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Phenomenology of the flavour messenger sector

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based on: L.C., Z. Lalak, S. Pokorski, R. Ziegler, arXiv:1203.1489 [hep-ph] and arXiv:1204.1275 [hep-ph]

Motivations

Hierarchy of SM fermion masses and mixing

Up quarks

$$\frac{m_c}{m_t} \approx \epsilon^4, \quad \frac{m_u}{m_t} \approx \epsilon^8$$

Down quarks

$$\frac{m_s}{m_b} \approx \epsilon^3, \quad \frac{m_d}{m_b} \approx \epsilon^5$$

CKM matrix

$$V_{CKM} \approx \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

$$\epsilon \approx 0.23$$

A dynamical explanation?

Flavour models

- SM fermions charged under a new horizontal symmetry G_F
- G_F forbids Yukawa couplings at the renormalisable level
- G_F spontanously broken by "flavons" vevs $\langle \phi_I \rangle$
- Yukawas arise as higher dimensional operators

Froggatt Nielsen '79

Leurer Seiberg Nir '92, '93

$$W_{yuk} = y^U_{ij} q_i u^c_j h_u + y^D_{ij} q_i d^c_j h_d$$

$$y^{U,D}_{ij} \sim \prod_I \left(\frac{\langle \phi_I \rangle}{M} \right)^{n^{U,D}_{I,ij}}$$

$\phi_I < M \quad \Rightarrow \quad \epsilon_I \equiv \langle \phi_I \rangle / M \qquad n^{U,D}_{I,ij}$ dictated by the symmetry

What is G_F ?

G_F abelian or non-abelian, continous or discrete

U(1), U(1)xU(1), SU(2), SU(3), SO(3), A_4...

Froggatt Nielsen '79; Leurer Seiberg Nir '92, '93; Ibanez Ross '94; Dudas Pokorski Savoy '95; Binetruy Lavignac Ramond '96; Barbieri Dvali Hall '95; Pomarol Tommasini '95; King Ross '01; Altarelli Feruglio '05...

U(1) example

Chankowski et al. '05

$$q_{1,2,3} \;:\; (3,2,0) \qquad u^c_{1,2,3} \;:\; (3,2,0) \qquad d^c_{1,2,3} \;:\; (2,1,1) \qquad \phi \;:\; -1$$

$$\Rightarrow \quad y^U_{ij} \sim \epsilon^{q_i+u_j} \qquad y^D_{ij} \sim \epsilon^{q_i+d_j} \qquad \epsilon = \phi/M \approx 0.23$$

$$Y_u \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \qquad Y_d \sim \begin{pmatrix} \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^2 & \epsilon & \epsilon \end{pmatrix}$$

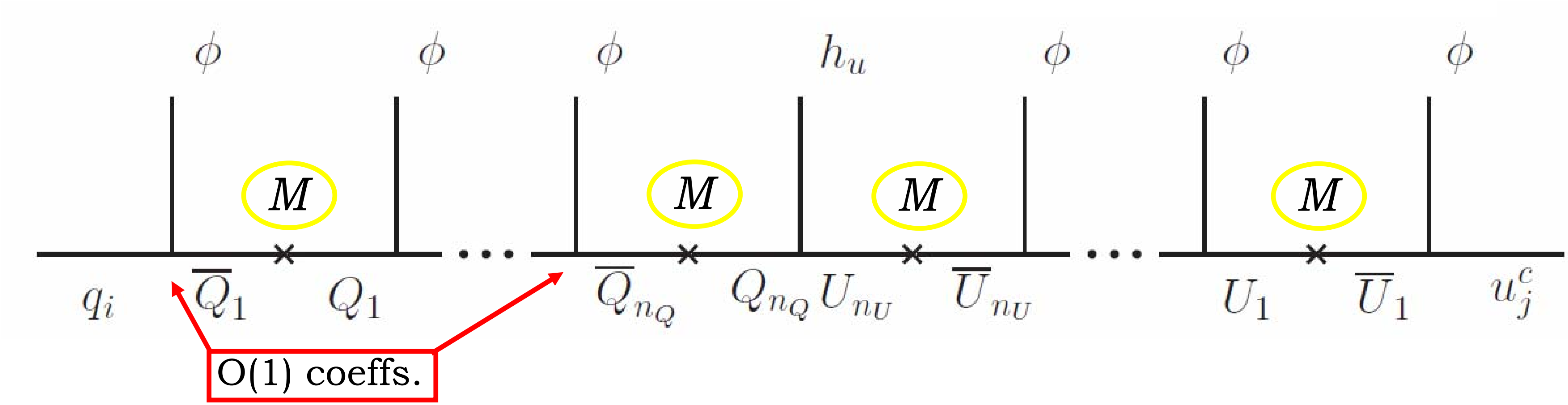
What is M ?

- If $M < M_{Pl}$ new degrees of freedom: "flavour messengers"
- They are in vector-like reprs. of the SM group and G_F-charged
- Two possibilities: heavy fermions (R_P +) or heavy scalars (R_P -)

⇨ mixing with (MS)SM fermions or Higgs fields

"Fermion" UV completion (FUVC)

Chiral superfields: $Q_\alpha + \overline{Q}_\alpha \quad U_\alpha + \overline{U}_\alpha \quad D_\alpha + \overline{D}_\alpha$



The messenger sector

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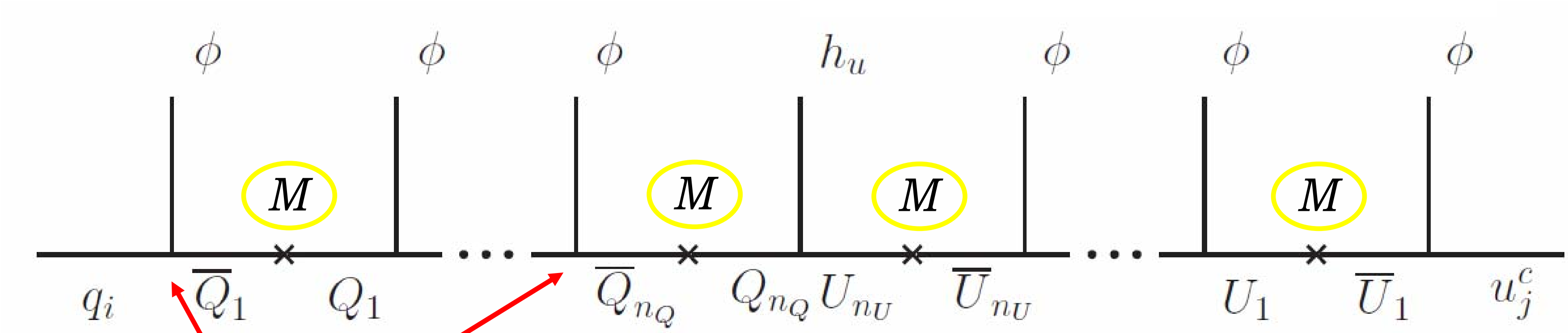

O(1) coeffs.

min. messenger #:

Full-rank Yukawas, if: $\det M^{u,d}_{\text{full}} \propto \det m^{u,d}_{\text{light}} \propto \prod_I \phi_I^{n_I} v^3_{u,d}$ ⇨ $N_{min} = \sum_I n_I$

Leurer Seiberg Nir ’92

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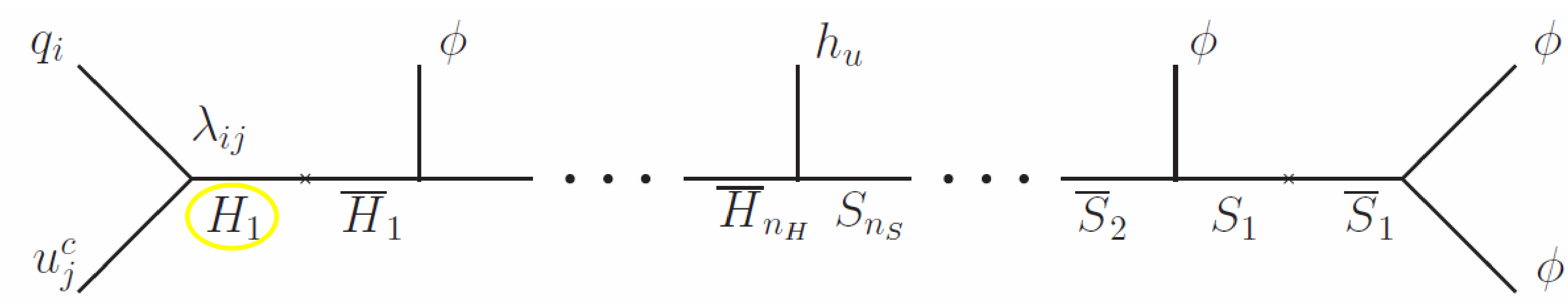
“Higgs” UV completion (FUVC)

Chiral superfields: $H_\alpha + \overline{H}_\alpha \quad S_\alpha + \overline{S}_\alpha$



$$\frac{\partial W}{\partial H_\alpha} = \frac{\partial W}{\partial \overline{H}_\alpha} = \ldots = 0 \quad \Longrightarrow \quad \langle H_\alpha \rangle = \epsilon^n \langle h_u \rangle$$

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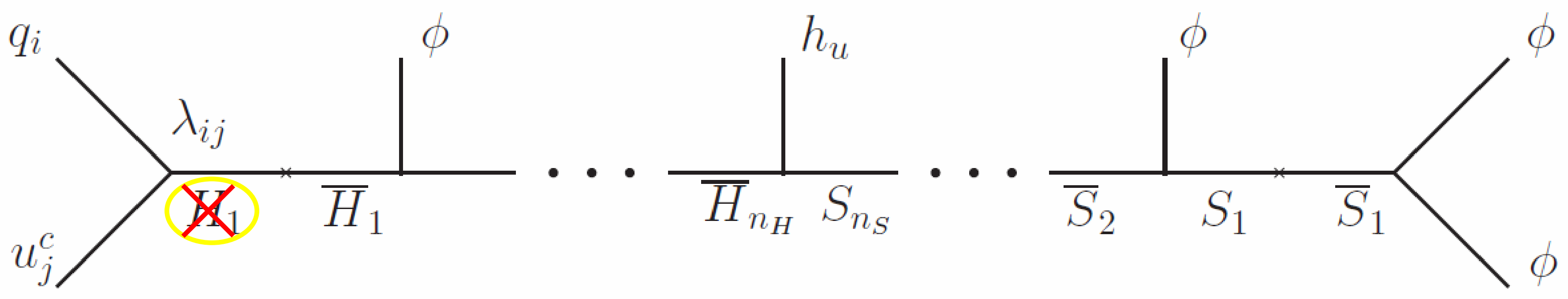


$$\frac{\partial W}{\partial H_\alpha} = \frac{\partial W}{\partial \overline{H}_\alpha} = \ldots = 0 \implies \langle H_\alpha \rangle = \epsilon^n \langle h_u \rangle$$ ⇨ easy to get texture zeros

Ramond Roberts Ross '93

How light can the messenger sector be?

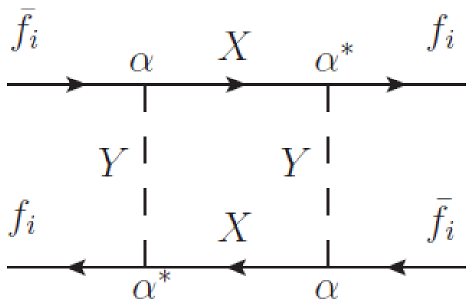
By construction always present couplings (with O(1) coeffs.) of the form:

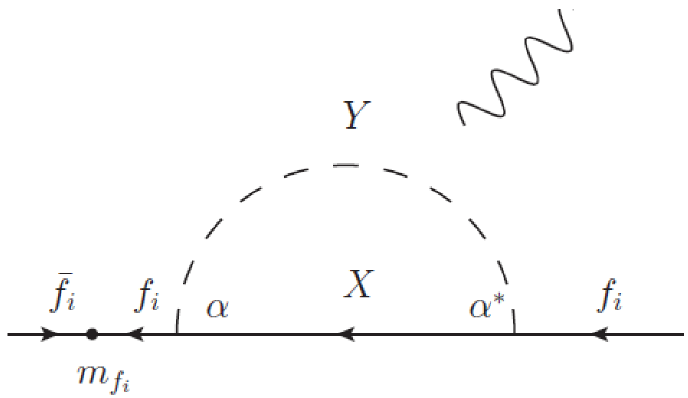
FUVC

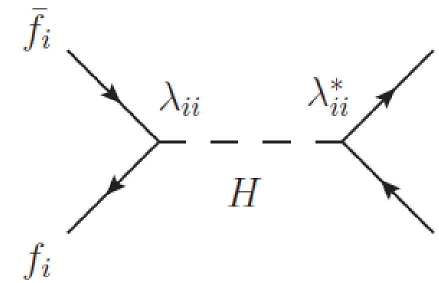
$$\mathcal{L} \supset \alpha^Q \, \overline{q}_{Li} Q_{R\alpha} \, \phi_I + \alpha^D \, \overline{D}_{L\beta} d_{Rj} \, \phi_J + \text{h.c.}$$

HUVC

$$\mathcal{L} \supset \lambda^D_{ij} \, \overline{q}_{Li} d_{Rj} \, H_\alpha + \text{h.c.}$$







$$\mathcal{L}_{eff} \supset \frac{|\alpha|^4}{16\pi^2 M^2} (\overline{f}_{Li} \gamma^\mu f_{Li})^2$$

$$\mathcal{L}_{eff} \supset \frac{|\alpha|^2}{16\pi^2 M^2} m_i \, \overline{f}_{Li} \sigma^{\mu\nu} f_{Ri} F_{\mu\nu}$$

$$\mathcal{L}_{eff} \supset \frac{|\lambda_{ij}|^2}{M^2} (\bar{d}_{Li} d_{Rj})(\bar{d}_{Rj} d_{Li})$$

Flavour conserving ⇨ Flavour violating in the mass basis: $d_{Li} \to d_{Li} + \sum_{j \neq i} \theta^{DL}_{ij} d_{Lj}$

Low-energy messengers

How light can the messenger sector be?

Process	Relevant operators	Bound on c/TeV^2 Re	Bound on c/TeV^2 Im
$\Delta m_K;\ \epsilon_K$	$(\bar{s}_X\gamma^\mu d_X)(\bar{s}_X\gamma^\mu d_X)$	9.0×10^{-7}	3.4×10^{-9}
	$(\bar{s}_L\gamma^\mu d_L)(\bar{s}_R\gamma^\mu d_R)$	1.9×10^{-7}	7.2×10^{-10}
	$(\bar{s}_L d_R)(\bar{s}_R d_L)$	4.7×10^{-9}	1.8×10^{-11}
$\Delta m_D;\ \lvert q/p\rvert_D, A_\Gamma$	$(\bar{c}_X\gamma^\mu u_X)(\bar{c}_X\gamma^\mu u_X)$	4.7×10^{-7}	1.3×10^{-7} [3.8×10^{-9}]
	$(\bar{c}_L\gamma^\mu u_L)(\bar{c}_R\gamma^\mu u_R)$	7.4×10^{-7}	2.1×10^{-7} [5.9×10^{-9}]
	$(\bar{c}_L u_R)(\bar{c}_R u_L)$	4.1×10^{-8}	1.1×10^{-8} [3.3×10^{-10}]
$\Delta m_{B_d};\ S_{\psi K_S}$	$(\bar{b}_X\gamma^\mu d_X)(\bar{b}_X\gamma^\mu d_X)$	2.9×10^{-6}	2.6×10^{-6}
	$(\bar{b}_L\gamma^\mu d_L)(\bar{b}_R\gamma^\mu d_R)$	4.8×10^{-6}	4.3×10^{-6}
	$(\bar{b}_L d_R)(\bar{b}_R d_L)$	4.2×10^{-7}	3.8×10^{-7}
$\Delta m_{B_s};\ S_{\psi\phi}$	$(\bar{b}_X\gamma^\mu s_X)(\bar{b}_X\gamma^\mu s_X)$	6.7×10^{-5}	5.7×10^{-5} [4.1×10^{-6}]
	$(\bar{b}_L\gamma^\mu s_L)(\bar{b}_R\gamma^\mu s_R)$	1.1×10^{-4}	9.4×10^{-5} [6.7×10^{-6}]
	$(\bar{b}_L s_R)(\bar{b}_R s_L)$	9.7×10^{-6}	8.2×10^{-6} [5.8×10^{-7}]
$\mu\to e\gamma$	$\bar{\mu}_X\sigma^{\mu\nu}e_Y F_{\mu\nu}$	2.9×10^{-10} [5.9×10^{-11}]	
$\mu\to eee$	$(\bar{\mu}_X\gamma^\mu e_X)(\bar{e}_X\gamma^\mu e_X)$	2.3×10^{-5} [2.3×10^{-7}]	
	$(\bar{\mu}_X e_Y)(\bar{e}_Y e_X)$	6.5×10^{-5} [6.5×10^{-7}]	

How light can the messenger sector be?

Bounds on M (in TeV):

CPC → HUVC; CPV → HUVC*

$K - \overline{K}$

θ_{12}^{DL}	θ_{12}^{DR}	HUVC	HUVC*	FUVC	FUVC*
ϵ	0	19	310	19	310
ϵ	ϵ	3,400	54,000	19	310
ϵ	1	4,900	80,000	42	680
0	1	42	680	42	680

$D - \overline{D}$

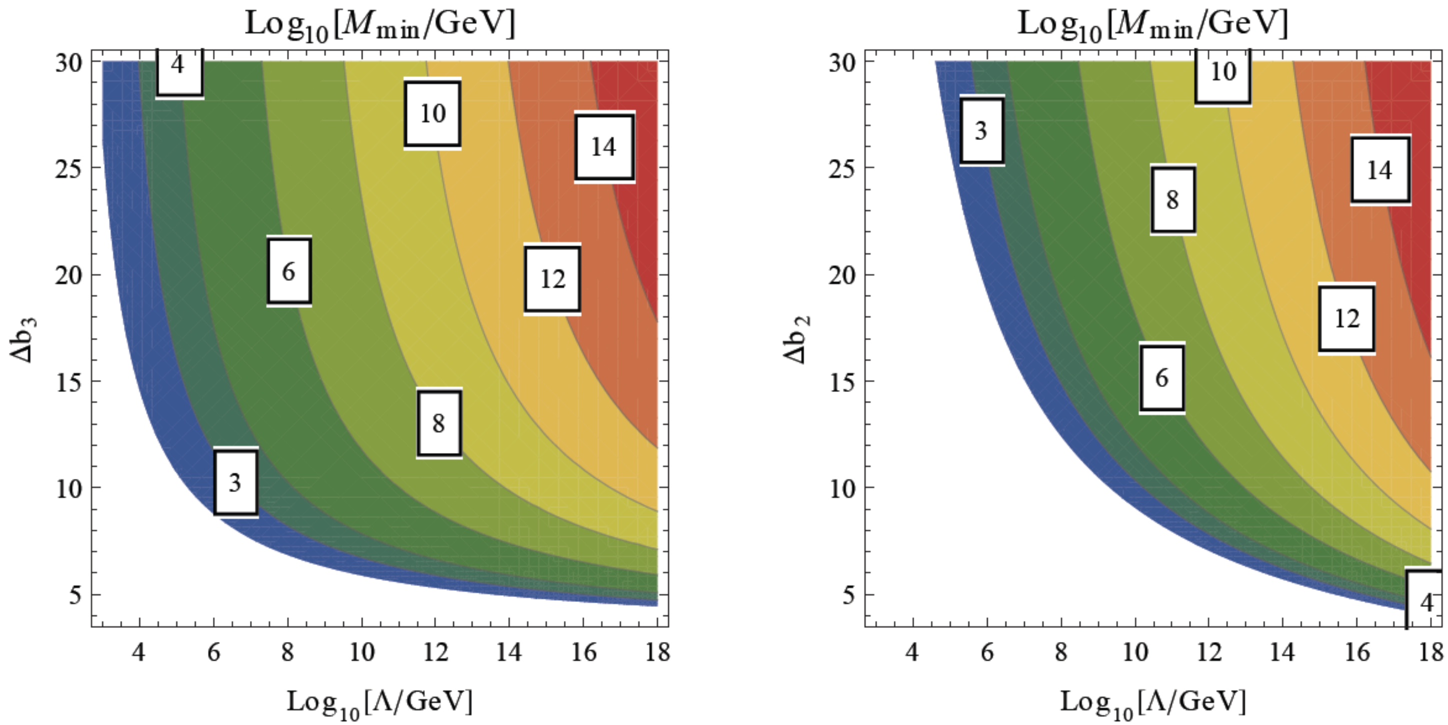
θ_{12}^{UL}	θ_{12}^{UR}	HUVC	HUVC*	FUVC	FUVC*
ϵ	0	27	51 [300]	27	51 [300]
ϵ	ϵ	1,100	2,200 [13,000]	27	51 [300]
ϵ	1	1,700	3,200 [19,000]	58	110 [650]
0	1	58	110 [650]	58	110 [650]

⇨ $M \gtrsim 20$ TeV ($M \gtrsim O(1)$ TeV non-abelian symm.)

Still possible: large effects in LFV decays, $B_{d,s}$ mixing and decays, etc.

Perturbativity constraints

Is the theory perturbative up to high energies?



Model	FUVC		HUVC	
	Δb_3	M_{min}	Δb_2	M_{min}
U(1)	19	10^{14}	11	10^{12}
$\mathrm{U}(1) \times \mathrm{U}(1)'$	8	10^{9}	11	10^{12}
SU(3)	12	10^{12}	6	10^{7}

Radiative effects on sfermion masses

Do ultra-heavy messengers still induce FV effects?

The messenger sector can still interfere with SUSY breaking and affect the sfermion masses

Even if sfermions are universal at M_{SUSY}, if $M < M_{SUSY}$:

$$\tilde{m}^2_{ij}(M_S) = \begin{pmatrix} \tilde{m}^2_0 & 0 \\ 0 & \tilde{m}^2_0 \end{pmatrix} \Rightarrow \tilde{m}^2_{ij}(M) = \begin{pmatrix} \tilde{m}^2_0 + \Delta\tilde{m}^2_{11} & \Delta\tilde{m}^2_{12} \\ \Delta\tilde{m}^2_{21} & \tilde{m}^2_0 + \Delta\tilde{m}^2_{22} \end{pmatrix}$$

universality radiatively broken by the presence of messengers

cf. Hall Kostelecky Raby '86

At low energy (in the SCKM basis): $\tilde{m}^2_{12} \approx \Delta\tilde{m}^2_{12} + \left(\Delta\tilde{m}^2_{22} - \Delta\tilde{m}^2_{11}\right)\theta_{12}$

Estimate (abelian case): $\tilde{m}^2_{12} \approx \left(\Delta\tilde{m}^2_{22} - \Delta\tilde{m}^2_{11}\right)\theta_{12} \approx \theta_{12}\dfrac{\tilde{m}^2_0}{16\pi^2}10\log\dfrac{M_S}{M}$

Non-abelian: additional suppression from correlated coefficients

RG effect as sizeable as the tree-level $\tilde{m}^2_{ij}$ expected by the flavour symm.!

Constraints on light quark rotations

rotation angle	$M_S/M = 10^8$		$M_S/M = 10$	
$\theta_{12}^{DL}, \theta_{12}^{DR}$	7.9×10^{-2} [Re]	1.0×10^{-2} [Im]	6.3×10^{-1} [Re]	8.2×10^{-2} [Im]
$\langle\theta_{12}^{D}\rangle$	1.6×10^{-3} [Re]	2.2×10^{-4} [Im]	1.3×10^{-2} [Re]	1.8×10^{-3} [Im]
$\theta_{12}^{UL}, \theta_{12}^{UR}$	8.6×10^{-2} [Re]	5.1×10^{-2} [Im]	6.9×10^{-1} [Re]	4.1×10^{-1} [Im]
$\langle\theta_{12}^{U}\rangle$	5.3×10^{-3} [Re]	3.4×10^{-3} [Im]	4.3×10^{-2} [Re]	2.7×10^{-2} [Im]
$\theta_{13}^{DL}, \theta_{13}^{DR}$	2.4×10^{-1} [Re]	5.1×10^{-1} [Im]	-	
$\langle\theta_{13}^{D}\rangle$	3.6×10^{-2} [Re]	1.5×10^{-2} [Im]	2.9×10^{-1} [Re]	1.2×10^{-1} [Im]
θ_{12}^{EL}	2.4×10^{-3}	$[4.9 \times 10^{-4}]$	1.9×10^{-2}	$[3.9 \times 10^{-3}]$
θ_{12}^{ER}	2.0×10^{-2}	$[3.9 \times 10^{-3}]$	1.6×10^{-1}	$[3.2 \times 10^{-2}]$
$\langle\theta_{12}^{E}\rangle$	1.5×10^{-3}	$[3.3 \times 10^{-4}]$	1.2×10^{-2}	$[2.6 \times 10^{-3}]$

$$\langle\theta_{12}^{D}\rangle \equiv \sqrt{\theta_{12}^{DL}\theta_{12}^{DR}}$$

SUSY masses at 1 TeV

(additional suppressions in non-abelian models)

Even assuming universality abelian models with $M < M_{SUSY}$ are in trouble

Conclusions

- Horizontal symmetries popular explanation of the SM flavour structure
- Flavour models can be UV completed with heavy "Fermion" and/or "Higgs" messengers
- The messenger sector can have important consequences for Yukawa couplings (textures) and sfermion masses
- FCNC processes directly induced by messenger exchange constrain the mass scale, $M > 20$ TeV (abelian symm.)
- Non-abelian messengers can be as light as the TeV scale
- Perturbativity up to the GUT/Planck scale typically requires $M > 10^{10}$ GeV
- The running of the soft-masses is affected by messengers for $M < M_{SUSY}$

⇒ Universality radiatively broken by messengers

Sfermion off-diagonal entries of the size expected at tree-level

Serdecznie dziękuję!

Additional slides

Off-diagonal entries from spurion analysis (U(1) example):

$$\tilde{m}^2_{ij} \sim \tilde{m}^2 \left(\frac{\phi}{M}\right)^{q_j - q_i}$$

Instead, considering messengers (with $M << M_{SUSY}$):

$$\tilde{m}^2 \left(a_i q_i^\dagger q_i + b_\alpha Q_\alpha^\dagger Q_\alpha + c_{i\alpha} q_i^\dagger Q_\alpha + d_\beta H_\beta^\dagger H_\beta + \ldots + \mathcal{O}(\phi/M_S)\right)$$

Running effects (U(1) HUVC example):

$$(m^2_{\tilde{d}})_{22} - (m^2_{\tilde{d}})_{11} \approx \frac{12}{16\pi^2}\tilde{m}_0^2 \left[(\lambda^{d\dagger}\lambda^d)_{11} - (\lambda^{d\dagger}\lambda^d)_{22}\right] \log\frac{M_S}{M},$$

$$(m^2_{\tilde{q}})_{22} - (m^2_{\tilde{q}})_{11} \approx \frac{6}{16\pi^2}\tilde{m}_0^2 \left[(\lambda^{u\dagger}\lambda^u)_{11} - (\lambda^{u\dagger}\lambda^u)_{22} + (\lambda^{d\dagger}\lambda^d)_{11} - (\lambda^{d\dagger}\lambda^d)_{22}\right] \log\frac{M_S}{M}$$

L and R in fundamentals:

$$\Delta_{12} \sim \phi_2\phi_2 \sim y_{22}$$

$$\Delta_{i3} \sim \phi_3\phi_3 \sim y_{33}$$

(SU(3), U(2)...)

Mass splitting	Suppression factor in $SU(3)_F$	Suppression factor in $U(2)_F$
Δ^U_{13}	$\mathcal{O}(1)$	$\mathcal{O}(1)$
Δ^U_{23}	$\mathcal{O}(1)$	$\mathcal{O}(1)$
Δ^U_{12}	ϵ^4	ϵ^4
Δ^D_{13}	$\epsilon^3 \tan\beta$	$\mathcal{O}(1)$
Δ^D_{23}	$\epsilon^3 \tan\beta$	$\mathcal{O}(1)$
Δ^D_{12}	$\epsilon^5 \tan\beta$	$\epsilon^5 \tan\beta$

Table 2: Additional suppression factors of diagonal sfermion mass splittings $\Delta_{ij} \equiv \tilde{m}^2_{ii} - \tilde{m}^2_{jj}$ in simple non-abelian models.

L in fund., R singlet (or viceversa):

$$\Delta_{12} \sim \phi_2\phi_2 \sim y^2_{22}$$

$$\Delta_{i3} \sim \phi_3\phi_3 \sim y^2_{33}$$

(SO(3), A_4...)

Larger suppr. But in the singlet sector no suppression → U(1) results