The inclusive Higgs width in the SMEFT

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based on 1906.06949
in collaboration with T. Corbett and M. Trott

The SMEFT

SMEFT = Effective Field Theory with **SM fields + symmetries**

a Taylor expansion in canonical dimensions $(v, E/\Lambda)$:

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

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

$\mathcal{O}_i$ invariant operators that form a complete basis

---

- describes impact of any UV
  - nearly decoupled: $\Lambda \gg v, E$
  - converges to SM in the limit $E \ll \Lambda$
- not just a parameterization but a consistent QFT → loops, RGE etc.

An important observable: the Higgs width

a crucial observable for the Higgs sector

SM: $$\Gamma_H \simeq 4 \text{ MeV} \quad \rightarrow \quad \frac{\Gamma_H}{m_H} \simeq 3 \cdot 10^{-5} \ll 1$$

$\Rightarrow$ Higgs measurements can be factored into

$$\sigma(i \rightarrow H) \times Br(H \rightarrow f)$$

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SMEFT: probe separately production and decay

$$Br(H \to f) = \frac{\Gamma(H \to f)}{\Gamma_H^{\mathrm{tot}}}$$

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SMEFT: probe separately production and decay

$$Br_{\rm SMEFT}(H \to f) = \left[\frac{\Gamma(H \to f)}{\Gamma_H^{\rm tot}}\right]_{\rm SM} \left[1 + \frac{\delta\Gamma(H \to f)}{\Gamma_{\rm SM}(H \to f)} - \frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,\rm SM}^{\rm tot}}\right]$$

- both $\delta\Gamma(H \to f)$ and $\delta\Gamma_H^{\rm tot}$ need to be determined
- $\delta\Gamma_H^{\rm tot}$ enters all processes $\to$ **strong impact** on global SMEFT analyses!

The Higgs width in the SMEFT - setup

Focus on the leading contributions:

- LO in the EFT: up to SM - $\mathcal{L}_6$ **interference**.

$$\Gamma_H = \Gamma_{H,\mathrm{SM}}\left[1+\frac{\delta\Gamma_H}{\Gamma_{H,\mathrm{SM}}}\right] \qquad \frac{\delta\Gamma_H}{\Gamma_{H,\mathrm{SM}}} = \sum_i a_i \bar{C}_i = \sum_i a_i \left(C_i \frac{v^2}{\Lambda^2}\right)$$

- **tree level**.

  SM couplings $H\gamma\gamma$, $HZ\gamma$, Hgg included as effective vertices for $H\to f\bar{f}\gamma\ /\ \gamma\gamma\ /\ gg$.
  Neglected in other channels.

- up to **4-body** decays.

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Conventions and assumptions:

- Warsaw basis — Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884
- **U(3)^5 flavor symmetry** $\to g_{Hff} \sim y_f$ also in the SMEFT
- **inclusive** calculation, not differential $\to$ CP odd terms do not contribute
- **2 input schemes**: $\{m_W, m_Z, G_F\}$, $\{\alpha_{\mathrm{em}}, m_Z, G_F\}$ — ⇝ backup

The Higgs width in the SMEFT

leading channels:

$$H \to \bar{f} f$$

$$H \to gg$$

$$H \to \gamma\gamma$$

$$H \to \bar{f} f \gamma$$

$$H \to 4f$$

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\mathrm{tot}} \to Br$

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$$\frac{\Gamma(H\to\bar{f}f)}{\Gamma_{SM}(H\to\bar{f}f)} \simeq 1 + 2\delta g_{Hff}$$

$$\delta g_{Hff} = \bar{C}_{H\Box} - \frac{\bar{C}_{HD}}{4} - \bar{C}^{(3)}_{Hl} + \frac{\bar{C}'_{ll}}{2} - \frac{5}{2}\bar{C}_{fH}$$

Alonso, Jenkins, Manohar, Trott 1312.2014

- renorm. of the H field
- contrib. to μ decay $\to G_F \to v$
- direct $\mathcal{O}_{fH}$ contribution $\left(-\frac{3}{2}\bar{C}_{fH}\right)$
  $+$
  contrib. to $m_f \to y_f$ $\left(-\bar{C}_{fH}\right)$

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$$\frac{\Gamma(h \to gg)}{\Gamma^{SM}(h \to gg)} \simeq 1 + \frac{16\pi^2}{g_s^2 I^g}\bar{C}_{HG}, \qquad I^g \simeq 0.375$$

Manohar,Wise 0601212

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$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma^{SM}(h\to\gamma\gamma)} \simeq 1 + \frac{16\pi^2}{e^2 I^\gamma}\mathscr{C}_{\gamma\gamma}, \qquad I^\gamma \simeq -1.65$$

$$\mathscr{C}_{\gamma\gamma} = s_\theta^2\,\bar{C}_{HW} + c_\theta^2\,\bar{C}_{HB} - s_\theta c_\theta\,\bar{C}_{HWB}$$

Bergström, Hulth Nucl.Phys.B259(1985)137
Manohar, Wise 0601212

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Bergström,Hulth Nucl.Phys.B259(1985)137
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loop-factor enhancement
in the relative correction:

tree-level SMEFT vs loop SM

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leading channels:

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$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f}f\gamma$

$H \to 4f$

available as $H \to ZZ^*$, $H \to WW^*$ $\times Br(Z,W)$ relying on narrow width approx. for Z, W.

good in SM but **not sufficient** in the SMEFT!

main reason: tree $\gamma\gamma, Z\gamma$ mediated diagrams

also missing:

- CC - NC interference
- crossed-current interference in ZZ diagrams
- $\delta\Gamma_V$, δm_V^2 corrections for off-shell boson

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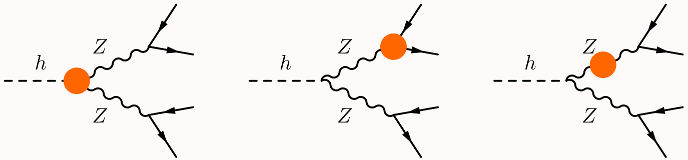
H → 4f in the SMEFT

① corrections to SM diagrams



$\propto g_{\mu\nu}$ (SM-like)

$\propto g_{\mu\nu} p\cdot q - p_\nu q_\mu \; (Z_{\mu\nu} Z^{\mu\nu} h)$

$\delta g_L, \delta g_R$

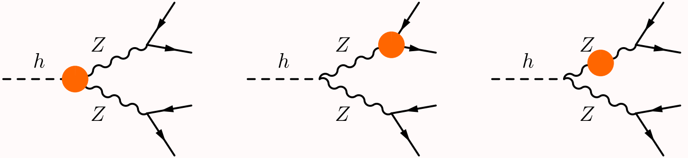
$$\frac{-i m_Z \delta\Gamma_Z + (2 m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

↑

hard to extract from MC simulation!
full treatment requires analytic calculation

H → 4f in the SMEFT

① corrections to SM diagrams



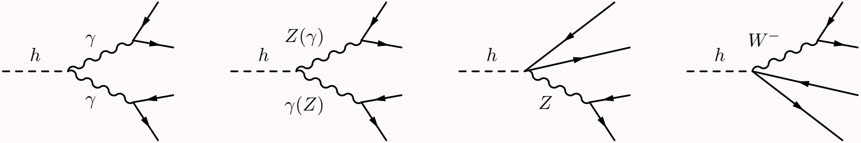
$\propto g_{\mu\nu}$ (SM-like)

$\propto g_{\mu\nu} p\cdot q - p_\nu q_\mu$ ($Z_{\mu\nu} Z^{\mu\nu} h$)

$\delta g_L, \delta g_R$

$$\frac{-i m_Z \delta\Gamma_Z + (2 m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

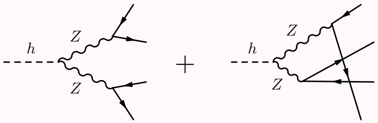
② genuine SMEFT diagrams



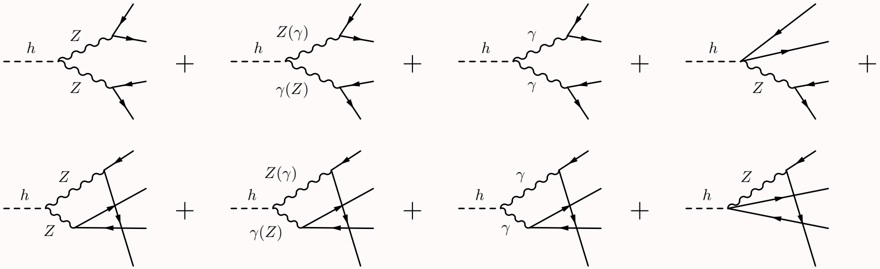
H → 4f in the SMEFT - complexity

$$h \to e^+ e^- e^+ e^-$$

SM



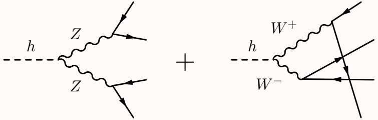
interfering with



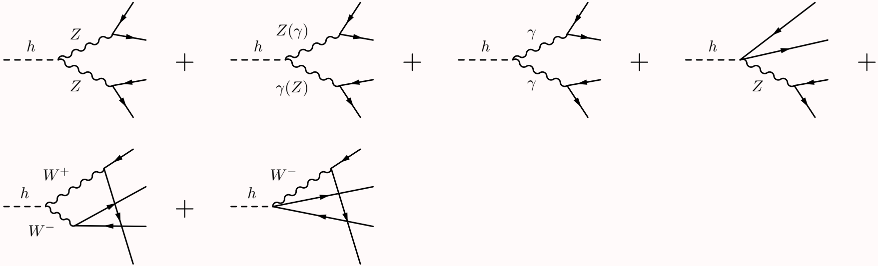
H $\rightarrow$ 4f in the SMEFT - complexity

$h \rightarrow \bar{u}\, u\, \bar{d}\, d$

SM

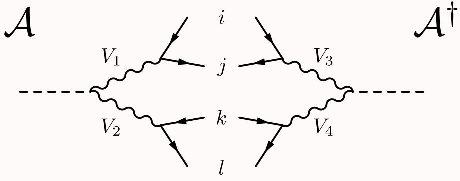


interfering with



H → 4f - analytic calculation

fully analytical treatment. automated with general decomposition:



$$\mathcal{A}\mathcal{A}^\dagger \sim g_{HV_1V_2}\ g_{HV_3V_4}\ \sum_n \mathcal{T}^{(n)}$$

$$\mathcal{T}^{(n)} = \mathcal{K}^{(n)}\left(g_{L,R}^{ij,V_1}, g_{L,R}^{ij,V_3}, g_{L,R}^{kl,V_2}, g_{L,R}^{kl,V_4}\right)\ \mathcal{F}^{(n)}_{V_1V_2V_3V_4}(p_a, m_a), \quad a = \{i,j,k,l\}$$

for $m_a \equiv 0$ there are only **8** independent $\mathcal{F}_{V_1V_2V_3V_4}$. For each $\{V\}$ set:

- numerical integration of phase space: `Vegas` in `Mathematica` T. Hahn 0404043
- cross-check: `RAMBO` + 2 independent parameterizations of phase space

Kleiss,Stirling,Ellis
Comput.Phys.Commun.40(1986)359

H $\longrightarrow$ 4f - results

Example: $H \to e^+ e^- \mu^+ \mu^-$ $\quad m_f \equiv 0$, m_W scheme

$$\frac{\delta\Gamma(H \to e^+ e^- \mu^+ \mu^-)}{\Gamma_{\rm SM}(H \to e^+ e^- \mu^+ \mu^-)} = \sum_i a_i \bar{C}_i = \sum_i a_i \left(C_i \frac{v^2}{\Lambda^2} \right)$$

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}_{Hl}^{(1)}$	$\bar{C}_{Hl}^{(3)}$	$\bar{C}_{He}$	$\bar{C}_{Hq}^{(1)}$	$\bar{C}_{Hq}^{(3)}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
Z	-0.78	-0.22	0.30	2	0.17	4.38	-1.62	-3.52					3.
A	1.04	-1.08	-0.68										
E						-2.23	-2.23	1.80					
G			-0.38		0.06	0.15	1.14	0.15	-0.39	-1.34	-0.20	0.15	-0.83
tot	0.26	-1.30	-0.76	2.	0.23	2.30	-2.71	-1.58	-0.39	-1.34	-0.20	0.15	2.17

Z	corrections to SM diagram
A	γ diagrams
E	contact diagrams ($HZee$)
G	$\delta\Gamma_Z^{\rm tot}/\Gamma_{Z,SM}$ on + off-shell Z

H → 4f - results

Example: $H \to e^+ e^- \mu^+ \mu^-$ $m_f \equiv 0$, m_W scheme

$$\frac{\delta\Gamma(H\to e^+e^-\mu^+\mu^-)}{\Gamma_{\rm SM}(H\to e^+e^-\mu^+\mu^-)} = \sum_i a_i \bar{C}_i = \sum_i a_i \left(C_i \frac{v^2}{\Lambda^2}\right)$$

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\square}$	$\bar{C}_{HD}$	$\bar{C}_{Hl}^{(1)}$	$\bar{C}_{Hl}^{(3)}$	$\bar{C}_{He}$	$\bar{C}_{Hq}^{(1)}$	$\bar{C}_{Hq}^{(3)}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
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Impact of previously neglected contributions

(1) photon-mediated diagrams

$\mathcal{O}(1-250)\%$ effect

	with γ			without γ		
	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$
$h \to e^+e^-\mu^+\mu^-$	0.26	-1.30	-0.38	-0.77	-0.22	0.30
$h \to \bar{u}u\bar{c}c$	1.45	-2.63	-0.29	-0.77	-0.22	1.33
$h \to e^+e^-\bar{d}d$	0.50	-1.55	-0.37	-0.77	-0.22	0.47
$h \to e^+e^-e^+e^-$	0.02	-2.28	0.27	-0.76	-0.21	0.44
$h \to \bar{u}u\bar{u}u$	1.39	-2.72	-0.14	-0.76	-0.21	1.19
$h \to e^+e^-\bar{\nu}_e\nu_e$	-1.49	0.01	-0.06	-1.48	-0.007	-0.07

Impact of previously neglected contributions

(2) $Z - W$ interference terms

$\mathcal{O}(1-200)\%$ effect

$\delta\Gamma(H \to e^+ e^- \bar\nu_e \nu_e)/\Gamma_{\rm SM}$ omitting γ and $\delta\Gamma_Z, \delta\Gamma_W$ contrib.

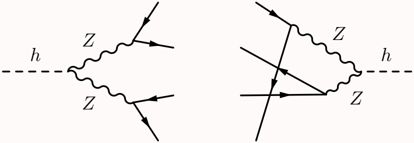
	$\bar C_{HW}$	$\bar C_{HB}$	$\bar C_{HWB}$	$\bar C_{H\Box}$	$\bar C_{HD}$	$\bar C_{Hl}^{(1)}$	$\bar C_{Hl}^{(3)}$	$\bar C_{He}$	$\bar C_{Hq}^{(1)}$	$\bar C_{Hq}^{(3)}$	$\bar C_{Hu}$	$\bar C_{Hd}$	$\bar C'_{ll}$
ZZ	-0.04	-0.01	-0.003	0.09	-0.008	0.004	-0.19	-0.04	0	0	0	0	0.14
WW	-1.49	0	0	2.0	-0.50	0	-3.77	0	0	0	0	0	3.00
WZ	0.04	0.004	**-0.06**	-0.10	-0.04	**-0.01**	0.21	0	0	0	0	0	-0.14
full	-1.49	-0.007	-0.07	2.	-0.55	-0.008	-3.74	-0.04	0	0	0	0	3.
NW	-1.46	-0.01	-0.003	2.	-0.49	0.004	-3.77	-0.04	0.	0.	0.	0.	3.

full	$ZZ + WW + WZ$
NW	$ZZ + WW$

Impact of previously neglected contributions

(3) NC crossed - interference terms

$\mathcal{O}(\text{few} - 40)\%$ effect



$\delta\Gamma(H \to e^+e^-e^+e^-)/\Gamma_{\rm SM}$ incl. only ZZ and $HZee$ diagrams

	$\bar C_{HW}$	$\bar C_{HB}$	$\bar C_{HWB}$	$\bar C_{H\Box}$	$\bar C_{HD}$	$\bar C_{Hl}^{(1)}$	$\bar C_{Hl}^{(3)}$	$\bar C_{He}$	$\bar C_{Hq}^{(1)}$	$\bar C_{Hq}^{(3)}$	$\bar C_{Hu}$	$\bar C_{Hd}$	$\bar C'_{ll}$
full	-0.75	-0.22	0.43	2.	0.28	2.09	-3.91	-1.64	0	0	0	0	3.
NW	-0.78	-0.221	0.30	2.	0.17	2.15	-3.85	-1.73	0.	0.	0.	0.	3.

full	$\lvert\mathcal{A}_{ijkl}\rvert^2 + \lvert\mathcal{A}_{ilkj}\rvert^2 + 2\mathrm{Re}\mathcal{A}_{ijkl}\mathcal{A}^\dagger_{ilkj}$
NW	$\lvert\mathcal{A}_{ijkl}\rvert^2 + \lvert\mathcal{A}_{ilkj}\rvert^2$

Impact of previously neglected contributions

(4) $\delta\Gamma_V$, δm_V from off-shell boson

$\mathcal{O}(\text{few})\%$ effect

narrow width approx.:

$$\frac{\delta\Gamma(H\to VV^*\to 4f)}{\Gamma_{SM}(H\to VV^*\to 4f)} = (-1)\,\frac{\delta\Gamma_V}{\Gamma_{V,SM}} + \dots$$

full calculation:

$h\to e^+e^-\mu^+\mu^-$	$-0.820 \quad \delta\Gamma_Z/\Gamma_{Z,SM}$
$h\to e^+e^-e^+e^-$	$-0.748 \quad \delta\Gamma_Z/\Gamma_{Z,SM}$
$h\to e^+\nu_e\bar\nu_\mu\mu^-$	$-0.915 \quad \delta\Gamma_W/\Gamma_{W,SM}$
$h\to e^+\nu_e\bar\nu_e e^-$	$-0.914 \quad \delta\Gamma_W/\Gamma_{W,SM} - 0.038 \quad \delta\Gamma_Z/\Gamma_{Z,SM}$

H → 4f summary

- we did a **fully analytic** calculation, with numerical integration of phase space
- also generated all channels with MG5_aMC@NLO using SMEFTsim
  → agreement to 1% or better ✓

  Brivio, Jiang, Trott 1709.06492
- analytic treatment has a few advantages:
  - allows to separate contributions
  - easier to linearize in $\delta\Gamma_V, \delta m_V$
  - more stable for the massless fermions case with γ diagrams
  - cancellations are reproduced exactly
  - calculation can be **automated** in a dedicated package

    ⇝ a new reweighting tool coming soon
- some previously neglected contributions turn out to be relevant:
  γ diagrams and $Z - W$ interference

The total Higgs width in the SMEFT

putting together all the main contributions* we obtain

$$\Gamma_H^{\rm tot} = \Gamma_{H,SM}^{\rm tot}\left[1 + \frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,SM}^{\rm tot}}\right]$$

$$\Gamma_{H,SM}^{\rm tot} = 4.100 \text{ MeV}$$

$$\begin{aligned}\frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,SM}^{\rm tot}} =& -1.50\,\tilde{C}_{HB} - 1.21\,\tilde{C}_{HW} + 1.21\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG} \\ &+ 1.83\,\tilde{C}_{H\Box} - 0.43\,\tilde{C}_{HD} + 1.17\,\tilde{C}'_{ll} \\ &- 7.85\,Y_c\,\Re\tilde{C}_{uH} - 48.5\,Y_b\,\Re\tilde{C}_{dH} - 12.3\,Y_\tau\,\Re\tilde{C}_{eH} \\ &+ 0.002\,\tilde{C}_{Hq}^{(1)} + 0.06\,\tilde{C}_{Hq}^{(3)} + 0.001\,\tilde{C}_{Hu} - 0.0007\,\tilde{C}_{Hd} \\ &- 0.0009\,\tilde{C}_{Hl}^{(1)} - 2.32\,\tilde{C}_{Hl}^{(3)} - 0.0006\,\tilde{C}_{He},\end{aligned}$$

$^{*}gg + \gamma\gamma + \bar{b}b + \bar{c}c + \tau^+\tau^- + 4f + \bar{f}f\gamma$

Conclusions

- the inclusive Higgs width is a crucial observable for the Higgs sector

- improved calculation of $H \to 4f,\ H \to \bar{f}f\gamma$
  without relying on the narrow width approx. for Z, W
  → important for LHC measurements

- joined all the main channels into $\delta\Gamma_H^{\rm tot}$

- Br's and $\Gamma_H^{\rm tot}$ are computed **once and for all!**
  → can be used directly without further MC generation

- an automated package for `lhe` reweighting to appear soon!

- possible refinements:
  full massive fermions treatment
  phase space integration with cuts
  ...

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Shifts from input parameters

SM case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar{\theta}}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

$$\alpha_{\rm em} = \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2} \qquad m_Z = \frac{\bar{g}_2\bar{v}}{2c_{\bar{\theta}}} \qquad G_f = \frac{1}{\sqrt{2}\bar{v}^2}$$

$$\rightarrow$$

$$\hat{v}^2 = \frac{1}{\sqrt{2}G_f}$$

$$\sin\hat{\theta}^2 = \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_f m_Z^2}}\right)$$

$$\hat{g}_1 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}}$$

$$\hat{g}_2 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}}$$

in the SM at tree-level $\bar{\kappa} = \hat{\kappa}$

Shifts from input parameters

SMEFT case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar\theta}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

$$
\begin{aligned}
\alpha_{\rm em} &= \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2}\left[1+\bar{v}^2 C_{HWB}\frac{\bar{g}_2^3/\bar{g}_1}{\bar{g}_1^2+\bar{g}_2^2}\right]\\
m_Z &= \frac{\bar{g}_2\bar{v}}{2c_{\bar\theta}} + \delta m_Z(C_i)\\
G_f &= \frac{1}{\sqrt{2}\bar{v}^2} + \delta G_f(C_i)
\end{aligned}
\qquad \rightarrow \qquad
\begin{aligned}
\hat{v}^2 &= \frac{1}{\sqrt{2}G_f}\\
\sin\hat\theta^2 &= \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_f m_Z^2}}\right)\\
\hat{g}_1 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat\theta}\\
\hat{g}_2 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat\theta}
\end{aligned}
$$

in the SM at tree-level $\bar\kappa = \hat\kappa$

in the SMEFT $\bar\kappa = \hat\kappa + \delta\kappa(C_i)$

Shifts from input parameters

To have numerical predictions it is necessary to replace $\bar{\kappa} \to \hat{\kappa} + \delta\kappa(C_i)$ for all the parameters in the Lagrangian.

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

$$\delta m_Z^2 = m_Z^2 \hat{v}^2 \left(\frac{c_{HD}}{2} + 2 c_{\hat\theta} s_{\hat\theta} c_{HWB} \right)$$

$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221} \right)$$

$$\delta g_1 = \frac{s_{\hat\theta}^2}{2(1-2s_{\hat\theta}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{c_{\hat\theta}^3}{s_{\hat\theta}} c_{HWB} \hat{v}^2 \right)$$

$$\delta g_2 = -\frac{c_{\hat\theta}^2}{2(1-2s_{\hat\theta}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{s_{\hat\theta}^3}{c_{\hat\theta}} c_{HWB} \hat{v}^2 \right)$$

$$\delta s_\theta^2 = 2 c_{\hat\theta}^2 s_{\hat\theta}^2 (\delta g_1 - \delta g_2) + c_{\hat\theta} s_{\hat\theta} (1 - 2 s_{\hat\theta}^2) c_{HWB} \hat{v}^2$$

$$\delta m_h^2 = m_h^2 \hat{v}^2 \left(2 c_{H\Box} - \frac{c_{HD}}{2} - \frac{3 c_H}{2 lam} \right)$$

Shifts from input parameters

To have numerical predictions it is necessary to replace $\bar{\kappa} \to \hat{\kappa} + \delta\kappa(C_i)$ for all the parameters in the Lagrangian.

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

$$\delta m_Z^2 = m_Z^2 \hat{v}^2 \left(\frac{c_{HD}}{2} + 2 c_{\hat{\theta}} s_{\hat{\theta}} c_{HWB} \right)$$

$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221} \right)$$

$$\delta g_1 = -\frac{1}{2} \left(\sqrt{2} \delta G_f + \frac{1}{s_{\hat{\theta}}^2} \frac{\delta m_Z^2}{m_Z^2} \right)$$

$$\delta g_2 = -\frac{1}{\sqrt{2}} \delta G_f$$

$$\delta s_\theta^2 = 2 c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 (\delta g_1 - \delta g_2) + c_{\hat{\theta}} s_{\hat{\theta}} (1 - 2 s_{\hat{\theta}}^2) c_{HWB} \hat{v}^2$$

$$\delta m_h^2 = m_h^2 \hat{v}^2 \left(2 c_{H\Box} - \frac{c_{HD}}{2} - \frac{3 c_H}{2 lam} \right)$$

The SMEFTsim package

Brivio, Jiang, Trott 1709.06492
feynrules.irmp.ucl.ac.be/wiki/SMEFT

an **UFO & FeynRules model** with*:

1. the complete B-conserving Warsaw basis for 3 generations, including all complex phases and ~~CP~~ terms

2. automatic field redefinitions to have **canonical kinetic terms**

   ⇝ **backup**

3. automatic **parameter shifts** due to the choice of an input parameters set

Main scope:

estimate **tree-level** $|\mathcal{A}_{\mathbf{SM}}\mathcal{A}^*_{\mathbf{d=6}}|$ **interference** terms → theo. accuracy $\gtrsim 1\%$

* at the moment only LO, unitary gauge implementation

The SMEFTsim package

6 different implementations available

Brivio,Jiang,Trott 1709.06492

③ flavor structures: general / $U(3)^5$ symmetric / linear MFV

$\times$

② input schemes: $\hat{\alpha}_{\rm em},\, \hat{m}_Z,\, \hat{G}_f$ / $\hat{m}_W,\, \hat{m}_Z,\, \hat{G}_f$

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

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

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Pre-exported UFO files (include restriction cards)

	Set A		Set B	
	α scheme	m_W scheme	α scheme	m_W scheme
Flavor general SMEFT	SMEFTsim_A_general_alphaScheme_UFO.tar.gz	SMEFTsim_A_general_MwScheme_UFO.tar.gz	SMEFT_alpha_UFO.zip	SMEFT_mW_UFO.zip
MFV SMEFT	SMEFTsim_A_MFV_alphaScheme_UFO.tar.gz	SMEFTsim_A_MFV_MwScheme_UFO.tar.gz	SMEFT_alpha_MFV_UFO.zip	SMEFT_mW_MFV_UFO.zip
$U(3)^5$ SMEFT	SMEFTsim_A_U35_alphaScheme_UFO.tar.gz	SMEFTsim_A_U35_MwScheme_UFO.tar.gz	SMEFT_alpha_FLU_UFO.zip	SMEFT_mW_FLU_UFO.zip