The SMEFTsim package

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feynrules.irmp.ucl.ac.be/wiki/SMEFT

Brivio, Jiang, Trott JHEP 1712 (2017) 070

arXiv: 1709.06492

Motivation

Goals

- enable Monte Carlo event generation in SMEFT
- enable **global analyses** at the numerical level
- provide a handy tool with all the theory manipulations automated

Scope

- LO: tree-level
- complete calculations at $\mathcal{O}(\Lambda^{-2})$
- **full** Warsaw basis (B-conserving)
- complete treatment of flavor structure and input parameters

SMEFTsim – current version (v2)

Brivio, Jiang, Trott 1709.06492

a set of **FeynRules** models, pre-exported to **6 UFOs**

2 input schemes × 3 flavor assumptions

$\{\alpha_{em}, m_Z, G_F\}$
$\{m_W, m_Z, G_F\}$

general
$U(3)^5$ symmetry
linear MFV

⇝ **backup**

- SM Higgs couplings hgg, $h\gamma\gamma$, $hZ\gamma$ included in the $m_t \to \infty$ limit
  → effective vertices with **oh-shell** loop functions $I(m_t, m_W)$ hard coded

- interaction order `NP` associated to SMEFT parameters
  → allows to separate SM / interference / squared contributions

- supports `WCxf` exchange format

Aebischer et al. 1712.05298

SMEFTsim 3.0

to be released before Christmas!

- general improvement of the code
- 2 new flavors
- a new feature for propagator effects
- better modeling of *hgg*, up to *hgggg*
- all vertices now included
- parameterization moved from `Abs/Ph` to `Re/Im`
- individual interaction orders for each operator
- will be available on GitHub `https://SMEFTsim.github.io`
  → better version control
  → public forum for issues and questions
- set B not maintained anymore

Two new flavor structures: `top`, `topU3l`

Follow standards for **top quark physics** proposed in Aguilar-Saavedra et al 1802.07237

Based on $U(2)$ symmetry in quark sector Barbieri et al. 1105.2296,1203.4218

→ 1st, 2nd gen.	(q_L, u_R, d_R)	$U(2)_q \times U(2)_u \times U(2)_d$
→ 3rd gen.	(Q_L, t_R, b_R)	no sym

$V_{CKM} \equiv \mathbb{1}$

Two alternative options for lepton sector

`top`	$[U(1)_{l+e}]^3$	→ only diagonal entries. allows $e \neq \mu \neq \tau$
`topU3l`	$U(3)_l \times U(3)_e$	→ same as $U(3)^5$ model. diagonal + $e = \mu = \tau$ imposed

Two new flavor structures: `top`, `topU3l`

quarks

- 4-fermion operators rotated according to recommendations. eg.

$$Q_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u) \qquad\qquad Q^{(1)}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$$

$$Q'_{tu} = (\bar{u}\gamma_\mu t)(\bar{t}\gamma^\mu u) \quad \longrightarrow \quad Q^{(8)}_{tu} = (\bar{t}\,T^a\gamma_\mu t)(\bar{u}\,T^a\gamma^\mu u)$$

$$Q_{tu} = Q^{(1)}_{tu}$$

$$Q'_{tu} = \frac{1}{3}Q^{(1)}_{tu} + 2Q^{(8)}_{tu}$$

- symmetry $\Rightarrow$ different Yukawa dependence between generations

$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\,\tilde{H}\,Y_u^\dagger\,u)$$

$$\mathcal{Q}_{tH} = (H^\dagger H)(\bar{Q}\,\tilde{H}\,t)$$

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$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\,\tilde{H}\;Y_u^\dagger\;u)$$
$$\mathcal{Q}_{tH} = (H^\dagger H)(\bar{Q}\,\tilde{H}\,t)$$

leptons

- different Yukawa dependence and # parameters between the two models

`top`	$(\mathcal{Q}_{eH})_{pp} = (H^\dagger H)(\bar{l}_p\,H\,e_p)$	$\rightarrow$ 3 independent operators
`topU3l`	$\mathcal{Q}_{eH} = (H^\dagger H)(\bar{l}\,H\;Y_l^\dagger\;e)$	$\rightarrow$ 1 operator

Parameter counting

	general		U35		MFV		top		topU31	
	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$
$\mathscr{L}_6^{(1)}$	4	2	4	2	2	-	4	2	4	2
$\mathscr{L}_6^{(2,3)}$	3	-	3	-	3	-	3	-	3	-
$\mathscr{L}_6^{(4)}$	8	4	8	4	4	-	8	4	8	4
$\mathscr{L}_6^{(5)}$	54	27	6	3	7	-	14	7	10	5
$\mathscr{L}_6^{(6)}$	144	72	16	8	20	-	36	18	28	14
$\mathscr{L}_6^{(7)}$	81	30	9	1	14	-	21	2	15	2
$\mathscr{L}_6^{(8a)}$	297	126	8	-	10	-	31	-	16	-
$\mathscr{L}_6^{(8b)}$	450	195	9	-	19	-	40	2	27	2
$\mathscr{L}_6^{(8c)}$	648	288	8	-	28	-	54	4	31	4
$\mathscr{L}_6^{(8d)}$	810	405	14	7	13	-	64	32	40	20
tot	2499	1149	85	25	120	-	275	71	182	53

Improved description of SM $gg \to h$

v2 $$\mathscr{L} = \frac{g_s^2}{16\pi^2} I_f\left(\frac{m_h^2}{4m_t^2}\right)(\partial_\mu G_\nu^a - \partial_\nu G_\mu^a)^2 \frac{h}{v}$$

loop function expanded up to $\mathcal{O}(m_t^{-6})$, Higgs on-shell.

Improved description of SM $gg \to h$

v2 $$\mathscr{L} = \frac{g_s^2}{16\pi^2} I_f\left(\frac{m_h^2}{4m_t^2}\right)(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu)^2 \frac{h}{v}$$

loop function expanded up to $\mathcal{O}(m_t^{-6})$, Higgs on-shell.

v3 $$\mathscr{L} = \frac{g_s^2}{48\pi^2}\left[O^{(1)}_{gg} - \frac{7}{60m_t^2}\mathcal{O}^{(2)}_{gg} + \frac{g}{5m_t^2}\mathcal{O}^{(3)}_{gg} + \frac{1}{30m_t^2}\mathcal{O}^{(4)}_{gg} + \frac{3}{5m_t^2}\mathcal{O}^{(5)}_{gg}\right]$$

complete basis of HG operators up to $d = 7$: "top-EFT"

Neill 0908.1573
Harlander,Neumann 1309.2225
Dawson,Lewis,Zeng 1409.6299

$$\mathcal{O}^{(1)}_{gg} = G^a_{\mu\nu} G^{a\mu\nu} \frac{h}{v}\,,$$

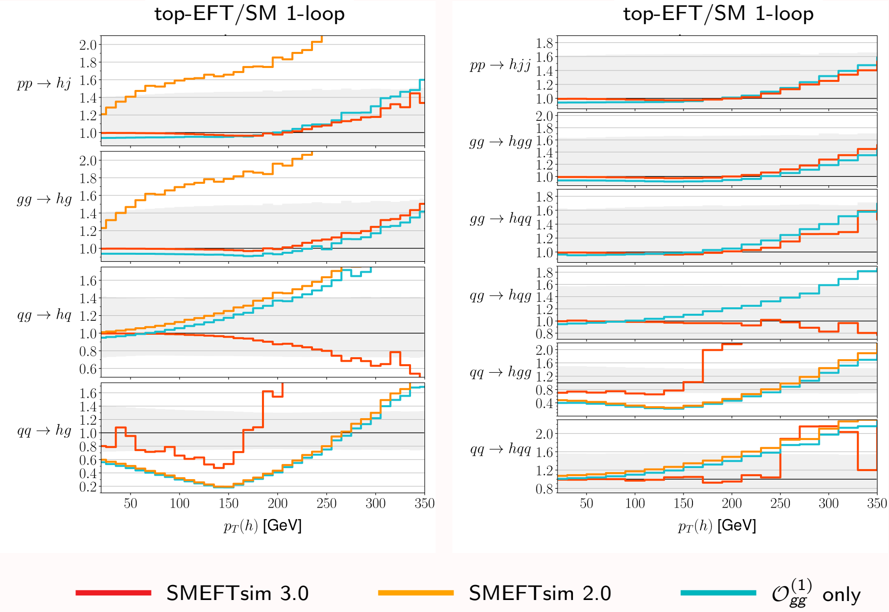
$$\mathcal{O}^{(2)}_{gg} = D_\sigma G^a_{\mu\nu} D^\sigma G^{a\mu\nu} \frac{h}{v}\,, \quad \mathcal{O}^{(3)}_{gg} = f_{abc} G^{a\nu}_{\mu} G^{b\sigma}_{\nu} G^{c\mu}_{\sigma} \frac{h}{v}\,,$$

$$\mathcal{O}^{(4)}_{gg} = D^\mu G^a_{\mu\nu} D_\sigma G^{a\sigma\nu} \frac{h}{v}\,, \quad \mathcal{O}^{(5)}_{gg} = G^{a\mu\nu} D_\nu D^\sigma G^a_{\sigma\mu} \frac{h}{v}\,.$$

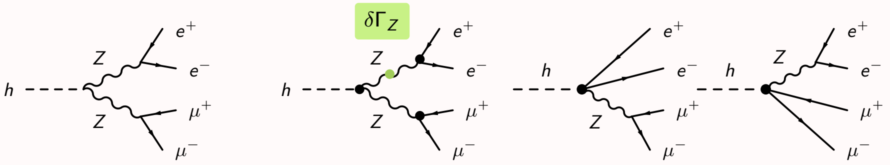
→ complete basis for hg^2, hg^3, hg^4 vertices at $\mathcal{O}(m_t^{-2})$

→ full momentum dependence: Higgs can be off-shell.

Improved description of SM $gg \to h + \text{jets}$



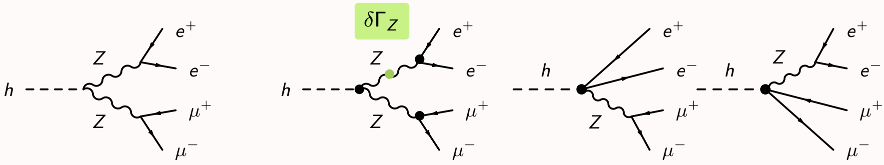
Propagator corrections



SM | SMEFT d=6

$$m_Z \equiv m_Z^{SM}, \quad \Gamma_Z = \Gamma_Z^{SM} + \delta\Gamma_Z$$

Propagator corrections



SM | SMEFT d=6

$$m_Z \equiv m_Z^{SM}, \quad \Gamma_Z = \Gamma_Z^{SM} + \delta\Gamma_Z$$

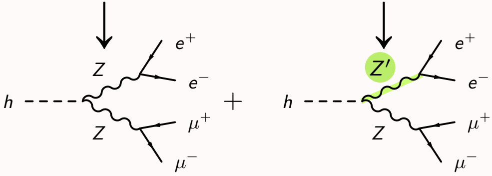
$$\mathcal{A} \propto \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z} = \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \left[1 - \frac{i m_Z}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \delta\Gamma_Z \right] + \mathcal{O}(\delta\Gamma_Z^2)$$

linearization usually not possible in a MC

only options: include $(\Gamma_Z^{SM} + \delta\Gamma_Z)$ at the denominator

analytic treatment Brivio,Corbett,Trott 1906.06949

$$\mathcal{A} \propto \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z} = \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \left[1 - \frac{i m_Z}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \delta\Gamma_Z \right] + \mathcal{O}(\delta\Gamma_Z^2)$$

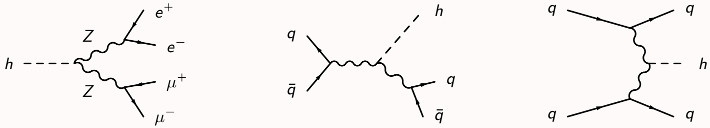


Dummy fields W', Z', h', t' are added whose propagator is **the pure linearized shift**

Gröber,Mattelaer,Mimasu – Les Houches 2017 1803.10379

Insertions controlled by interaction order `NPprop` in dummy vertices
→ e.g. interference piece `NPprop<=2 NPprop^2==2`

Propagator corrections examples



total width

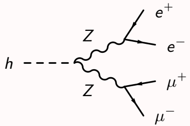
STXS bin $p_{Th} < 200$

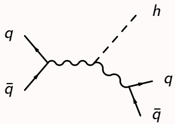
$60 \leqslant m_{jj} \leqslant 120$ | $m_{jj} \geqslant 350$

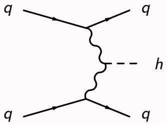
$$\frac{X_{SMEFT}}{X_{SM}} = 1 + \sum_\alpha \frac{X_\alpha}{X_{SM}} \bar{C}_\alpha + \mathcal{O}(\Lambda^{-4})$$

$$X = \Gamma, \sigma \qquad \bar{C}_\alpha = \frac{v^2}{\Lambda^2} C_\alpha$$

Propagator corrections examples







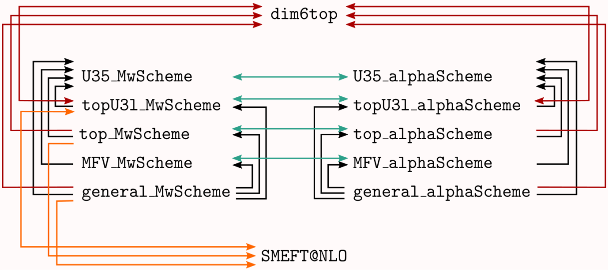
	total width		STXS bin $p_{Th} < 200$, $60 \leqslant m_{jj} \leqslant 120$		STXS bin $p_{Th} < 200$, $m_{jj} \geqslant 350$	
	direct	propagators	direct	propagators	direct	propagators
$\bar{C}_{He}$	-1.724	0.153		0.0526		$5.32 \cdot 10^{-5}$
$\bar{C}_{Hl}^{(1)}$	2.144	0.153		0.0526		$5.32 \cdot 10^{-5}$
$\bar{C}_{Hl}^{(3)}$	-3.856	1.147	-6	1.258	-6	$1.351 \cdot 10^{-3}$
$\bar{C}_{Hq}^{(1)}$		-0.39	-0.197	-0.135	0.109	$-1.363 \cdot 10^{-4}$
$\bar{C}_{Hq}^{(3)}$		-1.353	25.66	-1.329	-5.345	$-1.423 \cdot 10^{-3}$
$\bar{C}_{Hu}$		-0.203	1.926	-0.070	-0.323	$-7.092 \cdot 10^{-5}$
$\bar{C}_{Hd}$		0.150	-0.608	0.0518	0.103	$5.24 \cdot 10^{-5}$
$\bar{C}'_{ll}$	3	-0.839	3	-0.936	3	$-1. \cdot 10^{-3}$

Brivio,Corbett,Trott 1906.06949, ATLAS-CONF-2020-053

Validation of the UFO models

followed the procedure in Durieux et al. 1906.12310

- models are compared pair-wise
- uses dedicate MG plugin that computes $|\mathcal{A}_{SM}|^2$, $2Re\mathcal{A}_{SM}\mathcal{A}_6^\dagger$, $|\mathcal{A}_6|^2$ at 1 phase-space point per process, for all SMEFT parameters. repeated over $\sim$ 90 processes.
- **conversion tables** `dim6top`, `SMEFT@NLO` $\leftrightarrow$ `general, top, topU3l` produced as byproduct



What next?

- update of WCxf interface
- UFOs in Python 3
- implementation of $h\gamma\gamma$, $hZ\gamma$, hgg in $m_t \to \infty$ limit at NLO SMEFT ?
- additional input schemes?
- suggestions are welcome!

Backup slides

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Input schemes for the EW sector

$\{\alpha_{\rm em}, \mathbf{m_Z}, \mathbf{G_f}\}$ scheme

$$\bar{v}^2 = \frac{1}{\sqrt{2}G_F} + \frac{\Delta G_F}{G_F}$$

$$\bar{s_\theta}^2 = \frac{1}{2}\left[1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2}}\right]\left[1+\frac{c_{2\theta}}{2\sqrt{2}}\Delta G_F + \frac{c_{2\theta}}{4}\frac{\Delta m_Z^2}{m_Z^2} + \frac{3s_{4\theta}}{8}\frac{v^2}{\Lambda^2}C_{HWB}\right]$$

$$\bar{e}^2 = 4\pi\alpha \; +0$$

$$\bar{g}_1 = \frac{e}{c_\theta}\left[1+\frac{s_\theta^2}{2c_{2\theta}}\left(\sqrt{2}\Delta G_f + \frac{\Delta m_Z^2}{m_Z^2} + 2\frac{c_\theta^3}{s_\theta}\frac{\hat{v}^2}{\Lambda^2}C_{HWB}\right)\right]$$

$$\bar{g}_w = \frac{e}{s_\theta}\left[1-\frac{c_\theta^2}{2c_{2\theta}}\left(\sqrt{2}\Delta G_f + \frac{\Delta m_Z^2}{m_Z^2} + 2\frac{s_\theta^3}{c_\theta}\frac{\hat{v}^2}{\Lambda^2}C_{HWB}\right)\right]$$

$$\bar{m}_W^2 = m_Z^2 c_\theta^2 + \left[1 - \frac{\sqrt{2}s_\theta^2}{c_{2\theta}}\Delta G_F + -\frac{c_\theta^2}{c_{2\theta}}\frac{\Delta m_Z^2}{m_Z^2} - s_\theta^2 t_{2\theta}\frac{\hat{v}^2}{\Lambda^2}C_{HWB}\right]$$

with

$$\Delta m_Z^2 = m_Z^2\frac{v^2}{\Lambda^2}\left[\frac{C_{HD}}{2} + s_{2\theta}C_{HWB}\right] \qquad \Delta G_F = \frac{v^2}{\Lambda^2}\left[(C_{Hl}^3)_{11} + (C_{Hl}^3)_{22} - (C_{ll})_{1221}\right]$$

Input schemes for the EW sector

$\{m_W, m_Z, G_f\}$ scheme

$$\bar{v}^2 = \frac{1}{\sqrt{2}G_F} + \frac{\Delta G_F}{G_F}$$

$$\bar{s_\theta}^2 = \left(1 - \frac{m_W^2}{m_Z^2}\right)\left[1 - c_\theta^2 \frac{\Delta m_Z^2}{m_Z^2} + \frac{s_{4\theta}}{4}\frac{v^2}{\Lambda^2} C_{HWB}\right]$$

$$\bar{e}^2 = 4\sqrt{2} G_F m_W \left(1 - \frac{m_W^2}{m_Z^2}\right)\left[1 - \frac{\Delta G_F}{\sqrt{2}} - \frac{c_\theta^2}{2s_\theta^2}\frac{\Delta m_Z^2}{m_Z^2} - \frac{s_{2\theta}}{2}\frac{v^2}{\Lambda^2} C_{HWB}\right]$$

$$\bar{g}_1 = \frac{e}{c_\theta}\left[1 - \frac{\Delta G_F}{\sqrt{2}} - \frac{1}{2s_\theta^2}\frac{\Delta m_Z^2}{m_Z^2}\right]$$

$$\bar{g}_W = \frac{e}{s_\theta}\left[1 - \frac{\Delta G_F}{\sqrt{2}}\right]$$

$$\bar{m}_W^2 = m_W^2 + 0$$

with

$$\Delta m_Z^2 = m_Z^2 \frac{v^2}{\Lambda^2}\left[\frac{C_{HD}}{2} + s_{2\theta} C_{HWB}\right] \qquad \Delta G_F = \frac{v^2}{\Lambda^2}\left[(C_{Hl}^3)_{11} + (C_{Hl}^3)_{22} - (C_{ll})_{1221}\right]$$

SMEFTsim - available flavor assumptions

- Flavor general

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completely general flavor indices:

2499 C_i parameters including all complex phases

SMEFTsim - available flavor assumptions

- Flavor general
- $U(3)^5$ flavor symmetric

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assume a **flavor symmetry**

$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

The Yukawas are the only **spurions** breaking the symmetry:

$$Y_u \mapsto U_u Y_u U_q^\dagger \qquad Y_d \mapsto U_d Y_d U_q^\dagger \qquad Y_l \mapsto U_e Y_l U_l^\dagger$$

- only 85 C_i parameters (incl. phases)

Examples:

$$\begin{aligned}
\mathcal{Q}_{Hu} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_r \gamma^\mu u_s)\ \delta_{rs} \\
\mathcal{Q}_{eB} &= B_{\mu\nu}(\bar{l}_r H \sigma^{\mu\nu} e_s)\ (Y_l)_{rs} \\
\mathcal{Q}_{ll} &= (\bar{\ell}_r \gamma^\mu \ell_s)(\bar{\ell}_m \gamma_\mu \ell_n)\ \delta_{rs}\delta_{mn} \text{ or } \delta_{rn}\delta_{ms} \to C_{ll}, C'_{ll}
\end{aligned}$$

SMEFTsim - available flavor assumptions

- Flavor general
- $U(3)^5$ flavor symmetric
- Linear Minimal Flavor Violation

MFV: assume $\boldsymbol{U(3)^5}$ symmetry + **CKM only source of ~~CP~~**

- $C_i \in \mathbb{R}$ — 120 C_i parameters
- CP odd bosonic operators are absent ($\propto J_{CP} \simeq 10^{-5}$)
- includes the first order in flavor violation expansion. E.g.:

$$\mathcal{Q}_{Hu} \to (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_r \gamma^\mu u_s) \left[C_{Hu}^{(0)} \mathbb{1} + (\Delta C_{Hu}) \, (Y_u Y_u^\dagger) \right]_{rs}$$

$$\mathcal{Q}_{Hq}^{(1)} \to (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_r \gamma^\mu q_s) \left[C_{Hq}^{(1)(0)} \mathbb{1} + (\Delta^u C_{Hq}^{(1)}) \, (Y_u^\dagger Y_u) + (\Delta^d C_{Hq}^{(1)}) \, (Y_d^\dagger Y_d) \right]_{rs}$$