Flavor symmetries in the SMEFT

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SMEFT

Standard **M**odel **E**ffective **F**ield **T**heory

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

$\mathcal{O}_i^{(d)}$ = gauge-invariant operators

SMEFT describes **any nearly-decoupled ($\Lambda \gg v$) BSM physics**
with "good" analyticity/geometry properties in the scalar sector

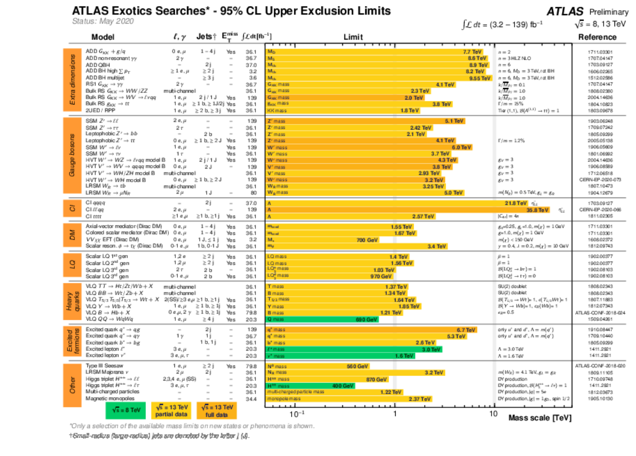
- **SM symmetries** → fully $SU(3) \times SU(2) \times U(1)$ invariant
- **SM fields** → 5 × 3 independent fermionic fields

$$q_\alpha,\ l_\alpha,\ u_\alpha,\ d_\alpha,\ e_\alpha \qquad \alpha = 1, 2, 3$$

- no RH neutrinos: only Majorana m_ν through $\mathcal{L}_5$

The global SMEFT program

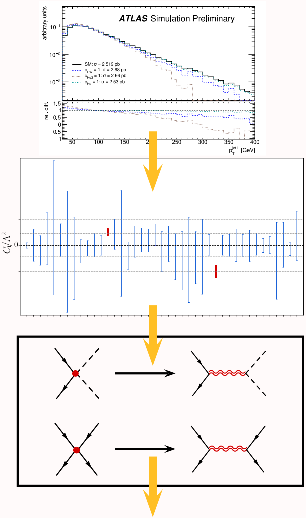
resonance searches @ LHC suggest that NP is likely nearly decoupled



at the same time, no UV scenario is preferred in a compelling way

The global SMEFT program

agnostic approach: let data tell us what NP looks like



$\mathcal{L}_{UV}$

SMEFT parameterizes
anomalous rates & spectral distortions

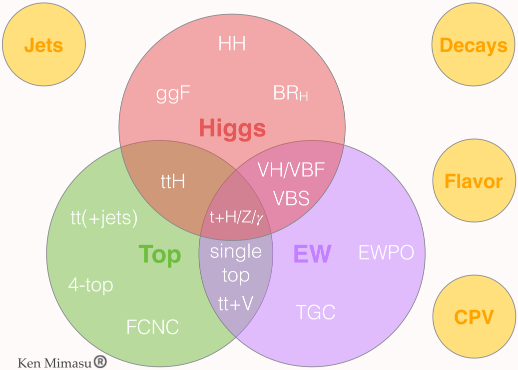
Global analysis → identify $C_i \neq 0$

Identify compatible simplified models

Embed in UV-complete model

The SMEFT program at the LHC (and beyond)

- "indirect" searches to complement bump hunt
- make the most of future luminosities → LHC as a precision machine
- agnostic approach requires **combining** multiple sectors

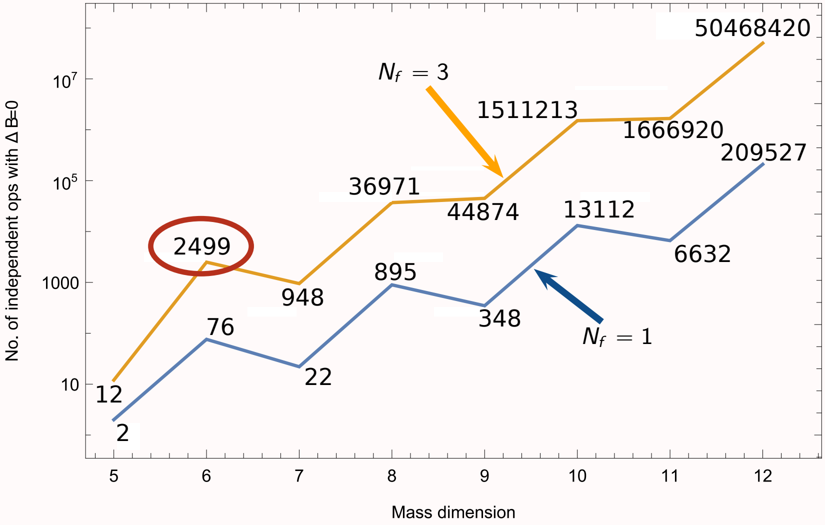


👉 theory studies performed for ∼10 years, ATLAS+CMS program starting

👉 longer term plan: merge with lower E measurements

A very large parameter space

Henning,Lu,Melia,Murayama 1512.03433



A very large flavorful parameter space

Classification within Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

Class	CP	$\not{CP}$	Total
X^3	2	2	4
$\varphi^6 + \varphi^4 D^2$	3	-	3
$\varphi^2 X^2$	4	4	8
$\varphi^2\psi^2$	27	27	54
$\varphi X \psi^2$	72	72	144
$\varphi^2 D\psi^2$	51	30	81
$(\bar{L}L)(\bar{L}L)$	171	126	297
$(\bar{R}R)(\bar{R}R)$	255	195	450
$(\bar{L}L)(\bar{R}R)$	360	288	648
$(\bar{L}R)(\bar{R}L)$	81	81	162
$(\bar{L}R)(\bar{L}R)$	324	324	648

- most parameters from **fermionic** terms
- **flavor** has dramatic impact on counting

Examples:

$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	9 + 9
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	6 + 3
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	27 + 18
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	45 + 36
$(\bar{l}_i^l e_j)(\bar{d}_k q_l^l)$	81 + 81

Good reasons to have flavor symmetries in SMEFT

1. reduce the SMEFT parameter space

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   - not all entries are independent, some contractions forbidden

	no sym.	$U(3)^5$	
$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	$9+9$	0	-
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	$6+3$	1	δ_{ij}
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	$27+18$	2	$\delta_{ij}\delta_{kl}, \delta_{il}\delta_{kj}$
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	$45+36$	1	$\delta_{ij}\delta_{kl}$
$(\bar{l}_i^I e_j)(\bar{d}_k q_l^I)$	$81+81$	0	-

Good reasons to have flavor symmetries in SMEFT

1. reduce the SMEFT parameter space
   - not all entries are independent, some contractions forbidden
   - parameters organized according to an additional expansion
     $\rightarrow$ **multiple NP scales** $(\Lambda_{\mathrm{sym}}, \Lambda_{\cancel{\mathrm{sym}}})$

Example: **MFV** $= U(3)^5$ broken by SM Yukawas as spurions

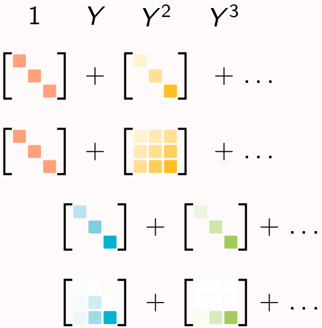
[up basis]

$(\bar{u}_i \gamma^\mu u_j) \quad C_{ij} = C^{(0)} \delta_{ij} + C^{(2)} (Y_u^\dagger Y_u)_{ij} + \dots$

$(\bar{d}_i \gamma^\mu d_j) \quad C_{ij} = C^{(0)} \delta_{ij} + C^{(2)} (Y_d^\dagger Y_d)_{ij} + \dots$

$(\bar{q}_i \tilde{\varphi} u_j) \quad C_{ij} = C^{(1)} (Y_u)_{ij} + C^{(3)} (Y_u Y_u^\dagger Y_u)_{ij} + \dots$

$(\bar{q}_i \varphi d_j) \quad C_{ij} = C^{(1)} (Y_d)_{ij} + C^{(3)} (Y_d Y_d^\dagger Y_d)_{ij} + \dots$



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3. $\mathscr{L}_{SM}$ has a peculiar flavor structure, so $\mathscr{L}_{\geqslant 6}$ is unlikely to be fully anarchical
   → approximate potentially realistic patterns

!! symmetries of SMEFT ≠ symmetries of the UV completion
can be accidental, reflecting specific UV dynamics

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   !! symmetries of SMEFT $\neq$ symmetries of the UV completion
   can be accidental, reflecting specific UV dynamics

4. can be used to reflect the experimental sensitivity

   → a way to resum/combine contributions undistinguishable in the measurement

Candidate symmetries for SMEFT at the LHC

IB,(Jiang,Trott) 1709.06492, 2012.11343, Bordone,Catá,Feldmann 1910.02641
Faroughy et al 2005.05366, Greljo et al 2203.09561
LPCC note 1802.07237, LHC EFT WG discussions [link]

Quark sector

- $\mathbf{U(3)^3} = U(3)_q \times U(3)_u \times U(3)_d$ (MFV) Chivukula,Georgi 1987, Hall,Randall 1990 D'Ambrosio et al 0207036

→ SMEFT effects do not alter SM flavor pattern. mostly capture **"flavor blind" NP**

→ max suppression of non-SM flavor structure: constraints consistent with **lower Λ**

gen.	$\Lambda^2/\|C_{uW}^{23}\| \gtrsim (2.2\,\mathrm{TeV})^2$	from $t \to Zc$	ATLAS-CONF-2021-049
MFV	$\Lambda^2/\|C_{uW}\| \gtrsim \|(Y_u^\dagger)_{23}\| \cdot (2.2\,\mathrm{TeV})^2 \simeq (0.4\,\mathrm{TeV})^2$		(down b.)

→ **correlates** top with u, c physics, bottom with d, s.

currently means:
- $tt\gamma, ttZ, tbW$ non-dipole operators most bounded by EWPO
- constraints on hdd, hss corrections can be inferred from $h \to bb$
- tension between B anomalies and $pp \to \mu\mu$ Greljo,Marzocca 1704.09015

...

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  $\rightarrow$ 3rd gen. left out: t, b independent of light flavors
  $\rightarrow$ spurions are not fully determined in terms of masses and CKM
  $\rightarrow$ chirality-flip (Yukawas, dipoles) t, b interactions unsuppressed by spurions

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- $\mathbf{U(2)^3} \times \mathbf{U(1)_b} = U(2)_q \times U(2)_u \times U(2)_d \times U(1)_b$

$U(1)_b$ restores spurion suppression ($\sim y_b$) in chirality-flip bottom couplings
→ lowers Λ bound from $h \to bb$ constraints
→ gives a rationale to neglect certain operators, e.g. b-dipoles O_{bB}, O_{bW}, O_{bG}

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- $\mathbf{U(2)^3} \times \mathbf{U(1)_b} = U(2)_q \times U(2)_u \times U(2)_d \times U(1)_b$
- $\mathbf{U(2)^2} \times \mathbf{U(3)} = U(2)_q \times U(2)_u \times U(3)_d$

  → symmetry of $\mathscr{L}_{SM}$ in 5-flavor scheme ($m_b = 0$)
  → more complex spurion structure
  → op. structure: like $U(2)^3$ for up-quarks, like $U(3)^3$ for down-quarks

Candidate symmetries for SMEFT at the LHC

Lepton sector

- $\mathbf{U(3)^2} = U(3)_l \times U(3)_e$ (MFV)

- $\mathbf{U(2)^2} = U(2)_l \times U(2)_e$

  → allows LFUV only in τ vs (e, μ)

- $\mathbf{U(2)^2} \times \mathbf{U(1)} = U(2)_l \times U(2)_e \times U(1)_\tau$

  → reintroduces chirality-flip suppression for τ currents

- $\mathbf{U(1)^3} = (U(1)_{l+e})^3$

  → allows full LFUV but still forbids FCNC
  → exact. no spurions needed!
  → chirality-flip interactions un-suppressed

☞ LHC sensitivity $\sim U(2)^3_{q,u,d} \times (U(1)_{l+e})^3$

☞ less restrictive options required only to compare to other measurements

Automation

- SMEFTflavor : construction of full set of invariants in Warsaw basis, imposing arbitrary flavor symmetries with spurions — Greljo,Palavric,Thomsen 2203.09561 github.com/aethomsen/SMEFTflavor

- UFO models for Monte Carlo simulations already implement:

$U(3)^5$	SMEFTsim U35, MFV
$U(2)^3_{q,u,d} \times U(3)^2_{l,e}$	SMEFTsim topU3l
$U(2)^3_{q,u,d} \times U(1)^3_{l+e}$	SMEFTsim top, dim6top
$U(2)^2_{q,u} \times U(3)_d \times U(1)^3_{l+e}$	SMEFT@NLO

SMEFTsim: IB,(Jiang,Trott) 1709.06492, 2012.11343
SMEFT@NLO: Degrande,Durieux,Maltoni,Mimasu,Vryonidou,Zhamg 2008.11743
dim6top: Durieux,Zhang 1802.07237

→ allow to simulate directly in terms of parameters in symmetric $\mathscr{L}_6$

Number of independent parameters

adapted from Greljo,Palavric,Thomsen 2203.09561

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector									
		MFV$_L$		$U(2)^2 \times U(1)^2$		$U(2)^2$		$U(1)^3$		No symm.	
Quark sector	MFV$_Q$	41	6	59	6	62	9	93	18	207	132
	$U(2)^2 \times U(3)_d$	72	10	95	10	100	15	140	28	281	169
	$U(2)^3 \times U(1)_{d_3}$	86	10	111	10	116	12	158	28	305	175
	$U(2)^3$	93	17	118	17	124	23	168	38	321	191
	No symmetry	703	570	756	591	786	621	906	705	1350	1149

☞ not all of them enter observables of interest!

typical counts for current H + EW + top fits: between 25 and 50

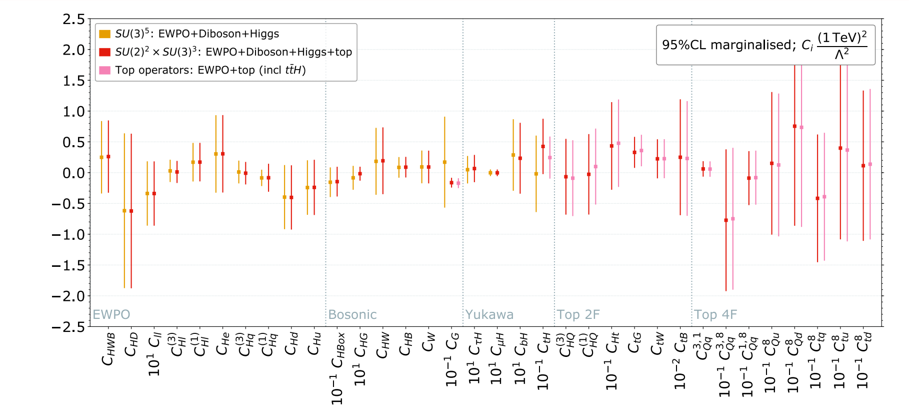
largely depends on:

- processes included
- tree / loop
- linear / quadratic

state-of-the-art fitting tools can handle 30 – 35 simultaneously

Example global fit results

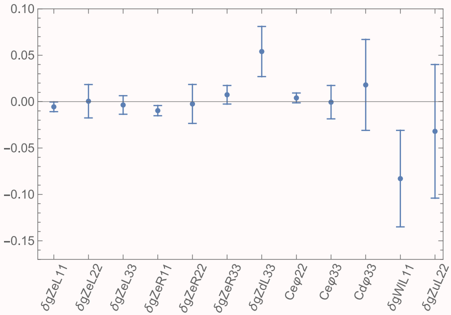
Ellis, Madigan, Mimasu, Sanz, You 2012.02779

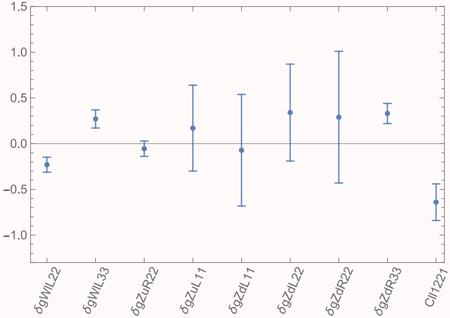


Flavor sensitivity from EWPO

Falkowski,Straub 1911.07866
also: Efrati,Falkowski,Soreq 1503.07872

- EWPO + Higgs signal strengths + diboson (no top) → **31** parameters
- no FCNC, but each flavor treated independently
- linear parameterization



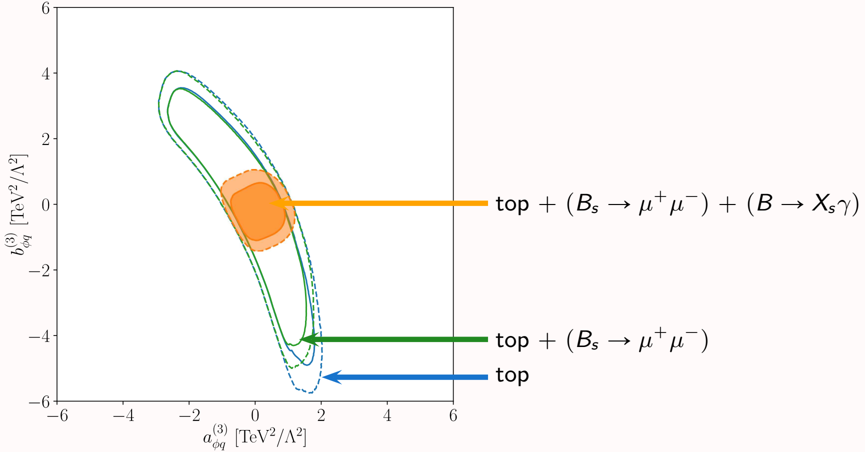


Combining top constraints with B physics

Bruggisser,Schäfer,vanDyk,Westhoff 2101.07273
also: Aoude,Hurth,Renner,Shepherd 2003.05432
Bißman,Grunwald,Hiller,Kröninger 2012.10456

$C_{\phi q}^{(3)} = a_{\phi q}^{(3)} \mathbb{1} + b_{\phi q}^{(3)} (Y_u Y_u^\dagger)$ in up basis

$O_{\phi q}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$



Summary

- SMEFT allows an ambitious program of **"agnostic" NP searches**
- Flavor symmetries play a major role in
  - the classification of (ir)relevant SMEFT parameters
  - the interpretation of constraints in terms of NP
- candidate flavor symmetries for LHC program:
  $U(2)^3_{q,u,d} \times (U(1)_{l+e})^3$ and larger $\leftrightarrow$ exp. sensitivity
- **EWPO** can already help distinguish flavors in current fits.
  main block: too many parameters
- Interplay with B physics interesting! only a few studies yet
- Future: incorporating more and more flavor observables
  $\rightarrow$ "global SMEFT likelihood"

Backup slides

$\mathcal{L}_6$: the Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$\mathcal{L}_6$: the Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

Greljo,Palavric,Thomsen 2203.09561

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector															
		MFV_L		$\mathrm{U}(3)_V$		$\mathrm{U}(2)^2\times\mathrm{U}(1)^2$		$\mathrm{U}(2)^2$		$\mathrm{U}(2)_V$		$\mathrm{U}(1)^6$		$\mathrm{U}(1)^3$		No symm.	
Quark sector	MFV_Q	41	6	45	9	59	6	62	9	67	13	81	6	93	18	207	132
	$\mathrm{U}(2)^2 \times \mathrm{U}(3)_d$	72	10	78	15	95	10	100	15	107	21	122	10	140	28	281	169
	$\mathrm{U}(2)^3 \times \mathrm{U}(1)_{d_3}$	86	10	92	15	111	10	116	12	123	21	140	10	158	28	305	175
	$\mathrm{U}(2)^3$	93	17	100	23	118	17	124	23	132	30	147	17	168	38	321	191
	No symmetry	703	570	734	600	756	591	786	621	818	652	813	612	906	705	1350	1149

Counting with spurions

Faroughy,Isidori,Wilsch,Yamamoto 2005.05366

		No symmetry				$U(3)^5$					
		3 Gen.		1 Gen.		Exact		$\mathcal{O}(Y^1_{e,d,u})$		$\mathcal{O}(Y^1_e, Y^1_d Y^2_u)$	
Class	**Operators**										
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
8	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
	$(\bar{L}L)(\bar{R}R)$	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

Counting with spurions

Faroughy, Isidori, Wilsch, Yamamoto 2005.05366

$$Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_l \\ 0 & 1 \end{pmatrix} \qquad Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ 0 & 1 \end{pmatrix} \qquad Y_d = y_b \begin{pmatrix} \Delta_d & x_b V_q \\ 0 & 1 \end{pmatrix}$$

	$U(2)^5$ [terms summed up to different orders]													
Operators	Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1V^1)$		$\mathcal{O}(V^3,\Delta^1V^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6
ψ^2H^3	3	3	6	6	6	6	9	9	9	9	12	12	12	12
ψ^2XH	8	8	16	16	16	16	24	24	24	24	32	32	32	32
ψ^2H^2D	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

Counting with spurions

Faroughy,Isidori,Wilsch,Yamamoto 2005.05366

$$Y_e = \begin{pmatrix} \Delta_e & x_\tau V_l \\ 0 & \kappa_\tau X_\tau \end{pmatrix} \qquad Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ 0 & 1 \end{pmatrix} \qquad Y_d = \begin{pmatrix} \Delta_d & x_b V_q \\ 0 & \kappa_b X_b \end{pmatrix}$$

	$U(2)^5 \otimes U(1)_b \otimes U(1)_\tau$ [terms summed up to different orders]															
Operators	Exact		$\mathcal{O}(X^2)$		$\mathcal{O}(V^1, X^2)$		$\mathcal{O}(V^2, V^1X^2)$		$\mathcal{O}(\Delta^1, V^1X^2)$		$\mathcal{O}(V^2, \Delta^1, V^1X^2)$		$\mathcal{O}(\Delta^1V^1, V^2X^2, \Delta^1X^1)$		$\mathcal{O}(V^3, \Delta^1V^1, V^2X^2, \Delta^1X^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6	9	6
ψ^2H^3	1	1	3	3	4	4	6	6	9	9	9	9	12	12	12	12
ψ^2XH	3	3	8	8	11	11	16	16	24	24	24	24	32	32	32	32
ψ^2H^2D	14	–	15	1	19	5	23	5	19	5	23	5	25	7	25	7
$(\bar{L}L)(\bar{L}L)$	23	–	23	–	40	17	67	24	40	17	67	24	67	24	74	31
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–	29	–	38	9	38	9
$(\bar{L}L)(\bar{R}R)$	32	–	32	–	48	16	64	16	50	18	66	18	77	29	77	29
$(\bar{L}R)(\bar{R}L)$	–	–	1	1	1	1	3	3	3	3	3	3	6	6	6	6
$(\bar{L}R)(\bar{L}R)$	–	–	4	4	4	4	12	12	18	18	18	18	38	38	38	38
total:	111	10	124	23	165	64	229	88	201	100	248	107	304	163	311	170