepsilon_d^3 & -2\varepsilon_d^2 & 2 \end{pmatrix}$$

$SU(3)_f$ model

[Phys.Rev.D 95, 035001]

After canonical normalization & SCKM basis

$$\mathbf{A}_u \quad \to \quad m_{3/2}\, y_t \begin{pmatrix} 0.3\,\varepsilon_u^2\,\varepsilon_d^2 & -0.7\,\varepsilon_u^2\,\varepsilon_d & 0.3\,\varepsilon_u^2\,\varepsilon_d \\ -0.7\,\varepsilon_u^2\,\varepsilon_d & -7.6\,\varepsilon_u^2 & \varepsilon_u^2 \\ 0.4\,\varepsilon_u^2\,\varepsilon_d & 1.3\,\varepsilon_u^2 & 5.0 \end{pmatrix}$$

$$\mathbf{A}_d \quad \to \quad m_{3/2}\, y_b \begin{pmatrix} -5.3\,\varepsilon_d^4 & -2.3\,\varepsilon_d^3 & 2.3\,\varepsilon_d^3 \\ -2.3\,\varepsilon_d^3 & 5.2\,\varepsilon_d^2 & -1.5\,\varepsilon_d^2 \\ 3.1\,\varepsilon_d^3 & -2.0\,\varepsilon_d^2 & 5.0 \end{pmatrix}$$

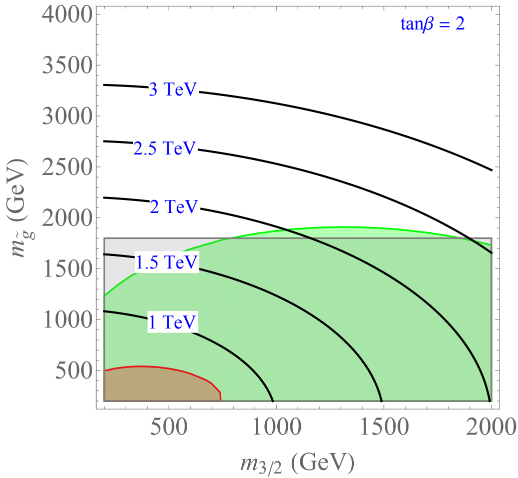
$$\mathbf{m^2}_{\mathrm{soft},\bar{u}} \quad \to \quad m_{3/2}^2 \begin{pmatrix} 1+0.1\,\varepsilon_d^2 & -4\,\varepsilon_u^3 & 3\,\varepsilon_u^3 \\ -4\,\varepsilon_u^3 & 1+\varepsilon_u^2 & -3\,\varepsilon_u^2 \\ 3\,\varepsilon_u^3 & -3\,\varepsilon_u^2 & 1.3 \end{pmatrix}$$

$$\mathbf{m^2}_{\mathrm{soft},\bar{d}} \quad \to \quad m_{3/2}^2 \begin{pmatrix} 1+2\,\varepsilon_d^4 & 0.5\,\varepsilon_d^3 & 2\,\varepsilon_d^3 \\ 0.5\,\varepsilon_d^3 & 1+3\,\varepsilon_d^2 & -2\,\varepsilon_d^2 \\ 2\,\varepsilon_d^3 & -2\,\varepsilon_d^2 & 1.3 \end{pmatrix}$$

$SU(3)_f$ model

[Phys.Rev.D 95, 035001]

Phenomenological Analysis



Red area: excluded by ΔM_K

Green area: excluded by ϵ_K

Gray rectangle: LHC direct limits

Black solid lines: average quark mass

Conclusions

- **Flavour sector** remains one of the most puzzling legacies of the **SM**.
  $\rightsquigarrow$ Supersymmetry may provide new flavour interactions with phenomenological implications for flavour observables.

- We have analysed the effect of introducing a FLASY within a SUSY model and shown that even for a flavour symmetric UV theory, the soft-terms below Λ_f can be strongly **non-universal**

- These results are generically valid for any supersymmetric effective model where the scale of mediation of SUSY breaking is above the flavour.

- The $\mathcal{O}(1)$ **coefficients** relating $Y_{ij} \leftrightarrow A_{ij}$ and $K_{ij} \leftrightarrow (m^2_{\mathrm{soft},ij})$ have been explicitly computed.

- **Future work**:
  1. Leptonic sector ✓ see Aurora's talk **[JHEP 1711 (2017) 162]**
  2. Quarks & leptons models ✓ see Aurora's talk **[hep-ph/1807.00860]**
  3. Neutrinos and charged leptons ✗ In progress...
  4. Other extensions of the SM ✗ to do!

Thanks for your attention!