Flavor Symmetries in the SMEFT

$U(3)^5$ and $U(2)^5$ flavor symmetry

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Based on:
JHEP 08 (2020) 166, [arXiv:2005.05366]
D. A. Faroughy, G. Isidori, FW, K. Yamamoto

Outline

Flavor Symmetries in the SMEFT

- General flavor structure of the SMEFT
- (Dis-) Advantages of using flavor symmetries
- Examples of flavor symmetries:
  - $U(3)^5$ symmetry and Minimal Flavor Violation
  - $U(2)^5$ symmetry with minimal breaking
- Parameter counting and operator classification
- Application to LHC searches at high-p_T

General Flavor Structure in the SMEFT

Operators

- Warsaw basis — dimension-six
- Electroweak structures: 59
  - 19 fermion bilinears
  - 25 fermion quadrilinears
- Free parameters in the SMEFT:
  - 1 generation — general:

    $76 = 53 + 23$

    CP-even CP-odd

Flavor

  - 3 generations — general:

    $2499 = 1350 + 1149$

    Alonso et al. [arXiv:1312.2014]
  - 3 generations — $U(3)^5$:

    $47 = 41 + 6$

➡ Significant reduction of parameters

5–7: Fermion Bilinears

non-hermitian ($\bar{L}R$)							
5: ψ^2H^3+ h.c.		6: ψ^2XH+ h.c.					
Q_{eH}	$(H^\dagger H)(\bar{\ell}_p e_r H)$	Q_{eW}	$(\bar{\ell}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\tilde{H}G^A_{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)HG^A_{\mu\nu}$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \tilde{H})$	Q_{eB}	$(\bar{\ell}_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\tilde{H}W^I_{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I HW^I_{\mu\nu}$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$			Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tilde{H}B_{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)HB_{\mu\nu}$

hermitian ($+\,Q_{Hud}$) $\sim$ 7: ψ^2H^2D					
($\bar{L}L$)		($\bar{R}R$)		($\bar{R}R'$)	
$Q^{(1)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}_p\gamma^\mu\ell_r)$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	Q_{Hud} + h.c.	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$
$Q^{(3)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p\tau^I\gamma^\mu\ell_r)$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$		
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$		
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$				

8: Fermion Quadrilinears

hermitian								
($\bar{L}L$)($\bar{L}L$)			($\bar{R}R$)($\bar{R}R$)			($\bar{L}L$)($\bar{R}R$)		
$Q_{\ell\ell}$	[a]	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{\ell}_s\gamma^\mu\ell_t)$	Q_{ee}	[a$_2$]	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$Q_{\ell e}$	[a]	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{e}_s\gamma^\mu e_t)$
$Q^{(1)}_{qq}$	[a]	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	[a$_1$]	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$Q_{\ell u}$	[b]	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{u}_s\gamma^\mu u_t)$
$Q^{(3)}_{qq}$	[a]	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	[a$_1$]	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{\ell d}$	[b]	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{d}_s\gamma^\mu d_t)$
$Q^{(1)}_{\ell q}$	[b]	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	[b]	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	[b]	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q^{(3)}_{\ell q}$	[b]	$(\bar{\ell}_p\gamma_\mu\tau^I\ell_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	[b]	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q^{(1)}_{qu}$	[a]	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
			$Q^{(1)}_{ud}$	[b]	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q^{(8)}_{qu}$	[a]	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
			$Q^{(8)}_{ud}$	[b]	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	[a]	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
						$Q^{(8)}_{qd}$	[a]	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

non-hermitian					
($\bar{L}R$)($\bar{R}L$) + h.c.			($\bar{L}R$)($\bar{L}R$) + h.c.		
$Q_{\ell edq}$	[a]	$(\bar{\ell}^j_p e_r)(\bar{d}_s q_{tj})$	$Q^{(1)}_{quqd}$	[b]	$(\bar{q}^j_p u_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
			$Q^{(8)}_{quqd}$	[b]	$(\bar{q}^j_p T^A u_r)\epsilon_{jk}(\bar{q}^k_s T^A d_t)$
			$Q^{(1)}_{\ell equ}$	[a]	$(\bar{\ell}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$
			$Q^{(3)}_{\ell equ}$	[a]	$(\bar{\ell}^j_p\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu} u_t)$

Absence of Flavor Symmetries

Difficulties without flavor symmetries

- Number of free parameters: 2499
- In natural EFT all couplings are expected to be of the same scale
  - Bounds on light generations ⇒ NP scale pushed up to $\mathcal{O}(10^5\ \mathrm{TeV})$
    Isidori et al. [arXiv:1002.0900]
  - Hierarchy problem for the Higgs mass
  - Most of SMEFT operators irrelevant in current experiments

- **But:** flavor is highly non-generic in the SM
  - SM is completely flavor universal & conserving except for the Yukawas
  - Yukawa couplings: $y_e \sim \mathcal{O}(10^{-6}) - y_t \sim \mathcal{O}(1)$

➡ Motivated and natural to apply some flavor symmetry assumptions

Flavor Symmetries

Motivation

- Flavor symmetries can significantly lowering overall cutoff scale

  ⇒ diminishing the hierarchy problem

- Significant reduction of the number of free/relevant parameters

- Increase consistency of EFT with bounds on flavor conserving or violating processes

- Employing flavor symmetries introduces some model dependence

- The chosen flavor symmetries should:
  - Respect the structure of the SM Yukawas
  - Suppress non-standard contributions to flavor-violating observables

- Flavor symmetries can be accidental symmetries (not necessarily fundamental)

$U(3)^5$ Symmetry

Minimal Flavor Violation

- Maximal symmetry group compatible with SM gauge group and fields

$$\boxed{U(3)^5 = U(3)_\ell \otimes U(3)_e \otimes U(3)_q \otimes U(3)_u \otimes U(3)_d}$$

- Most restrictive choice to suppress non-standard contributions to flavor violating processes

- Exact symmetry of SM gauge sector, but broken by Yukawas Y_e, Y_u, Y_d :

$$\mathscr{L}_{\text{Yuk.}} = \bar{\ell} Y_e e H + \bar{q} Y_u u H_c + \bar{q} Y_d d H + \mathrm{h.c.}$$

- <u>**M**inimal **F**lavor **V**iolation (**MFV**):</u>

Chivukula et al. [Phys. Lett. B 188 (1987) 99]
D`Ambrosio et al. [hep-ph/0207036]

  - SM Yukawas as the only source of $U(3)^5$ breaking
  - Spurion analysis with Yukawas as spurions:
    $Y_e = (3,\bar{3},1,1,1), \quad Y_u = (1,1,3,\bar{3},1), \quad Y_d = (1,1,3,1,\bar{3})$

Parameter counting for MFV

Number of free parameters:

No symmetry — $\mathrm{U}(3)^5$ with MFV

		No symmetry				$U(3)^5$					
Class	Operators	3 Gen.		1 Gen.		Exact		$\mathcal{O}(Y^1_{e,d,u})$		$\mathcal{O}(Y^1_e, Y^1_d Y^2_u)$	
1–4	X^3, H^6, H^4D^2, X^2H^2	9	6	9	6	9	6	9	6	9	6
5	$\psi^2 H^3$	27	27	3	3	–	–	3	3	4	4
6	$\psi^2 XH$	72	72	8	8	–	–	8	8	11	11
7	$\psi^2 H^2 D$	51	30	8	1	7	–	7	–	11	1
	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
8	$(\bar{L}L)(\bar{R}R)$	360	288	8	–	8	–	8	–	18	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1	–	–	–	–	–	–
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4	–	–	–	–	4	4
total:		1350	1149	53	23	41	6	52	17	85	26

CP-even CP-odd

Table 1: Number of independent operators in $U(3)^5$, MFV and without symmetry. In each column the left (right) number corresponds to the number of CP-even (CP-odd) coefficients. $\mathcal{O}(X^n)$ stands for including terms up to $\mathcal{O}(X^n)$.

$\Rightarrow$ Significant reduction of the number of free parameters in the MFV case

Minimal Flavor Violation

Features

- All flavor non-universality and flavor-violation linked to Yukawas
- Magnitude of flavor-violation:
  - In quarks sector completely controlled by CKM ⇒ normalized to SM size
  - In leptons sector forbidden

➡ Very strong UV assumption

- Top quark Yukawa $y_t \sim \mathcal{O}(1)$, or more precisely $\left[Y_u Y_u^\dagger\right]_{33}, \left[Y_u^\dagger Y_u\right]_{33} \sim \mathcal{O}(1)$
  - Y_u contains an $\mathcal{O}(1)$ breaking term
  - No clear power counting for the spurions
- Insertion of an arbitrary power of y_t triggers the breaking

$$U(3)_q \otimes U(3)_u \xrightarrow{y_t} U(2)_q \otimes U(2)_u \otimes U(1)_{q_L^3+t_R}$$

- Assuming $y_{t,b,\tau} \sim \mathcal{O}(1)$ yields breaking: $U(3)^5 \to U(2)^5$

$U(2)^5$ Symmetry

The symmetry group

Barbieri et al. [arXiv: 1105.2296, 1203.4218]
Blankenburg et al. [arXiv:1204.0688]

- $U(2)^5$ symmetry acting on light generations

$$\boxed{U(2)^5 = U(2)_L \otimes U(2)_E \otimes U(2)_Q \otimes U(2)_U \otimes U(2)_D}$$

  - 1st and 2nd generation fields transform as doublets L, E, Q, U, D
  - 3rd generation fields transform as singlets $\ell_3, e_3, q_3, u_3, d_3$

- Allows for much richer structure of 3rd generation dynamics
  - Motivated assumption in many UV models

- MFV-like structure (for light generations)
  - Protection of non-standard flavor-violation in the quark sector
  - Helicity suppression of right-handed mixing

- Efficient framework for analyzing the recent evidence for LFUV from B-anomalies
  Fuentes-Martín et al. [arXiv:1909.02519]

$\mathrm{U(2)^5}$ Symmetry

Spurions — Minimal breaking pattern

- 5 spurions: $$\boxed{\begin{array}{l} V_\ell \sim (2,1,1,1,1), \quad V_q \sim (1,1,2,1,1) \\ \Delta_e \sim (2,\bar{2},1,1,1), \quad \Delta_u \sim (1,1,2,\bar{2},1), \quad \Delta_d \sim (1,1,2,1,\bar{2}) \end{array}}$$

- Parametrization in *interaction basis*
  (using residual $U(2)^5$ invariance, no alignment enforced)

$$V_{\ell,q} = e^{i\bar{\phi}_{\ell,q}} \begin{pmatrix} 0 \\ \epsilon_{\ell,q} \end{pmatrix} , \quad \Delta_e = O_e^{\mathrm{T}} \begin{pmatrix} \delta'_e & 0 \\ 0 & \delta_e \end{pmatrix} , \quad \Delta_{u,d} = U_{u,d}^{\dagger} \begin{pmatrix} \delta'_{u,d} & 0 \\ 0 & \delta_{u,d} \end{pmatrix}$$

($\bar{\phi}_{\ell,q}$: phase, O_e : Orthogonal $2 \times 2-$matrix, $U_{u,d}$: unitary $2 \times 2-$matrix)

- Yukawa matrices

$$Y_u = y_t \begin{array}{c} \begin{pmatrix} \Delta_u & x_t V_q \\ 0 & 1 \end{pmatrix}^{U(2)_Q}, \\ U(2)_U \end{array} \quad Y_d = y_b \begin{array}{c} \begin{pmatrix} \Delta_d & x_b V_q \\ 0 & 1 \end{pmatrix}^{U(2)_Q}, \\ U(2)_D \end{array} \quad Y_e = y_\tau \begin{array}{c} \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}^{U(2)_L} \\ U(2)_E \end{array}$$

- Hierarchy from Yukawas: $\boxed{1 \gg \epsilon_i \gg \delta_i \gg \delta'_i > 0}$

$$\epsilon_i = \mathcal{O}\left(10^{-1}\right), \quad \delta_i = \mathcal{O}\left(10^{-2}\right), \quad \delta'_i = \mathcal{O}\left(10^{-3}\right) \longrightarrow \boxed{\text{No } \mathcal{O}(1) \text{ breaking}}$$

  - Similar protection of flavor-violating processes as in MFV case

$U(2)^5$ in the SMEFT

Basis

- Construction of a basis respecting the $U(2)^5$ flavor symmetry up to $\boxed{\mathcal{O}(V^3, \Delta^1 V^1)} \sim \mathcal{O}(10^{-3})$
- Classify operators according to field content and chiral structure

Fermion Bilinears

$$(\bar{L}L) - \Sigma_{LL}^{pr}\left(\bar{\ell}_p \Gamma \ell_r\right) \quad \text{with} \quad \Sigma_{LL} = \begin{pmatrix} a_1 & 0 & 0 \\ 0 & a_1 + c_1\epsilon_\ell^2 & \beta_1\epsilon_\ell \\ 0 & \beta_1^*\epsilon_\ell & a_2 \end{pmatrix} + \mathcal{O}(\delta_e^2)\,.$$

V^0	V^1	V^2	Δ^1	$\Delta^1 V^1$
$2+0$	$1+1$	$1+0$	$0+0$	$0+0$

$$(\bar{R}R) - \Sigma_{RR}^{pr}\left(\bar{e}_p \Gamma e_r\right) \quad \text{with} \quad \Sigma_{RR} = \begin{pmatrix} a_1 & 0 & \sigma_1^*\epsilon_\ell s_e \delta_e' \\ 0 & a_1 & \sigma_1^*\epsilon_\ell \delta_e \\ \sigma_1\epsilon_\ell s_e \delta_e' & \sigma_1 \epsilon_\ell \delta_e & a_2 \end{pmatrix} + \mathcal{O}(\delta_e^2)\,.$$

V^0	V^1	V^2	Δ^1	$\Delta^1 V^1$
$2+0$	$0+0$	$0+0$	$0+0$	$1+1$

$$(\bar{L}R) - \Sigma_{LR}^{pr}\left(\bar{\ell}_p \Gamma e_r\right) \quad \text{with} \quad \Sigma_{LR} = \begin{pmatrix} \rho_1\delta_e' & -\rho_1 s_e \delta_e & 0 \\ \rho_1 s_e \delta_e' & \rho_1\delta_e & \beta_1\epsilon_\ell \\ \sigma_1\epsilon_\ell s_e\delta_e' & \sigma_1\epsilon_\ell\delta_e & \alpha_1 \end{pmatrix} + \mathcal{O}(\delta_e\epsilon_\ell^2)\,.$$

V^0	V^1	V^2	Δ^1	$\Delta^1 V^1$
$1+0$	$1+1$	$0+0$	$1+1$	$1+1$

$\mathrm{U(2)}^5$ in the SMEFT

Fermion Quadrilinears

- Example: semi-leptonic operator

$$\Sigma_{\ell q}^{prst}\,(\bar{\ell}_p \Gamma \ell_r)(\bar{q}_s \tilde{\Gamma} q_t)$$

- Number of parameters:
  - Without flavor symmetry:
    $81 = 45 + 36$
  - With $U(2)^5$ flavor symmetry:
    $24 = 16 + 8$ [up to $\mathcal{O}(V^3, \Delta^1 V^1)$]

V^0	V^1	V^2	V^3	Δ^1	$\Delta^1 V^1$
$4+0$	$4+4$	$6+2$	$2+2$	$0+0$	$0+0$

➡Significant reduction of free parameters

➡Rich 3rd generation dynamics

$\Sigma_{\ell q}^{prst}$

	(11)	(12)	(13)	(21)	(22)	(23)	(31)	(32)	(33)
(11)	a_1				a_1, $c_3\epsilon_q^2$	$\beta_3\epsilon_q$		$\beta_3^*\epsilon_q$	a_2
(12)									
(13)									
(21)									
(22)	a_1, $c_1\epsilon_\ell^2$				a_1, $c_1\epsilon_\ell^2$, $c_3\epsilon_q^2$	$\beta_3\epsilon_q$, $\xi_1\epsilon_\ell^2\epsilon_q$		$\beta_3^*\epsilon_q$, $\xi_1^*\epsilon_\ell^2\epsilon_q$	a_2, $c_2\epsilon_\ell^2$
(23)	$\beta_1\epsilon_\ell$				$\beta_1\epsilon_\ell$, $\xi_2\epsilon_q^2\epsilon_\ell$	$\gamma_1\epsilon_\ell\epsilon_q$		$\gamma_2\epsilon_\ell\epsilon_q$	$\beta_2\epsilon_\ell$
(31)									
(32)	$\beta_1^*\epsilon_\ell$				$\beta_1^*\epsilon_\ell$, $\xi_2^*\epsilon_q^2\epsilon_\ell$	$\gamma_2^*\epsilon_\ell\epsilon_q$		$\gamma_1^*\epsilon_\ell\epsilon_q$	$\beta_2^*\epsilon_\ell$
(33)	a_3				a_3, $c_4\epsilon_q^2$	$\beta_4\epsilon_q$		$\beta_4^*\epsilon_q$	a_4

Rows: lepton flavor indices (pr) — Columns: quark flavor indices (st)

$\Sigma_{\ell q}^{prst}$ in the interaction basis

[Rotation to the down-mass basis might be necessary]

Parameter counting for $\mathrm{U}(2)^5$

Results

- Number of free parameters up to different orders in the spurion expansion

$U(2)^5$ [terms summed up to different orders]

Operators	Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1 V^1)$		$\mathcal{O}(V^3, \Delta^1 V^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6
$\psi^2 H^3$	3	3	6	6	6	6	9	9	9	9	12	12	12	12
$\psi^2 X H$	8	8	16	16	16	16	24	24	24	24	32	32	32	32
$\psi^2 H^2 D$	15	1	19	5	23	5	19	5	23	5	28	10	28	10
$(\bar{L}L)(\bar{L}L)$	23	–	40	17	67	24	40	17	67	24	67	24	74	31
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–	53	24	53	24
$(\bar{L}L)(\bar{R}R)$	32	–	48	16	64	16	53	21	69	21	90	42	90	42
$(\bar{L}R)(\bar{R}L)$	1	1	3	3	4	4	5	5	6	6	10	10	10	10
$(\bar{L}R)(\bar{L}R)$	4	4	12	12	16	16	24	24	28	28	48	48	48	48
total:	124	23	182	81	234	93	212	111	264	123	349	208	356	215

Enough if masses of light generation fermions is

CP-even

CP-odd

Depending on the process of interest and desired accuracy, only subsets of operators relevant

➡Substantial reduction of the number of free parameters

Comparison $\mathrm{U}(2)^5$ vs. $\mathrm{U}(3)^5$

Parameter Counting:

No symmetry – **$\mathrm{U}(3)^5$ with MFV** – **$\mathrm{U}(2)^5$ with minimal breaking**

Operators	No symmetry: 3 Gen.		No symmetry: 1 Gen.		$U(3)^5$: Exact		$U(3)^5$: $\mathcal{O}(Y^1_{e,d,u})$		$U(3)^5$: $\mathcal{O}(Y_e^1, Y_d^1 Y_u^2)$	
total:	1350	1149	53	23	41	6	52	17	85	26

Operators	$U(2)^5$ [terms summed up to different orders]: Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1 V^1)$		$\mathcal{O}(V^3, \Delta^1 V^1)$	
total:	124	23	182	81	234	93	212	111	264	123	349	208	356	215

CP-even CP-odd

- Smaller symmetry group $\Rightarrow$ more parameters than MFV
- Still significant reduction of parameters compared to general case

Flavor symmetries at low-/high-energies

- Flavor symmetries are a useful tool for:
  - Analyzing low-energy observables
  - Simplifying and organizing the analysis of high-p_T observables
    Greljo et al. [arXiv:1704.09015]
- High invariant mass tails can yield complementary information to low-energy observables Fuentes-Martín et al. [arXiv:2003.12421]

➡ Combined analysis of low and high-energy observables desirable
Work in progress with L. Allwicher, D. A. Faroughy, O. Sumensari, FW

- in general flavor case
- in $U(2)^5$ setup

High-p_T tails at LHC

LFV Example: high invariant mass tail for $pp \to \bar{\ell}\tau$

Consider only four-fermion operators contributing:

$$\boxed{\sigma(pp \to \bar{\ell}\tau) = \frac{s}{144\pi\Lambda^4}\mathrm{Tr}\left(F_q^{\ell\tau}(\{C_i\}) \cdot K_q\right)} \propto s \leftarrow \text{enhancement at high energies}$$

- PDF dependence: $K_q = \int \mathrm{d}\tau\, \tau\, \mathscr{L}_{q_t\bar{q}_s}(\tau)$, with parton luminosity $\mathscr{L}_{q_t\bar{q}_s}(\tau)$, encoding flavor structure of PDFs

- Operator/Wilson coefficient dependence: $F_q^{\ell\tau}(\{C_i\})$, only considering the contribution from $\mathcal{O}_{\ell q}^{(1,3)}$ we find

$$F_d^{\ell\tau,st} = \left|\Sigma_{\ell q}^{(1)\,\ell\tau,st} + \Sigma_{\ell q}^{(3)\,\ell\tau,st}\right|^2, \quad \text{and} \quad F_u^{\ell\tau,st} = \left|V_{\mathrm{CKM}}^{sn}V_{\mathrm{CKM}}^{tm\,*}\left(\Sigma_{\ell q}^{(1)\,\ell\tau,nm} - \Sigma_{\ell q}^{(3)\,\ell\tau,nm}\right)\right|^2$$

Simple $U(2)^5$ structure

(here the $\Sigma_{\ell q}$ are rotated to the down-mass basis)

Conclusion

Flavor symmetries in the SMEFT

- SMEFT at dimension-six:
  up to 2499 parameters
- Advantage:
  - Significantly reduce parameters
  - Explain suppression of certain couplings
  - Allow for a classification of operators
- Useful tool for analyzing low-/high-energy observables
- Disadvantage:
  - Introduction of model dependence

$U(2)^5$ with minimal breaking

- Free parameters:

Operators	$U(2)^5$ Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$	
total:	124	23	182	81	234	93

- Special treatment and richer dynamics for 3rd generation fermions
- Simplification of RG evolution
  [Work in progress with G. Isidori, S. Renner, FW]
- Allows for construction of a consistent EFT:
  - At relatively low scale
  - With a consistent power counting
  - Protection from non-standard flavor mixing
  - relatively few parameters

Thank you for listening!

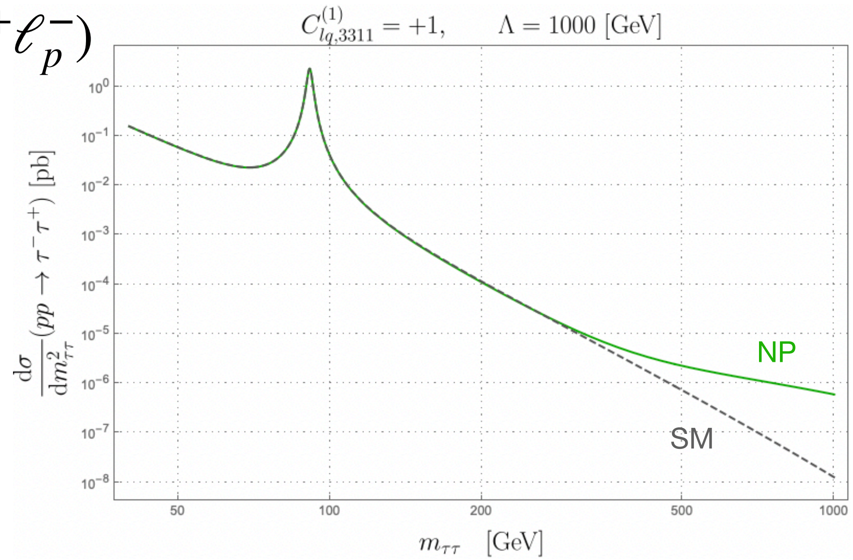
Backup

Flavor Symmetries in the SMEFT

More details on high-$\mathrm{p_T}$ tails

High-$\mathrm{p_T}$ tails of the invariant di-lepton mass

illustration energy enhancement



- Analysis of semi leptonic NC process: $\sigma(\bar{q}_s q_t \to \ell_r^+ \ell_p^-)$
  - invariant mass of the di-lepton pair at high-p_T
- NP can contribution in 3 different ways:
  - Dipole operators
  - Modification of Z-boson couplings
  - Four-fermion contact interactions $\leftarrow$ energy enhanced w.r.t. SM contributions
- Full analysis considering all contributions desirable
- Advantages of assuming the minimally broken $U(2)^5$ flavor symmetry:
  - Computation of the amplitude simplifies and can be organized
  - Allows to sum the contributions of different quark-flavor in the pp collisions with appropriate weights
  - Less parameters to be fitted

Renormalization Group Evolution for $\mathrm{U}(2)^5$

Work in progress with G. Isidori, S. Renner, FW

- Full RGE for the Warsaw basis derived in
  Jenkins et al. [arXiv: 1308.2627, 1310.4838, 1312.2014]
- The $U(2)^5$ symmetry and minimal breaking pattern are preserved by the RGE
- Simplification of the RGE structure expected
  - At given order in the spurions only a subset of the possible mixing can contribute

$$Y_{lh} \sim \mathcal{O}(V^1)$$
$$Y_{ll} \sim \mathcal{O}(\Delta^1)$$

<u>**Operator:**</u> <u>**RGE contributions**</u>

$$\mathcal{O}\big(V^0\Delta^0\big): \quad \mathcal{O}\big(V^0\Delta^0\big),\ Y_{lh}\mathcal{O}\big(V^1\Delta^0\big),\ \mathcal{O}\big(V^2\Delta^0\big),\ Y_{lh}^2\mathcal{O}\big(V^0\Delta^0\big)$$
$$\mathcal{O}\big(V^1\Delta^0\big): \quad \mathcal{O}\big(V^1\Delta^0\big),\ Y_{lh}\mathcal{O}\big(V^0\Delta^0\big),\ \mathcal{O}\big(V^3\Delta^0\big),\ Y_{lh}\mathcal{O}\big(V^2\Delta^0\big),\ Y_{lh}^2\mathcal{O}\big(V^1\Delta^0\big)$$
$$\mathcal{O}\big(V^2\Delta^0\big): \quad \mathcal{O}\big(V^2\Delta^0\big),\ Y_{lh}\mathcal{O}\big(V^1\Delta^0\big),\ Y_{lh}^2\mathcal{O}\big(V^0\Delta^0\big)$$
$$\mathcal{O}\big(V^0\Delta^1\big): \quad \mathcal{O}\big(V^0\Delta^1\big),\ Y_{ll}\mathcal{O}\big(V^0\Delta^0\big)$$
$$\mathcal{O}\big(V^1\Delta^1\big): \quad \mathcal{O}\big(V^1\Delta^1\big),\ Y_{lh}\mathcal{O}\big(V^0\Delta^1\big),\ Y_{ll}\mathcal{O}\big(V^1\Delta^0\big),\ Y_{ll}Y_{lh}\mathcal{O}\big(V^0\Delta^0\big)$$

Breaking Patterns

Breaking: $\mathbf{U(3)^5 \to U(2)^5}$

- Breaking of the global $U(3)^5$ flavor symmetry group through 3rd generation Yukawas of order $\mathcal{O}(1)$
  - Two step breaking of $U(3)^3$ in the quark sector to $U(2)^3$

$$\boxed{U(3)_q \otimes U(3)_u \otimes U(3)_d \xrightarrow{y_t} U(2)_Q \otimes U(2)_U \otimes U(3)_d \otimes U(1)_{q_L^3+t_R} \xrightarrow{y_{t,b}} U(2)_Q \otimes U(2)_U \otimes U(2)_D \otimes U(1)_{q_L^3+t_R+b_R}}$$

  - One step breaking of $U(3)^2$ in the lepton sector to $U(2)^2$

$$\boxed{U(3)_\ell \otimes U(3)_e \xrightarrow{y_\tau} U(2)_L \otimes U(2)_E \otimes U(1)_{\ell_L^3+\tau_R}}$$

- *Is there an intermediate breaking step worth to consider?*
  - in particular: $U(2)_Q \otimes U(2)_U \otimes U(3)_d$

Alternative Flavor Symmetries

$\mathbf{U(2)_Q \otimes U(2)_U \otimes U(3)_d}$

- For the $U(2)^3 = U(2)_Q \otimes U(2)_U \otimes U(2)_D$ group we chose the spurion such that the Yukawas could be written as:

$$Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ \tilde{V}_u & 1 \end{pmatrix}^{U(2)_Q}_{U(2)_U}, \qquad Y_d = y_b \begin{pmatrix} \Delta_d & x_b V_q \\ \tilde{V}_d & 1 \end{pmatrix}^{U(2)_Q}_{U(2)_D}$$

$$V_q \sim 2_Q, \quad \Delta_u \sim 2_Q \otimes \bar{2}_U, \quad \Delta_d \sim 2_Q \otimes \bar{2}_D, \quad \tilde{V}_u \sim \bar{2}_U, \quad \tilde{V}_d \sim \bar{2}_D$$

Enforcing the hierarchy $|V_q| \gg |\Delta_{u,d}| \gg |\tilde{V}_{u,d}| \, (\sim 0)$ yields MFV-like structure

$\Rightarrow$ No alignment of spurions required if we neglect $\tilde{V}_{u,d}$ spurions

- For $U(2)_Q \otimes U(2)_U \otimes U(3)_d$ we have to choose different spurions:

$$Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ \tilde{V}_u & 1 \end{pmatrix}^{U(2)_Q}_{U(2)_U}, \qquad Y_d = y_b \begin{pmatrix} \Sigma_d \\ \Lambda_d \end{pmatrix}^{U(2)_Q}_{U(3)_d}$$

If we want to describe all down quark masses $m_{d,s,b} \neq 0$ we must require $\Sigma_d \neq 0$ and $\Lambda_d \neq 0$

$\Rightarrow$ Necessary tuning of the alignment of Σ_d and Λ_d in the $U(3)_d$ space

Alternative Flavor Symmetries

$\mathbf{U(2)^5 \otimes U(1)_b \otimes U(1)_\tau}$

- Amending the $U(2)^5$ group with two $U(1)$ factors
  - Only b_R and τ_R are charged under the additional $U(1)$ factors
- In unbroken case only the Yukawa coupling of the top quark y_t is present
  - To allow for non-vanishing $y_{b,\tau}$ we have to introduce two further spurions $X_{b,\tau}$ breaking the $U(1)_{b,\tau}$ groups
- The Yukawas can be expressed as

$$Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ 0 & 1 \end{pmatrix}, \quad Y_d = y_b \begin{pmatrix} \Delta'_d & x'_b V_q X_b \\ 0 & \kappa_b X_b \end{pmatrix}, \quad Y_e = y_\tau \begin{pmatrix} \Delta'_e & x'_\tau V_\ell X_\tau \\ 0 & \kappa_\tau X_\tau \end{pmatrix}$$

- Additional structure for the classification and counting of operator including bottom-quarks and tau-leptons
- Can be analyzed similar to the $U(2)^5$ case

The spurions of $\mathrm{U}(2)^5$

Minimal breaking spurions

- The spurions:
  $V_\ell \sim (2,1,1,1,1), \quad V_q \sim (1,1,2,1,1), \quad \Delta_e \sim (2,\bar{2},1,1,1), \quad \Delta_u \sim (1,1,2,\bar{2},1), \quad \Delta_d \sim (1,1,2,1,\bar{2})$

$$V_{\ell,q} = e^{i\bar{\phi}_{\ell,q}} \begin{pmatrix} 0 \\ \epsilon_{\ell,q} \end{pmatrix}, \quad \Delta_e = O_e^{\mathrm{T}} \begin{pmatrix} \delta'_e & 0 \\ 0 & \delta_e \end{pmatrix}, \quad \Delta_{u,d} = U_{u,d}^\dagger \begin{pmatrix} \delta'_{u,d} & 0 \\ 0 & \delta_{u,d} \end{pmatrix}$$

where $O_e = \begin{pmatrix} c_e & s_e \\ -s_e & c_e \end{pmatrix}$, $U_q = \begin{pmatrix} c_q & s_q e^{i\alpha_q} \\ -s_q e^{-i\alpha_q} & c_q \end{pmatrix}$

- We can express the Yukawas as: $\boxed{Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ 0 & 1 \end{pmatrix}, \qquad Y_d = y_b \begin{pmatrix} \Delta_d & x_b V_q \\ 0 & 1 \end{pmatrix}, \qquad Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}}$

- Diagonalize Yukawas by unitary transformations of the type $\boxed{L_f^\dagger Y_f R_F = \mathrm{diag}(Y_f)}$

- Observe the hierarchy: $1 \gg \epsilon_i \gg \delta_i \gg \delta'_i > 0$

$$\epsilon_i = \mathcal{O}\left(\mathrm{Tr}(Y_u Y_u^\dagger) - \frac{\mathrm{Tr}(Y_u Y_u^\dagger Y_d Y_d^\dagger)}{\mathrm{Tr}(Y_d Y_d^\dagger)}\right)^{\frac{1}{2}} = \mathcal{O}(y_t |V_{ts}|) = \mathcal{O}(10^{-1})$$

$$\delta_i = \mathcal{O}\left(\frac{y_c}{y_t}, \frac{y_s}{y_b}, \frac{y_\mu}{y_\tau}\right) = \mathcal{O}(10^{-2}), \quad \delta'_i = \mathcal{O}\left(\frac{y_u}{y_t}, \frac{y_d}{y_b}, \frac{y_e}{y_\tau}\right) = \mathcal{O}(10^{-3})$$

- Not all parameters in the spurion decomposition can be related to SM parameters
  ⇒ Structure of spurions is not completely determined by CKM (contrary to MFV case)

The spurions of $\mathrm{U}(2)^5$

Possible spurions beyond minimal breaking

- Possible spurions can be categorized according to the transformation of fermion-bilinears and fermion-quadrilinears
- Focusing only on the bilinears we find:
  - **5 duplet** spurions $V_\psi \sim 2_\psi$ for $\psi \in \{\ell, e, q, u, d\}$
    In the Minimal setup only V_q and V_ℓ are present
  - **10 bi-duplet** spurions $\Delta_{\psi\psi'} \sim \bar{2}_\psi \times 2_{\psi'}$ with $\psi \neq \psi'$ (6 leptoquark, 3 di-quark and 1 di-lepton spurion)
    In the Minimal setup only the 3 Yukawa like Δ are present
  - **5 adjoint** spurions $A_\psi \sim 3_\psi$
    In the Minimal setup not present
- Operator classification can be done similarly for all spurions
- If any of the spurions not present in the minimal setup can compete in size with the spurion of the minimal setup:
  - CKM-like suppression of left-handed mixing is lost
  - Helicity suppression of mixing in right handed is lost

➡ Alignment of spurions in flavor space necessary to restore the protection from non-standard mixing