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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] & arXiv:1204.1275 [hep-ph]

$\boxed{\text{Hierarchy of SM fermion masses and mixing}}$

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

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

$$\boxed{\epsilon \approx 0.23}$$

A dynamical explanation?

- 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

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

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

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

What is G_F ?

G_F abelian or non-abelian, continuous 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

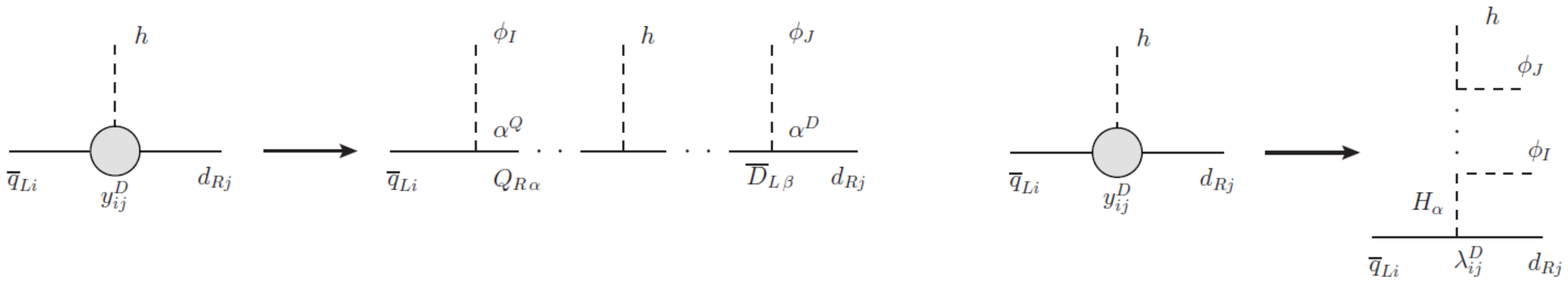
$$q_{1,2,3} : (3,2,0) \qquad u^c_{1,2,3} : (3,2,0) \qquad d^c_{1,2,3} : (2,1,1) \qquad \phi : -1$$

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

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

What is M ?

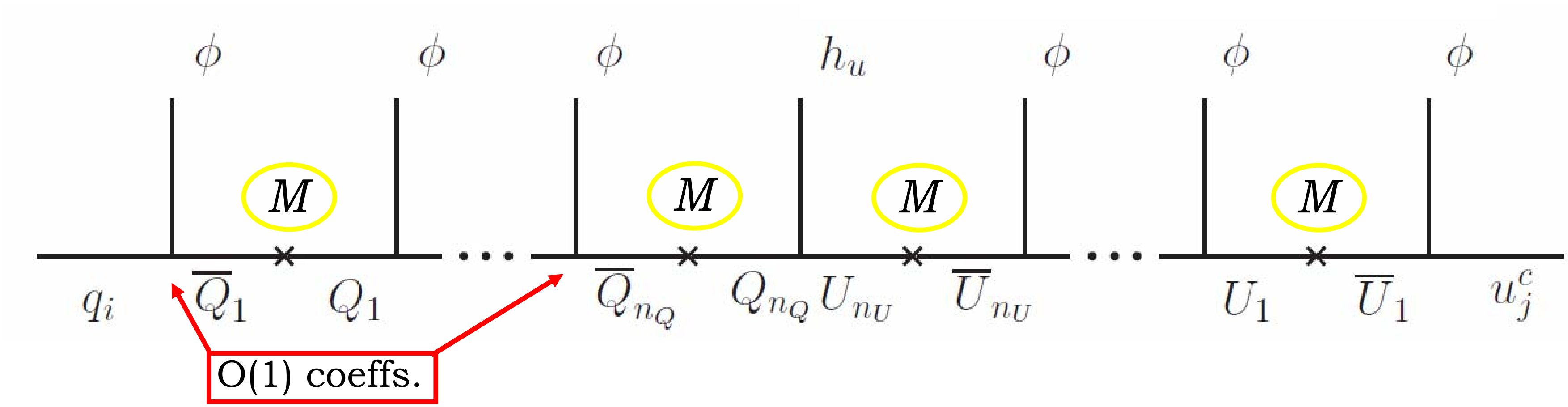
- If smaller than M_{Pl}, M can be interpreted as the mass scale of new degrees of freedom: the "flavour messengers"
- New fields in vector-like reprs. of the SM group and G_F-charged
- Effective Yukawa couplings generated by integrating out the messengers.
- Two possibilities: heavy fermions (R_P +) or heavy scalars (R_P -):



⇒ mixing with (MS)SM fermions or scalar fields

"Fermion" UV completion (FUVC)

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

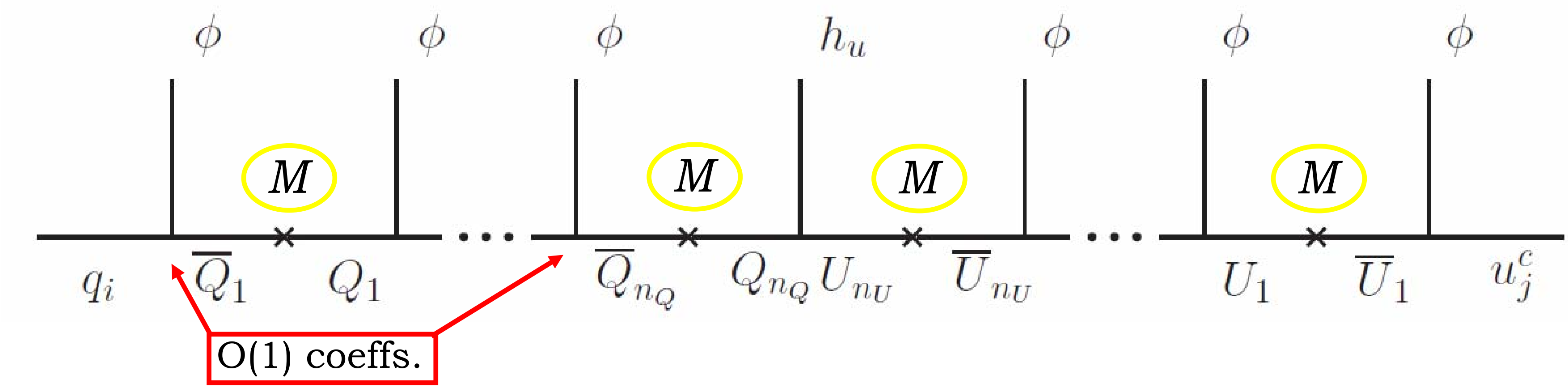


$$W \supset M_Q \overline{Q}_\alpha Q_\alpha + M_U \overline{U}_\alpha U_\alpha + \phi_I \left(\overline{Q}_\alpha Q_\beta + \overline{U}_\alpha U_\beta\right)$$
$$+ \phi_I \left(\overline{Q}_\alpha q_i + \overline{U}_\alpha u^c_i\right) + h_u \left(Q_\alpha U_\beta + Q_\alpha u^c_i + q_i U_\alpha\right)$$

In the fundamental theory small fermion masses arise from small mixing among SM fermion and messengers

“Fermion” UV completion (FUVC)

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



$$W \supset M_Q \overline{Q}_\alpha Q_\alpha + M_U \overline{U}_\alpha U_\alpha + \phi_I \left(\overline{Q}_\alpha Q_\beta + \overline{U}_\alpha U_\beta\right) + \phi_I \left(\overline{Q}_\alpha q_i + \overline{U}_\alpha u^c_i\right) + h_u \left(Q_\alpha U_\beta + Q_\alpha u^c_i + q_i U_\alpha\right)$$

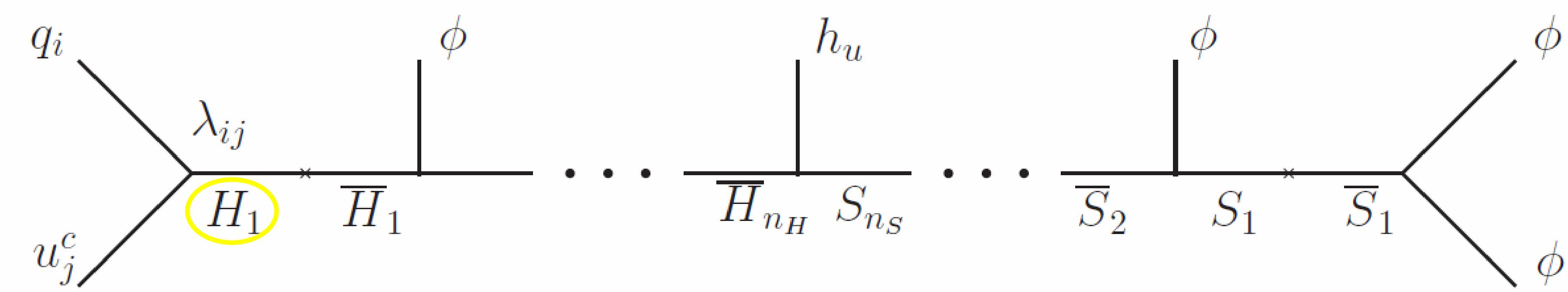
Full-rank Yukawas, if: $\det M^{u,d}_{\rm full} \propto \det m^{u,d}_{\rm light} \propto \prod_I \phi_I^{n_I} v^3_{u,d}$ $\Rightarrow$ min. messenger #: $N_{min} = \sum_I n_I$

Leurer Seiberg Nir ’92

The messenger sector

“Scalar” UV completion (HUVC)

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



$$W \supset M_H \overline{H}_\alpha H_\alpha + M_S \overline{S}_\alpha S_\alpha + \phi_I \left(\overline{H}_\beta H_\alpha + \overline{S}_\beta S_\alpha + \overline{S}_\alpha \phi_J \right)$$
$$+ \overline{H}_\alpha S_\beta h_u + \overline{H}_\alpha \phi_I h_u + q_i u^c_j H_\alpha$$

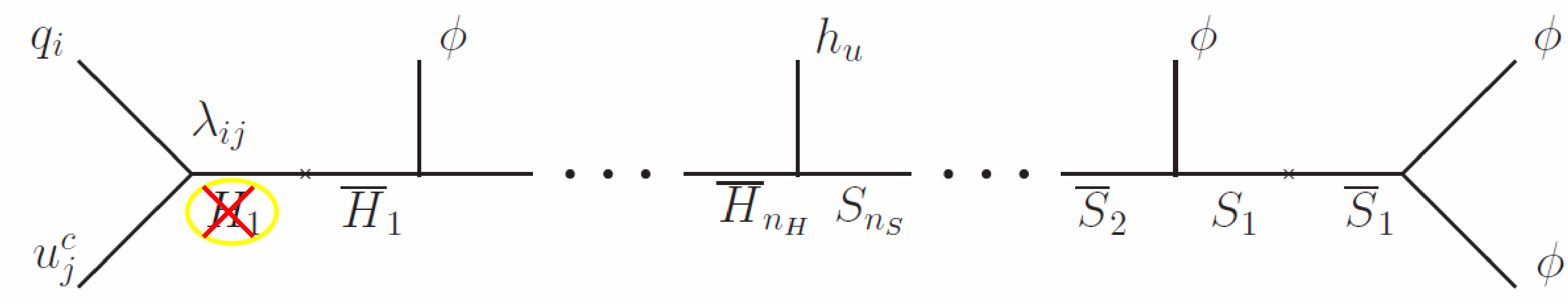
Small fermion masses arise from small H-messenger vevs

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

The messenger sector

$\boxed{\text{“Scalar” UV completion (HUVC)}}$

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



$$W \supset M_H \overline{H}_\alpha H_\alpha + M_S \overline{S}_\alpha S_\alpha + \phi_I \left(\overline{H}_\beta H_\alpha + \overline{S}_\beta S_\alpha + \overline{S}_\alpha \phi_J\right)$$
$$+ \overline{H}_\alpha S_\beta h_u + \overline{H}_\alpha \phi_I h_u + q_i u_j^c H_\alpha$$

Small fermion masses arise from small H-messenger vevs

⇨ easy to obtain texture zeros
(messenger sector can directly affect Yukawas)

Ramond Roberts Ross ’93

$\boxed{\text{How light can the messenger sector be?}}$

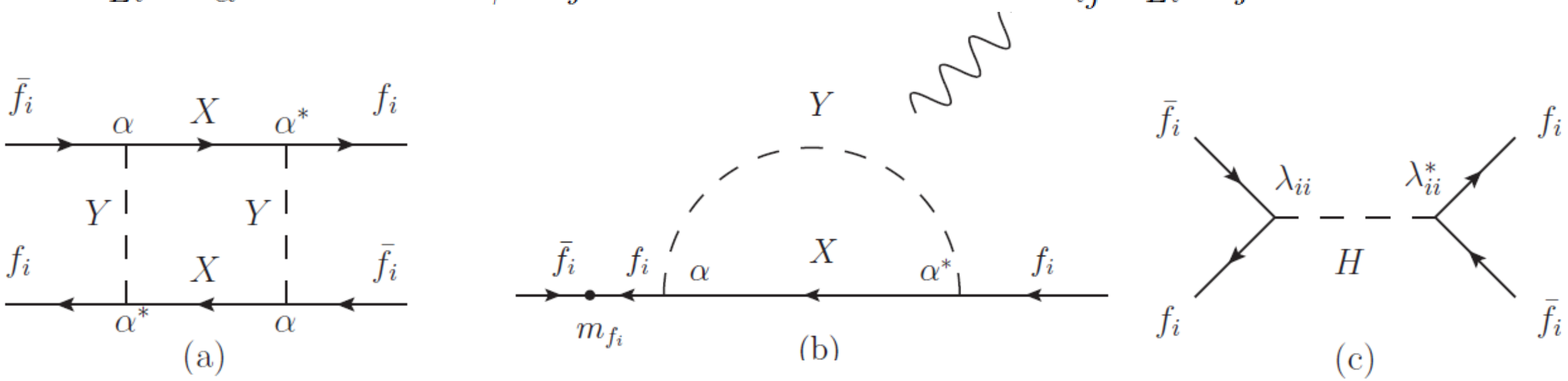
By construction always present couplings (with O(1) coeffs.) of the form:

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

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



$$\mathcal{L}_{eff} \supset \frac{|\alpha|^4}{16\pi^2 M^2} (\overline{f}_{Li}\gamma^\mu f_{Li})^2 \qquad \mathcal{L}_{eff} \supset \frac{|\alpha|^2}{16\pi^2 M^2} m_i \, \overline{f}_{Li}\sigma^{\mu\nu} f_{Ri} F_{\mu\nu} \qquad \mathcal{L}_{eff} \supset \frac{|\lambda_{ij}|^2}{M^2} (\overline{d}_{Li} d_{Rj})(\overline{d}_{Rj} d_{Li})$$

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

[Abelian models: no cancellations (different O(1) coefficients)]

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}]	

Fut. bounds

Operator	HUVC	FUVC	MFV
$(\bar{s}_L\gamma^\mu d_L)(\bar{s}_L\gamma^\mu d_L)$	$L\,\theta_{12}^{DL}\theta_{12}^{DL}$	$L\,\theta_{12}^{DL}\theta_{12}^{DL}$	ϵ^{10}
$(\bar{s}_R\gamma^\mu d_R)(\bar{s}_R\gamma^\mu d_R)$	$L\,\theta_{12}^{DR}\theta_{12}^{DR}$	$L\,\theta_{12}^{DR}\theta_{12}^{DR}$	$\epsilon^{10}y_d^2y_s^2$
$(\bar{s}_L d_R)(\bar{s}_R d_L)$	$\theta_{12}^{DL}\theta_{12}^{DR}$	≈ 0	$\epsilon^{10}y_d y_s$
$(\bar{c}_L\gamma^\mu u_L)(\bar{c}_L\gamma^\mu u_L)$	$L\,\theta_{12}^{UL}\theta_{12}^{UL}$	$L\,\theta_{12}^{UL}\theta_{12}^{UL}$	ϵ^{10}
$(\bar{c}_R\gamma^\mu u_R)(\bar{c}_R\gamma^\mu u_R)$	$L\,\theta_{12}^{UR}\theta_{12}^{UR}$	$L\,\theta_{12}^{UR}\theta_{12}^{UR}$	$\epsilon^{10}y_b^4y_u^2y_c^2$
$(\bar{c}_L u_R)(\bar{c}_R u_L)$	$\theta_{12}^{UL}\theta_{12}^{UR}$	≈ 0	$\epsilon^2 y_d^2 y_s^2 y_u y_c$
$(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma^\mu d_L)$	$L\,\theta_{13}^{DL}\theta_{13}^{DL}$	$L\,\theta_{13}^{DL}\theta_{13}^{DL}$	ϵ^6
$(\bar{b}_R\gamma^\mu d_R)(\bar{b}_R\gamma^\mu d_R)$	$L\,\theta_{13}^{DR}\theta_{13}^{DR}$	$L\,\theta_{13}^{DR}\theta_{13}^{DR}$	$\epsilon^6 y_d^2 y_b^2$
$(\bar{b}_L d_R)(\bar{b}_R d_L)$	$\theta_{13}^{DL}\theta_{13}^{DR}$	≈ 0	$\epsilon^6 y_d y_b$
$(\bar{b}_L\gamma^\mu s_L)(\bar{b}_L\gamma^\mu s_L)$	$L\,\theta_{23}^{DL}\theta_{23}^{DL}$	$L\,\theta_{23}^{DL}\theta_{23}^{DL}$	ϵ^4
$(\bar{b}_R\gamma^\mu s_R)(\bar{b}_R\gamma^\mu s_R)$	$L\,\theta_{23}^{DR}\theta_{23}^{DR}$	$L\,\theta_{23}^{DR}\theta_{23}^{DR}$	$\epsilon^4 y_s^2 y_b^2$
$(\bar{b}_L s_R)(\bar{b}_R s_L)$	$\theta_{23}^{DL}\theta_{23}^{DR}$	≈ 0	$\epsilon^4 y_s y_b$
$\bar{\mu}_X\sigma^{\mu\nu}e_Y F_{\mu\nu}$	$m_\mu L\max(\theta_{12}^{EL},\theta_{12}^{ER})$	$m_\mu L\max(\theta_{12}^{EL},\theta_{12}^{ER})$	-
$(\bar{\mu}_X\gamma^\mu e_X)(\bar{e}_X\gamma^\mu e_X)$	$L\,\theta_{12}^{EX}$	$L\,\theta_{12}^{EX}$	-
$(\bar{\mu}_X e_Y)(\bar{e}_Y e_X)$	$\theta_{12}^{EX}\theta_{12}^{EL}\theta_{12}^{ER}$	≈ 0	—

Table 2. Relevant operators and their minimal Wilson coefficients in units of $1/M^2$ for HUVC FUVC and MFV. Here $L \simeq 1/16\pi^2$, $X, Y = L, R$ with $Y \neq X$.

How light can the messenger sector be?

Bounds on M (in TeV):

CPC CPV

$K - \overline{K}$

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]

$\Rightarrow$ $\boxed{M \gtrsim 20 \text{ TeV}}$ ($M \gtrsim O(1)$ TeV non-abelian symm.)

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

Non-abelian suppressions

$$\mathcal{L}_{\rm eff} \sim |\alpha|^4 \left(\overline{f}_{L1}\gamma^\mu f_{L1} + \overline{f}_{L2}\gamma^\mu f_{L2}\right)^2 \;\Longrightarrow\; \mathcal{L}_{\rm eff} \sim |\alpha|^4 \left(\overline{f}_{L1}\gamma^\mu f_{L1} + \overline{f}_{L2}\gamma^\mu f_{L2} + \Delta_{12}\overline{f}_{L2}\gamma^\mu f_{L2}\right)^2$$

Universality of the couplings broken by the flavour symmetry breaking

- L and R in fundamentals: $\Delta_{12} \sim \phi_2\phi_2 \sim y_{22}$, $\Delta_{i3} \sim \phi_3\phi_3 \sim y_{33}$ (ex.: SU(3), U(2) ...)

- L in fund., R singlet: (or viceversa) $\Delta_{12} \sim \phi_2\phi_2 \sim y_{22}^2$, $\Delta_{i3} \sim \phi_3\phi_3 \sim y_{33}^2$ (ex.: SO(3), A_4 ...)

[Larger suppr. but in the singlet sector no suppression → U(1) results]

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}	$\epsilon^5\tan\beta$	$\epsilon^5\tan\beta$

$\boxed{\text{In non-abelian models, messengers can be as light as O(1) TeV}}$

θ_{12}^{ER}	θ_{12}^{EL}	HUVC = HUVC* $\mu \to e\gamma$	HUVC = HUVC* $\mu \to 3e$	FUVC = FUVC* $\mu \to e\gamma$	FUVC = FUVC* $\mu \to 3e$
ϵ	0	23 [51]	11 [110]	23 [51]	11 [110]
ϵ	ϵ	23 [51]	14 [140]	23 [51]	11 [110]
ϵ	1	34 [75]	42 [420]	34 [75]	12 [120]
0	1	34 [75]	12 [120]	34 [75]	12 [120]
1	1	34 [75]	88 [880]	34 [75]	12 [120]

$\boxed{\mathrm{BR}(\mu \to eee) < 10^{-16}}$

$\boxed{\mathrm{BR}(\mu \to e\gamma) < 10^{-13}}$

Estimate in HUVC:

$$\mathrm{BR}(\mu \to e\gamma) \simeq 5.3 \times 10^{-12} \left(\frac{19\ \mathrm{TeV}}{M}\right)^4 \left(\frac{\max(\theta_{12}^{EL}, \theta_{12}^{ER})}{\epsilon}\right)^2,$$

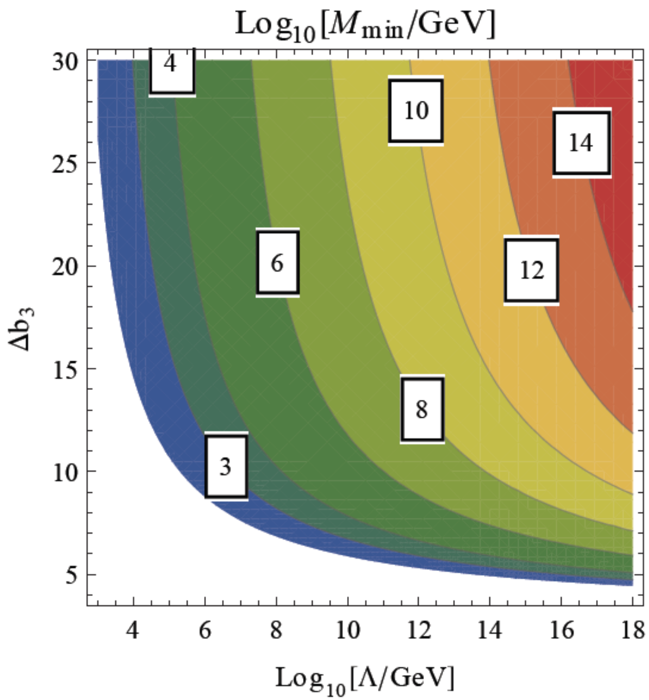
$$\mathrm{BR}(\mu \to eee) \simeq 2.9 \times 10^{-13} \left(\frac{19\ \mathrm{TeV}}{M}\right)^4 \left(\frac{\max(\theta_{12}^{EL}, \theta_{12}^{ER})}{\epsilon}\right)^2 \left(\frac{\theta_{12}^{EL}}{\epsilon}\right)^2 \left(\frac{\theta_{12}^{ER}}{\epsilon}\right)^2$$

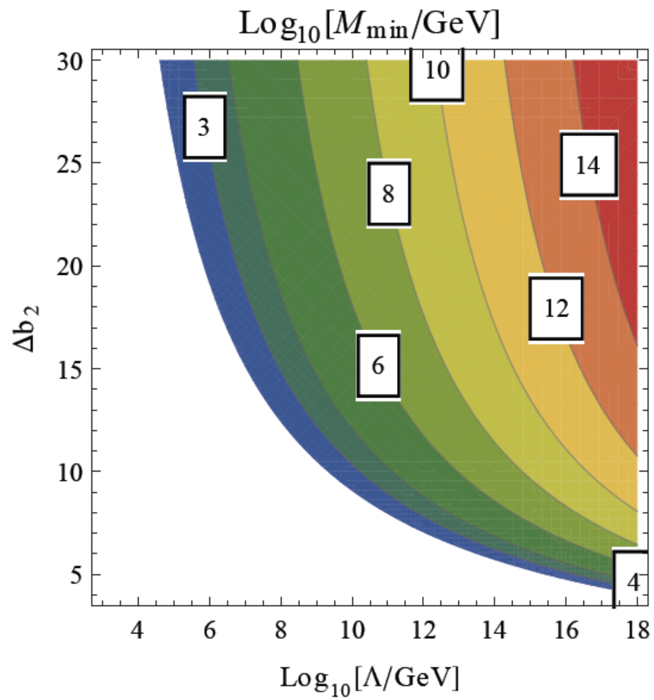
Large leptonic rotations $\Longrightarrow$ $\mathrm{BR}(\mu \to eee)/\mathrm{BR}(\mu \to e\gamma)$ up to O(10)

In SUSY: $\sim \alpha_{em}$ (both decays from dipole ops.)

Is the theory perturbative up to high energies?

Bounds from perturbativity of the gauge couplings (with SUSY):





Examples (for $\Lambda = M_{Planck}$):

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}

Do ultra-heavy messengers still induce FV effects?

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

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

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

Considering messengers (with $M << M_{SUSY}$):

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

(canonically normalized superfields)

Flavour violation in general induced by quark-messenger mixing, but:

no off-diagonal entries with only H-messengers or universal masses (e.g. GMSB)

Radiative breaking of flavour universality

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

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

universality radiatively broken by the presence of messengers

cf. Hall Kostelecky Raby '86

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

U(1) ex.: $\Delta\tilde{m}^2_{12} \propto \epsilon^{q_1 - q_2}\tilde{m}^2, \quad \Delta\tilde{m}^2_{22} - \Delta\tilde{m}^2_{11} \propto \tilde{m}^2, \quad \theta_{12} \sim \frac{y^D_{12}}{y^D_{22}} \propto \frac{\epsilon^{q_1+d_2}}{\epsilon^{q_2+d_2}} = \epsilon^{q_1-q_2}$

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

Non-abelian: additional suppression from correlated coefficients

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

Radiative breaking of flavour universality

Mass insertions:

$$\delta_{12} \equiv \tilde{m}^2_{12}/\sqrt{\tilde{m}^2_{11}\tilde{m}^2_{22}}$$

$$\delta^{\rm ab.}_{12} \approx \frac{\theta_{12}}{16\pi^2} 10\ \mathcal{R} \log \frac{M_S}{M}$$

rotation angle	U(1)	SU(3)
$\theta^{DL}_{12}, \theta^{DR}_{12}$	ϵ	$\epsilon\ (\epsilon^3)$
$\langle\theta^D_{12}\rangle$	ϵ	$\epsilon\ (\epsilon^3)$
$\theta^{UL}_{12}, \theta^{UR}_{12}$	ϵ	$\epsilon^2\ (\epsilon^6)$
$\langle\theta^U_{12}\rangle$	ϵ	$\epsilon^2\ (\epsilon^6)$
θ^{DL}_{13}	ϵ^3	$\epsilon^3\ (\epsilon^3)$
θ^{DR}_{13}	ϵ	$\epsilon^3\ (\epsilon^3)$
$\langle\theta^D_{13}\rangle$	ϵ^2	$\epsilon^3\ (\epsilon^3)$
$\theta^{EL}_{12}, \theta^{ER}_{12}$	ϵ	$\epsilon\ (\epsilon^3)$
$\langle\theta^E_{12}\rangle$	ϵ	$\epsilon\ (\epsilon^3)$

Bounds:

$(\delta^D_{XX})_{12}$	9.2×10^{-2} [Re]	1.2×10^{-2} [Im]
$\langle\delta^D_{12}\rangle$	1.9×10^{-3} [Re]	2.6×10^{-4} [Im]
$(\delta^D_{LR})_{12}$	5.6×10^{-3} [Re]	7.4×10^{-4} [Im]
$(\delta^U_{XX})_{12}$	1.0×10^{-1} [Re]	6.0×10^{-2} [Im]
$\langle\delta^U_{12}\rangle$	6.2×10^{-3} [Re]	4.0×10^{-3} [Im]
$(\delta^U_{LR})_{12}$	1.6×10^{-2} [Re]	1.6×10^{-2} [Im]
$(\delta^D_{XX})_{13}$	2.8×10^{-1} [Re]	6.0×10^{-1} [Im]
$\langle\delta^D_{13}\rangle$	4.2×10^{-2} [Re]	1.8×10^{-2} [Im]
$(\delta^D_{LR})_{13}$	6.6×10^{-2} [Re]	1.5×10^{-1} [Im]
$(\delta^E_{LL})_{12}$	2.8×10^{-3}	[5.7×10^{-4}]
$(\delta^E_{RR})_{12}$	2.3×10^{-2}	[4.6×10^{-3}]
$\langle\delta^E_{12}\rangle$	1.8×10^{-3}	[3.8×10^{-4}]
$(\delta^E_{LR})_{12}$	1.7×10^{-5}	[3.4×10^{-6}]

SUSY masses at 1 TeV $\quad \langle\delta^f_{ij}\rangle \equiv \sqrt{(\delta^f_{LL})_{ij}(\delta^f_{RR})_{ij}}$

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 scalar 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

Additional slides

U(1) example

$$\begin{array}{lcl} q_{1,2,3} & : & (3,2,0) \\ u^c_{1,2,3} & : & (3,2,0) \\ d^c_{1,2,3} & : & (2,1,1) \end{array} \qquad Y_u \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \qquad Y_d \sim \begin{pmatrix} \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^2 & \epsilon & \epsilon \end{pmatrix}$$

FUVC

$$q_1 - Q_2 - Q_1 - Q_0 - U_0 - U_1 - U_2 - u^c_1 \qquad q_1 - Q_2 - Q_1 - Q_0 - D_0 - D_1 - d^c_1$$

$$q_2 - Q'_1 - Q'_0 - U'_0 - U'_1 - u^c_2, \qquad q_2 - Q'_1 - Q'_0 - D'_0 - d^c_2$$

$$q_3 - D''_0 - d^c_3.$$

HUVC

$$H_u^{(x)} + H_d^{(x)} \quad x = -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5.$$

$$W \supset \sum_x M_x\, H_u^{(x)} H_d^{(x)} + \lambda^u_{ij}\, q_i u^c_j\, H_u^{-(\mathcal{H}(q_i)+\mathcal{H}(u_j))} + \lambda^d_{ij}\, q_i d^c_j\, H_d^{(\mathcal{H}(q_i)+\mathcal{H}(d_j))} +$$
$$\phi \left(\alpha_6 H_d^{(-6)} H_u^{(-5)} + \cdots + \alpha_1 H_d^{(-1)} h_u + \alpha_0 h_d H_u^{(1)} + \alpha_{-1} H_d^{(1)} H_u^{(2)} + \cdots + \alpha_{-4} H_d^{(4)} H_u^{(5)} \right)$$

Tree-level vs. radiative effects on sfermion masses

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):

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

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