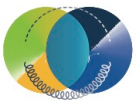
Flavour structures in BSM models

”RA4 Kickoff Meeting”
Dortmund, Nov 2025

Thorsten Feldmann (SI)

Universität Siegen
TP1 Theoretical Particle Physics
CPPS Center for Particle Physics Siegen



color meets flavor

- The SM gauge-kinetic sector is flavour-blind

  flavour symmetry: $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$

  for 3 copies ("generations") of 5 types of fermion multiplets (Q_L, U_R, D_R, L_L, E_R)

- flavour-symmetry breaking encoded in SM Yukawa sector:

$$\mathcal{L}_{\text{yuk}} = -Y_U^{ab}\, \bar{Q}^a \tilde{H} U^b - Y_D^{ab}\, \bar{Q}^a H D^b - Y_E^{ab}\, \bar{L}^a H E^b + \text{h.c.}$$

  $\rightarrow$ 54 real parameters in 3 complex 3×3 Yukawa matrices

- Yukawa sector preserves "accidental symmetries"

$$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

  (baryon number and lepton flavour)

Standard Model:

- $54 \to 13$ flavour parameters from Yukawas
- "natural" value for top-Yukawa only:

$$y_t \sim \mathcal{O}(1)\,, \qquad \text{while } y_{f\neq t} \ll 1$$

- small CKM angles (from (U_L, D_L) rotations)

$$1 \gg \theta_{12} \gg \theta_{23} \gg \theta_{13} \sim \theta_{12}\theta_{23}$$

- other rotations (U,D,E,L) not observable

Standard Model:

- $54 \to 13$ flavour parameters from Yukawas
- "natural" value for top-Yukawa only:

$$y_t \sim \mathcal{O}(1)\,, \qquad \text{while } y_{f\neq t} \ll 1$$

- small CKM angles (from (U_L, D_L) rotations)

$$1 \gg \theta_{12} \gg \theta_{23} \gg \theta_{13} \sim \theta_{12}\theta_{23}$$

- other rotations (U,D,E,L) not observable

Beyond the SM

- Many (!) new flavour-specific couplings
- No a-priori information about "natural" size
- So far, no direct hint for NP mass scale
- flavour mixing from right-handed quarks and charged leptons, too

Standard Model:

- $54 \to 13$ flavour parameters from Yukawas
- "natural" value for top-Yukawa only:

$$y_t \sim \mathcal{O}(1)\,, \qquad \text{while } y_{f\neq t} \ll 1$$

- small CKM angles (from (U_L, D_L) rotations)

$$1 \gg \theta_{12} \gg \theta_{23} \gg \theta_{13} \sim \theta_{12}\theta_{23}$$

- other rotations (U,D,E,L) not observable

Beyond the SM

- Many (!) new flavour-specific couplings
- No a-priori information about "natural" size
- So far, no direct hint for NP mass scale
- flavour mixing from right-handed quarks and charged leptons, too

Example: SMEFT

Assuming unbroken baryon- and lepton-#:

- 2499 new parameters @ dim-6
  most of them related to flavour-specific
  2- and 4-fermion operators

[Buchmüller/Wyler '86, Grzadkowski et al. 2010]

perfect flavour symmetry

$U(3)^5$ @high scale

\+ reduction of free parameters

\+ new flavour effects from RG, only

– working assumption not RG-invariant

– not compatible with $y_t \sim \mathcal{O}(1)$

perfect flavour symmetry

$U(3)^5$ @high scale

generic $\mathcal{O}(1)$ couplings

no symmetry constraints

$+$ no additional theory bias

$\pm$ flavour constraints imply huge NP scales

$-$ too many free parameters

$-$ dim-4 Yukawas appear fine-tuned (natural?)

perfect flavour symmetry

$U(3)^5$ @high scale

Minimal Flavour Violation

expand in Y_U, Y_D, Y_E from SM

[D'Ambrosio et al. 2002, Buras 2003]

- $+$ RG covariant
- $+$ NP scales can be relatively small
- $\pm$ SM-like suppression of rare flavour decays
- $-$ reversed logic? (IR $\mapsto$ UV)

generic $\mathcal{O}(1)$ couplings

no symmetry constraints

perfect flavour symmetry

$U(3)^5$ @high scale

Minimal Flavour Violation

expand in Y_U, Y_D, Y_E from SM

[D'Ambrosio et al. 2002, Buras 2003]

Froggatt-Nielsen Scenario

a single $U(1)$ broken@UV

[Froggatt/Nielsen '79]

\+ RG covariant

\+ self-consistent flavour power counting

– (too?) large NP flavour effects

generic $\mathcal{O}(1)$ couplings

no symmetry constraints

perfect flavour symmetry

$U(3)^5$ @high scale

Minimal Flavour Violation

expand in Y_U, Y_D, Y_E from SM

[D'Ambrosio et al. 2002, Buras 2003]

$\updownarrow$? to be explored …

Froggatt-Nielsen Scenario

a single $U(1)$ broken@UV

[Froggatt/Nielsen '79]

generic $\mathcal{O}(1)$ couplings

no symmetry constraints

- systematic classification of flavour scenarios,
  spurion-based implementation in AUTOEFT,
  interface to BSM analysis tools.

[TF/Harlander/Schaaf/Tong, in preparation]

- application to models with light invisibles (axions, …),
  phenomenological implications from rare flavour observables

[TF/Stamou/Stefkova]
RA2/RA4