FLAVOUR WITH LARGER IRREPS

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THE SM HAS A BROKEN $SU(3)^5$ FLAVOUR SYMMETRY

The SM has a broken $SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$ symmetry.

$$\mathcal{L} = i\overline{Q}^i \not{D} Q^i + i\overline{u}^i \not{D} u^i + [\text{sim. for } d, L, e]$$
$$- [y_u]_{ij} \overline{Q}^i \tilde{H} u^j + \text{h.c.} + [\text{sim. for } y_d, y_e]$$

The kinetic terms are invariant under $Q^i \to U_Q^{ij} Q^j$, $u^i \to U_u^{ij} u^j$, ...

The Yukawas break these symmetries — their components are *charged* under $SU(3)^5$. E.g. $y_u \sim \mathbf{3}_Q \otimes \overline{\mathbf{3}}_u$.

What if flavour breaking comes from a higher irrep of $SU(3)^5$?

REVIEW: MINIMAL FLAVOUR VIOLATION (MFV)

Flavour breaking from Yukawas, charged under $SU(3)^5$. E.g. $y_u \sim \mathbf{3}_Q \otimes \overline{\mathbf{3}}_u$.

$$\mathcal{L} = \mathcal{L}_{\text{SM}}[y_u, y_d, y_e] + \mathcal{L}_{\text{BSM}}[y_u, y_d, y_e] \xrightarrow{\text{low E}} \mathcal{L}_{\text{SM}}[y_u, y_d, y_e] + \mathcal{L}_{\text{SMEFT}}[y_u, y_d, y_e]$$

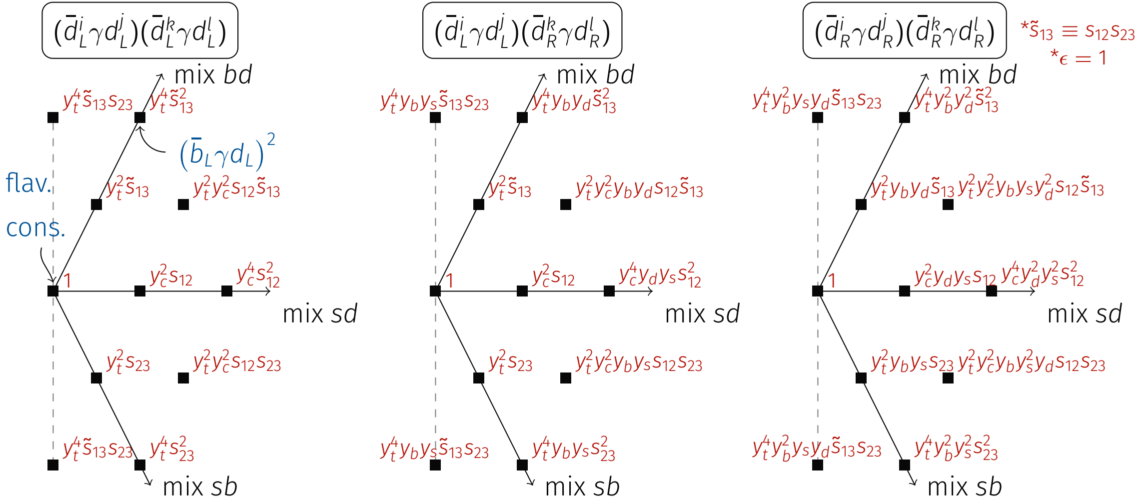
Responsible for flavour in SM and BSM/SMEFT sectors.

Flavour breaking suppressed by powers of Yukawas, e.g.,

$$\mathcal{L} \supset [y_u]_{ij} \overline{Q}^i \tilde{H} u^j + \left(\delta_{ij}\delta_{kl} + \epsilon^2 [y_u y_u^\dagger]_{ij} \delta_{kl} + \epsilon^2 \delta_{ij} [y_d^\dagger y_d]_{kl} + \ldots \right) \frac{\overline{Q}^i \gamma^\mu Q^j d^k \gamma_\mu d^l}{\Lambda_{\text{BSM}}^2}$$

(D'Ambrosio, Giudice, Isidori, and Strumia 2002)

MFV PATTERN IN DOWN BASIS



Every flavour violating direction suppressed, less so for left-handed sb.

Flavour breaking from flavon ϕ, unit charge under $U(1)$.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}[\phi] + \mathcal{L}_{\mathrm{BSM/SMEFT}}[\phi]$$

Individual generations also charged under $U(1)$. [Example in brackets]

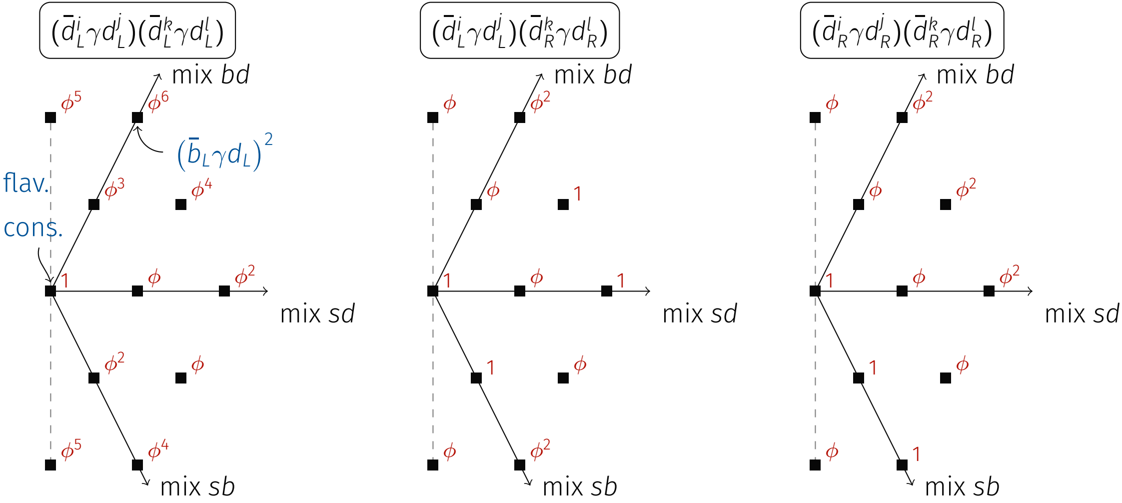
$$Q^i = \begin{pmatrix} Q^1\ [+3] \\ Q^2\ [+2] \\ Q^3\ [+0] \end{pmatrix} ; \quad u^i = \begin{pmatrix} u^1\ [-3] \\ u^2\ [-1] \\ u^3\ [+0] \end{pmatrix} ; \quad d^i = \begin{pmatrix} d^1\ [-3] \\ d^2\ [-2] \\ d^3\ [-2] \end{pmatrix}$$

Suppresses Yukawa entries and BSM/SMEFT, e.g.

$$\mathcal{L} \supset \overline{Q}^i \begin{pmatrix} \phi^6 & \phi^4 & \phi^3 \\ \phi^5 & \phi^3 & \phi^2 \\ \phi^3 & \phi^1 & 1 \end{pmatrix} \tilde{H} u^j + \phi \frac{\overline{Q}^1 \gamma^\mu Q^2 \overline{d}^3 \gamma_\mu d^2}{\Lambda_{\mathrm{BSM}}^2}$$

(Froggatt and Nielsen 1979)

FN PATTERN IN DOWN BASIS



Unsuppressed flavour violating directions! (Direction depends on charges.)

OUR IDEA: LARGER-IRREP MFV/NON-ABELIAN FN

Flavour breaking from $\mathcal{Y}$, larger irrep of $SU(3)^5$. E.g. $\mathcal{Y}_u \sim \mathbf{6}_Q \otimes \overline{\mathbf{6}}_u$.

$$\mathcal{L} = \mathcal{L}_{\text{SM}}[\mathcal{Y}_u, \mathcal{Y}_d, \mathcal{Y}_e] + \mathcal{L}_{\text{BSM/SMEFT}}[\mathcal{Y}_u, \mathcal{Y}_d, \mathcal{Y}_e]$$

Powers of $\mathcal{Y}$ build both Yukawas and BSM/SMEFT

$$\mathcal{L} \supset \left([\mathcal{Y}_u^2 \overline{\mathcal{Y}}_u]_{ij} + \epsilon [\mathcal{Y}_u^4]_{ij} + \epsilon [\mathcal{Y}_u \overline{\mathcal{Y}}_u^3]_{ij} + \ldots \right) \overline{Q}^i \tilde{H} u^j$$
$$+ \left(\delta_{ij}\delta_{kl} + \epsilon^2 [\mathcal{Y}_u \overline{\mathcal{Y}}_u]_{ij} \delta_{kl} + \ldots \right) \frac{\overline{Q}^i \gamma^\mu Q^j d^k \gamma_\mu d^l}{\Lambda_{\text{BSM}}^2}$$

TWO EXAMPLE WAYS TO GENERATE YUKAWA STRUCTURE

$$y \sim \mathcal{Y}^2\overline{\mathcal{Y}} + \epsilon\left(\mathcal{Y}^4 + \mathcal{Y}\overline{\mathcal{Y}}^3\right) + \mathrm{O}(\epsilon^2)$$

$\mathcal{Y} \sim$

	11	12	13	22	23	33
11						
12	1					
13					1	
22			1		1	
23						
33						

$$y \sim \begin{pmatrix} \epsilon & \epsilon & 0 \\ 0 & 0 & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix} + \mathrm{O}(\epsilon^2)$$

masses $\sim \epsilon^2, \epsilon, 1$

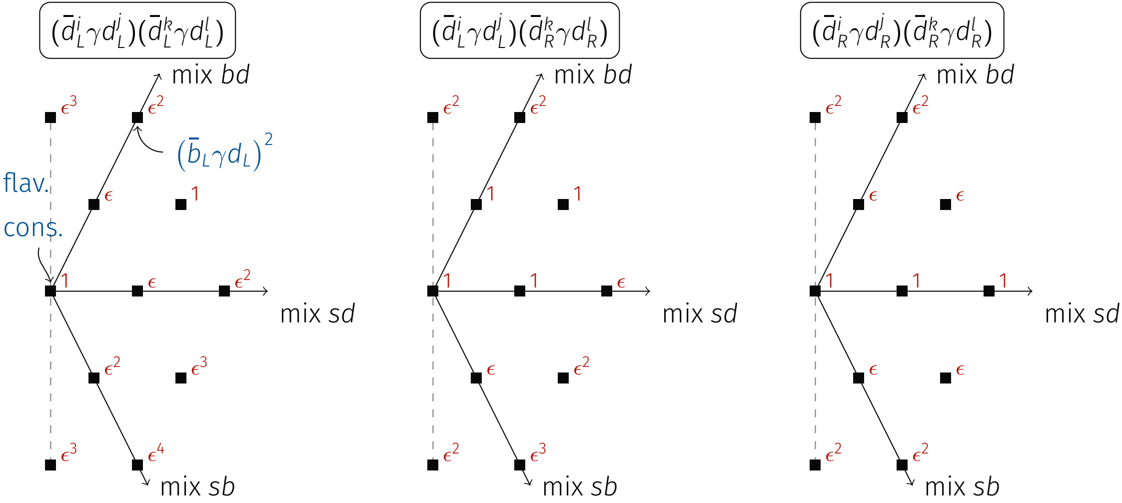
$\mathcal{Y} \sim$

	11	12	13	22	23	33
11						
12		1				
13			δ			
22					1	
23				1		
33						δ

$$y \sim \begin{pmatrix} \delta^2 & 0 & 0 \\ 0 & \delta & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathrm{O}(\epsilon)$$

masses $\sim \delta^2, \delta, 1$

PATTERN IN DOWN BASIS



Unsuppressed flavour violating directions! (Direction depends on charges.)

Minimally,

$$\mathcal{L} = -[y_e]_{ij}\overline{L}^i H e^j + \frac{c_{ij}}{\Lambda}(HL^i)(HL^j) + \text{h.c.}$$

where $y_e \sim \mathbf{3}_L \times \overline{\mathbf{3}}_e$ and $c \sim \mathbf{6}_L \times \mathbf{1}_e$. $\Lambda \approx 10^{11}$ TeV.

But if flavour comes from $\mathcal{Y}_e \sim \mathbf{6}_L \times \overline{\mathbf{6}}_e$ and $\mathcal{S} \sim \mathbf{1}_L \times \mathbf{21}_e$

$$\mathcal{L} = \frac{1}{\Lambda^2}[\mathcal{Y}_e^2\overline{\mathcal{Y}}_e]_{ij}\overline{L}^i H e^j + \frac{[\mathcal{Y}_e\mathcal{S}^4]_{ij}}{\Lambda^6}(HL^i)(HL^j) + \text{h.c.}$$

and Λ (also $\mathcal{Y}_e$ and $\mathcal{S}$) could be TeV scale!

SUMMARY

What if the sole source of flavour, $\mathcal{Y}$, is in a non-minimal irrep of $SU(3)^5$?

- 'Accidental' mass hierarchy from $\mathcal{O}(1)$ elements of $\mathcal{Y}$.
- Different correlations between SM and BSM flavour patterns
- Different BSM scales

Theoretically, lots of model space to explore.

Experimentally, different correlations motivate a broad flavour programme.

Thank you

Backup

If $\mathcal{Y}_u$, $\mathcal{Y}_d$ have form on slide 7(left), then need hierarchical rotation to diagonalise

$$U_q^L = \begin{pmatrix} \mathcal{O}(\epsilon_q) & \mathcal{O}(1) & \mathcal{O}(\epsilon_q^2) \\ \mathcal{O}(1) & \mathcal{O}(\epsilon_q) & \mathcal{O}(\epsilon_q) \\ \mathcal{O}(\epsilon_q) & \mathcal{O}(\epsilon_q^2) & \mathcal{O}(1) \end{pmatrix}$$

Gives hierarchical CKM with wrong hierarchy!

$$V_{\text{CKM}} = U_u^L (U_d^L)^\dagger = \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon) & \mathcal{O}(1) & \mathcal{O}(\epsilon^2) \\ \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon^2) & \mathcal{O}(1) \end{pmatrix} ,$$

POWER COUNTING

UV model: on top of $\mathcal{Y} \sim \mathbf{6}_Q \otimes \overline{\mathbf{6}}_u$, add

- Higgs-like scalar F in $\mathbf{3}_Q \times \overline{\mathbf{3}}_u$, and a $\mathbf{2}_{-\frac{1}{2}}$ of $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- neutral scalar $\mathcal{X}$ in $\mathbf{3}_Q \times \overline{\mathbf{3}}_u$

$$\mathcal{L}_{\text{scalar pot}} = \tilde{y}\overline{Q}Fu + \lambda FH\mathcal{X}^2 + \lambda' FH\mathcal{X}\mathcal{Y} + \mu\overline{HF}\mathcal{X} + A\mathcal{X}^3 + A'\mathcal{Y}^3 + A''\mathcal{X}^2\mathcal{Y} + B\overline{\mathcal{X}}^2\mathcal{Y}^2 + B'\mathcal{X}^2\overline{\mathcal{X}\mathcal{Y}} + B''\mathcal{X}\mathcal{Y}\overline{\mathcal{Y}}^2 + CF\overline{F}\mathcal{X}\overline{\mathcal{Y}} + \text{h.c.} + \text{cross quartics}$$

Integrating out $\mathcal{X}$ and F

$$y = \tilde{y}\frac{(B'')^*\mu}{M_{\mathcal{X}}^2 M_F^2}\mathcal{Y}^2\overline{\mathcal{Y}}\,; \qquad y_\epsilon = \tilde{y}\frac{B''(\lambda')^*}{M_{\mathcal{X}}^2 M_F^2}\mathcal{Y}\overline{\mathcal{Y}}^3\,.$$

y is $\mathrm{O}(1)$ and y_ϵ small if all couplings large except $\mathbb{Z}_2$ breaking λ'.

ALTERNATIVE WAY TO GENERATE YUKAWA STRUCTURE

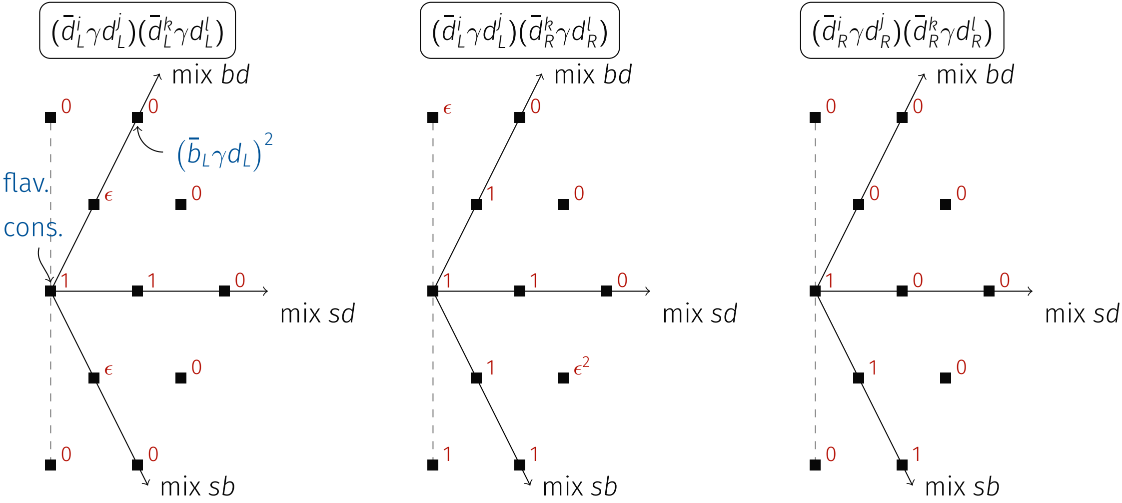
$$y \sim \mathcal{Y}^2\overline{\mathcal{Y}} + \epsilon\left(\mathcal{Y}^4 + \mathcal{Y}\overline{\mathcal{Y}}^3\right) + \mathrm{O}(\epsilon^2)$$

$$\mathcal{Y} \sim \begin{array}{c} \\ 11 \\ 12 \\ 13 \\ 22 \\ 23 \\ 33 \end{array} \begin{array}{c} \begin{array}{cccccc} 11 & 12 & 13 & 22 & 23 & 33 \end{array} \\ \begin{pmatrix} & 1 & 1 & & & \\ & & 1 & & & \\ & & & & & \\ & & & & & \\ & & & 1 & & \\ & & & & & \end{pmatrix} \end{array}$$

$$y \sim \begin{pmatrix} \epsilon & \epsilon & 0 \\ 0 & 0 & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix} + \mathrm{O}(\epsilon^2)$$

$$\text{masses} \sim \epsilon^2, \epsilon, 1$$

ALTERNATIVE PATTERN IN DOWN BASIS



Zeroes may be filled in beginning at $\mathcal{O}(\epsilon^2)$

- D'Ambrosio, G. et al. (2002). "Minimal flavor violation: An Effective field theory approach". In: *Nucl. Phys. B* 645, pp. 155–187. DOI: 10.1016/S0550-3213(02)00836-2. arXiv: hep-ph/0207036.
- Froggatt, C. D. and Holger Bech Nielsen (1979). "Hierarchy of Quark Masses, Cabibbo Angles and CP Violation". In: *Nucl. Phys. B* 147, pp. 277–298. DOI: 10.1016/0550-3213(79)90316-X.