The SMEFTsim package

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

Brivio, Jiang, Trott JHEP 1712 (2017) 070

arXiv: 1709.06492

The Niels Bohr International Academy

Outline

- Motivation: global SMEFT analysis @LHC
- What is SMEFTsim?
  - main characteristics
  - some details on the theory implementation
  - some technical specifications
- Validation
- Example of application: $h \to 4f$
- What's next?

The SMEFT for LHC experiments

lack of direct discoveries so far → systematic **indirect searches** needed

SMEFT is the best tool for this!

- reasonably **model-independent**
- **complete & well-defined** → long-term, extensible analysis plan
  → combination with other experiments

Most agnostic approach: minimize UV assumptions & arbitrary simplification

→ compute with the **full dim. 6 basis** ⇝ Mike's talk

- avoids theory inconsistencies / basis dependence
- allows one-loop improvement, RGE etc
- provides a universal language
- requires a dedicated tool for signal generation

The SMEFTsim package

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

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

1. the complete B-conserving Warsaw basis for 3 generations,
   including all complex phases and ~~CP~~ terms
   set up for unitary gauge, fermion mass basis

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

$\rightsquigarrow$ **backup**

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

Main scope:

estimate **LO SMEFT effects**: uncertainty is $\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) \rightarrow$ theo. accuracy $\gtrsim 1\%$

NLO not supported.

Shifts from input parameters

when testing a theory:

set of input measurements

SM:

$\Gamma(\mu \to e\nu\nu) \to \hat{G}_F(\bar{g}_1, \bar{g}_2, \bar{v})$
$\hat{m}_Z(\bar{g}_1, \bar{g}_2, \bar{v})$
Coulomb potential$\to \hat{\alpha_{\rm em}}(\bar{g}_1, \bar{g}_2)$
$\hat{m}_h(\bar{\lambda}, \bar{v})$
$\hat{m}_f(\bar{y}_f, \bar{v})$
$\vdots$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:

set of input measurements → infer numerical values to theory parameters

SM:

invert the relations:

$$\bar{v} = \hat{v}(\hat{G}_F)$$
$$\bar{\lambda} = \hat{\lambda}(\hat{m}_h, \hat{G}_F)$$
$$\bar{y}_f = \hat{y}_f(\hat{m}_f, \hat{G}_F)$$
$$\bar{g}_1 = \hat{g}_1(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z)$$
$$\bar{g}_2 = \hat{g}_2(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z)$$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:

set of input measurements → infer numerical values to theory parameters → numerical prediction of other observables

SM:

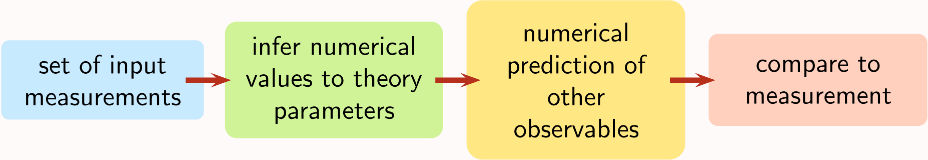
analytic calculations
Monte Carlo generation
...

e.g. at LO
$\bar{m}_W = \bar{m}_Z \cos\bar{\theta}$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:



SM:

$$\hat{m}_W \stackrel{?}{=} \bar{m}_W$$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:

set of input measurements → infer numerical values to theory parameters → numerical prediction of other observables → compare to measurement

SMEFT:

$\Gamma(\mu \to e\nu\nu) \to \hat{G}_F(\bar{g}_1, \bar{g}_2, \bar{v}, \mathbf{C_i})$
$\hat{m}_Z(\bar{g}_1, \bar{g}_2, \bar{v}, \mathbf{C_i})$
Coulomb potential$\to \hat{\alpha_{\rm em}}(\bar{g}_1, \bar{g}_2, \mathbf{C_i})$
$\hat{m}_h(\bar{\lambda}, \bar{v}, \mathbf{C_i})$
$\hat{m}_f(\bar{y}_f, \bar{v}, \mathbf{C_i})$
$\vdots$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Shifts from input parameters

when testing a theory:

set of input measurements → infer numerical values to theory parameters → numerical prediction of other observables → compare to measurement

SMEFT:

invert the relations linearizing the C_i dependence

$$\bar{v} = \hat{v}(\hat{G}_F) + \delta v$$
$$\bar{\lambda} = \hat{\lambda}(\hat{m}_h, \hat{G}_F) + \delta\lambda$$
$$\bar{y}_f = \hat{y}_f(\hat{m}_f, \hat{G}_F) + \delta y_f$$
$$\bar{g}_1 = \hat{g}_1(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z) + \delta g_1$$
$$\bar{g}_2 = \hat{g}_2(\hat{\alpha_{\rm em}}, \hat{G}_F, \hat{m}_Z) + \delta g_2$$

in a numeric code: convenient to replace
$\bar{X} \to \hat{X} + \delta X$ everywhere in $\mathcal{L}$

$\bar{X}$ = parameter in canonical $\mathcal{L}$. $\hat{X}$ = parameter inferred from SM relations.

Input parameter schemes for the EW sector

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

$$\hat{\alpha_{\rm em}} = \frac{\bar g_1 \bar g_2}{\bar g_1^2 + \bar g_2^2}\left[1 + \frac{\bar v^2}{\Lambda^2}\frac{\bar g_2^3/\bar g_1}{\bar g_1^2+\bar g_2^2} C_{HWB}\right]$$

$$\hat m_Z^2 = \frac{(\bar g_1^2 + \bar g_2^2)\bar v^2}{2} + \Delta m_Z^2 \qquad \Delta m_Z^2 = m_Z^2 \frac{\hat v^2}{\Lambda^2}\left[\frac{C_{HD}}{2} + \frac{2\bar g_1 \bar g_2}{\bar g_1^2+\bar g_2^2} C_{HWB}\right]$$

$$\hat G_f = \frac{1}{\sqrt{2}\bar v^2} + \Delta G_F \qquad \Delta G_f = \frac{\hat v^2}{\sqrt{2}\Lambda^2}\left[(C_{Hl}^{(3)})_{11} + (C_{Hl}^{(3)})_{22} - (C_{ll})_{1221}\right]$$

$\downarrow$

$$\delta v^2 = \frac{\Delta G_F}{G_F}$$

$$\delta g_1 = \frac{s_{\hat\theta}^2}{2(1-2s_{\hat\theta}^2)}\left(\sqrt{2}\Delta G_f + \frac{\Delta m_Z^2}{m_Z^2} + 2\frac{c_{\hat\theta}^3}{s_{\hat\theta}} C_{HWB}\hat v^2\right), \qquad s_{\hat\theta}^2 = \frac{1}{2}\left[1 - \sqrt{1 - \frac{4\pi\hat{\alpha_{\rm em}}}{\sqrt{2}\hat G_F \hat m_Z^2}}\right]$$

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

Input parameter schemes for the EW sector

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

$\rightsquigarrow$ Mike's talk

$$\hat{m}_W = \frac{\bar{g}_2^2 \bar{v}^2}{2}$$

$$\hat{m}_Z^2 = \frac{(\bar{g}_1^2 + \bar{g}_2^2)\bar{v}^2}{2} + \Delta m_Z^2 \qquad \Delta m_Z^2 = m_Z^2 \frac{\hat{v}^2}{\Lambda^2}\left[\frac{C_{HD}}{2} + 2c_{\hat{\theta}} s_{\hat{\theta}} C_{HWB}\right]$$

$$\hat{G}_f = \frac{1}{\sqrt{2}\bar{v}^2} + \Delta G_F \qquad \Delta G_f = \frac{\hat{v}^2}{\sqrt{2}\Lambda^2}\left[(C_{Hl}^{(3)})_{11} + (C_{Hl}^{(3)})_{22} - (C_{ll})_{1221}\right]$$

$\downarrow$

$$\delta v = \frac{\Delta G_F}{G_F}$$

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

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

SMEFTsim – implementations

6 different implementations available

Brivio, Jiang, Trott 1709.06492

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

× 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

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

---

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 81 C_i parameters (incl. phases)

Examples:

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

SMEFTsim - available flavor assumptions

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

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

- $C_i \in \mathbb{R}$

129 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.:

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

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

$$\hookrightarrow \bar{u}_L \gamma^\mu \left[\mathbb{1} + Y_u^\dagger Y_u + V_{\rm CKM} Y_d^\dagger Y_d V_{\rm CKM}^\dagger\right] u_L$$

$$+ \bar{d}_L \gamma^\mu \left[\mathbb{1} + V_{\rm CKM}^\dagger Y_u^\dagger Y_u V_{\rm CKM} + Y_d^\dagger Y_d\right] d_L$$

SMEFTsim - further specifications

- **SM** Higgs couplings HGG, $H\gamma\gamma$, $HZ\gamma$ included as effective vertices
  loop functions $I(m_t, m_W)$ hard coded in the couplings
  interaction order `SMHLOOP` associated to these terms

- interaction order `NP` associated to SMEFT parameters
  → in MG5: impose only 1 op./diagram with `NP<=1`
  → generate pure interference / quadratic with `NP^2==1, 2`

- restriction cards: `SMlimit`, `massless`, `CPconserving`,
  top physics flavor assumptions ($U(2)^5$, only for general UFO)

- SMEFTsim supports the `WCxf` exchange format
  `wcxf2smeftsim` → `param_card.dat`

Aebischer et al. 1712.05298
`https://wcxf.github.io`

⇝ Jacky's talk

- `Mathematica` notebook for analytic Feynman rules also available!

SMEFTsim validation

1. Internal validation: 2 independent versions (A, B)

σ(SM+int+quadratic) for $C_i = 1$, $\Lambda = 1$ TeV

process	coefficient	general α	general Mw	U(3)^5 α	U(3)^5 Mw	MFV α	MFV Mw
e+ e- > w+ w-	SMlimit	2.6156 0.059793	2.6788 0.061373	2.6156 0.059793	2.6788 0.061373	2.6156 0.059793	2.6788 0.061373
e+ e- > w+ w- NP=1	Hl3	-	-	4.3384 0.10296	4.4249 0.094337	4.3384 0.10296	4.4249 0.094337
e+ e- > w+ w- NP=1	Hl311	4.6686 0.098776	4.7797 0.10282	-	-	-	-
e+ e- > w+ w- NP=1	W	4.9648 0.10804	5.06 0.11063	4.9648 0.10804	5.06 0.11063	4.9648 0.10804	5.06 0.11063
e+ e- > w+ w- NP=1	Wtil	4.9895 0.10855	5.0848 0.1111	4.9895 0.10855	5.0848 0.1111	-	-
e+ e- > z h	SMlimit	0.013009 0.000032914	0.01302 0.000033124	0.013009 0.000032914	0.01302 0.000033124	0.013009 0.000032914	0.01302 0.000033124
e+ e- > z h NP=1	eW	-	-	0.013009 0.000032914	0.01302 0.000033124	0.013009 0.000032914	0.01302 0.000033124
e+ e- > z h NP=1	eW11	1.9983 0.0050475	0.01302 0.000033124	-	-	-	-
e+ e- > z h NP=1	He	-	-	1.1756 0.0031	1.1838 0.0031194	1.1756 0.0031	1.1838 0.0031194
e+ e- > z h NP=1	He11	1.1756 0.0031	1.1838 0.0031194	-	-	-	-
e+ e- > z h NP=1	HWB	0.040274 0.00009404	0.036476 0.000084148	0.040274 0.00009404	0.036476 0.000084148	0.040274 0.00009404	0.036476 0.000084148
p p > d s~	SMlimit	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.
p p > d s~ NP=1	Delta2qd1	-	-	-	-	690 240. 9319.7	690 240. 9319.7
p p > d s~ NP=1	DeltadHq3	-	-	-	-	703 760. 9607.7	703 760. 9607.7
p p > d s~ NP=1	DeltadW	-	-	-	-	690 240. 9319.7	690 240. 9319.7
p p > d s~ NP=1	dW	-	-	690 240. 9319.7	690 240. 9319.7	-	-
p p > d s~ NP=1	dW12	692 740. 9950.4	690 240. 9319.7	-	-	-	-
p p > d s~ NP=1	Hq312	706 050. 9205.5	706 050. 9205.5				

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err

MG5 results with set A

SMEFTsim validation

1. Internal validation: 2 independent versions

3 flavor assum. $\times$ 2 schemes

σ(SM+int+quadratic) for $C_i = 1$, $\Lambda = 1$ TeV

process	coefficient	general α	general Mw	U(3)^5 α	U(3)^5 Mw	MFV α	MFV Mw
e+ e- > w+ w-	SMlimit	2.6156 0.059793	2.6788 0.061373	2.6156 0.059793	2.6788 0.061373	2.6156 0.059793	2.6788 0.061373
e+ e- > w+ w- NP=1	Hl3	-	-	4.3384 0.10296	4.4249 0.094337	4.3384 0.10296	4.4249 0.094337
e+ e- > w+ w- NP=1	Hl311	4.6686 0.098776	4.7797 0.10282	-	-	-	-
e+ e- > w+ w- NP=1	W	4.9648 0.10804	5.06 0.11063	4.9648 0.10804	5.06 0.11063	4.9648 0.10804	5.06 0.11063
e+ e- > w+ w- NP=1	Wtil	4.9895 0.10855	5.0848 0.1111	4.9895 0.10855	5.0848 0.1111	-	-
e+ e- > z h	SMlimit	0.013009 0.000032914	0.01302 0.000033124	0.013009 0.000032914	0.01302 0.000033124	0.013009 0.000032914	0.01302 0.000033124
e+ e- > z h NP=1	eW	-	-	0.013009 0.000032914	0.01302 0.000033124	0.013009 0.000032914	0.01302 0.000033124
e+ e- > z h NP=1	eW11	1.9983 0.0050475	0.01302 0.000033124	-	-	-	-
e+ e- > z h NP=1	He	-	-	1.1756 0.0031	1.1838 0.0031194	1.1756 0.0031	1.1838 0.0031194
e+ e- > z h NP=1	He11	1.1756 0.0031	1.1838 0.0031194	-	-	-	-
e+ e- > z h NP=1	HWB	0.040274 0.00009404	0.036476 0.000084148	0.040274 0.00009404	0.036476 0.000084148	0.040274 0.00009404	0.036476 0.000084148
p p > d s~	SMlimit	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.	688 390. 11 858.
p p > d s~ NP=1	Delta2qd1	-	-	-	-	690 240. 9319.7	690 240. 9319.7
p p > d s~ NP=1	DeltadHq3	-	-	-	-	703 760. 9607.7	703 760. 9607.7
p p > d s~ NP=1	DeltadW	-	-	-	-	690 240. 9319.7	690 240. 9319.7
p p > d s~ NP=1	dW	-	-	690 240. 9319.7	690 240. 9319.7	-	-
[illegible]	W12	692 740. 9950.4	690 240. 9319.7	-	-	-	-
[illegible]	312	706 050. 9205.5	706 050. 9205.5				

5–10 coeff. $\times$ $\sim$ 20 processes

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err

MG5 results with set A

SMEFTsim validation

1. Internal validation: 2 independent versions (A, B)

2. Validation against `dim6top`

feynrules.irmp.ucl.ac.be/wiki/dim6top – G.Durieux,C.Zhang

Top WG note: Aguilar-Saavedra et al. 1802.07237

$\sigma(\text{int.})/\sigma(\text{SM})$ for $C_i = 1$, $\Lambda = 1$ TeV [permille]

		$pp \to t\bar{t}$	$pp \to t\bar{t}\,b\bar{b}$	$pp \to t\bar{t}\,t\bar{t}$	$pp \to t\bar{t}\,e^+\nu$	$pp \to t\bar{t}\,e^+e^-$	$pp \to t\bar{t}\,\gamma$	$pp \to t\bar{t}\,h$	$pp \to tj$	$pp \to t\,e^-\bar{\nu}$	$pp \to tj\,e^+e^-$	$pp \to tj\,\gamma$	$pp \to tj\,h$
SM	sm	5.2×10^2 pb	1.9 pb	0.0098 pb	0.02 pb	0.016 pb	1.4 pb	0.4 pb	55 pb	2.5 pb	0.0054 pb	0.39 pb	0.016 pb
c_{QQ}^{1}	cQQ1	-0.25	-1.9	-1×10^2		-1.6	-0.67	-0.71					
c_{QQ}^{8}	cQQ8	-0.16	-3.2	-34		-0.91	-0.5	-0.27					
c_{Qt}^{1}	cQt1	-0.15	-5.6	1×10^2		-0.76	-0.19	-0.55					
c_{Qt}^{8}	cQt8	-0.053	-1.8	-41		-0.18	-0.095	-0.15					
c_{Qb}^{1}	cQb1	-0.0055	0.72	-0.052		-0.015	-0.007	-0.026					
c_{Qb}^{8}	cQb8	0.14	3.9	0.12		0.35	0.16	0.56					
c_{tt}^{1}	ctt1			-1.8×10^2									
c_{tb}^{1}	ctb1	-0.0095	0.46	-0.059		-0.02	-0.026	-0.039					
c_{tb}^{8}	ctb8	0.13	3.5	0.11		0.26	0.31	0.56					
c_{QtQb}^{1}	cQtQb1												
c_{QtQb}^{8}	cQtQb8												
c_{QtQb}^{1I}	cQtQb1I												
c_{QtQb}^{8I}	cQtQb8I												
$c_{Qq}^{3,8}$	cQq83	2.7	-0.11	4.7	-85	-20	8.5	15	-3.4×10^{-15}		-6.4×10^{-15}	-5.2×10^{-15}	-4.1×10^{-15}
$c_{Qq}^{1,8}$	cQq81	12	7.1	25	2.6×10^2	71	40	75					
c_{tq}^{8}	ctq8	13	8.2	27	2.6×10^2	62	51	74					
c_{Qu}^{8}	cQu8	7.4	4.4	18		21	41	44					
c_{tu}^{8}	ctu8	7.4	3	16		14	22	45					
c_{Qd}^{8}	cQd8	5	3	11		17	7.3	29					
c_{td}^{8}	ctd8	5	2.1	10		12	10	28					
$c_{Qq}^{3,1}$	cQq13	3.3	3	5.8	1.1×10^2	22	11	18	-3.8×10^2		-7.9×10^2	-6.1×10^2	-4.6×10^2
$c_{Qq}^{1,1}$	cQq11	0.94	-1.4	-7.7	-5.9	-5	3	5.4					
c_{tq}^{1}	ctq1	0.65	2.4	-7.9	8.7	0.84	3.7	4.8					
c_{Qu}^{1}	cQu1	0.57	1.5	-5.2		1.5	2.9	4.3					
c_{tu}^{1}	ctu1	1.1	-0.29	-3.8		2.3	3.3	6.6					
c_{Qd}^{1}	cQd1	-0.19	0.55	-4		-0.66	-0.3	-1.4					
c_{td}^{1}	ctd1	-0.37	-1.3	-5		-0.91	-1.3	-2.1					
$c_{t\varphi}$	ctp		-0.00035	-9.1	-0.034	-0.0093		-1.2×10^2					-68
$c_{\varphi Q}^{-}$	cpQM	-0.063	1	-41	-0.76	-1×10^2	-0.13	-0.29			21		
$c_{\varphi Q}^{3}$	cpQ3	0.68	22	0.065	0.46	3.7	1.5	1.8	1.2×10^2	1.2×10^2	2.2×10^2	1.2×10^2	1.3×10^2
$c_{\varphi t}$	cpt	-0.024	2.8	42	-0.36	68	-0.058	-0.16			5.2		
$c_{\varphi tb}$	cptb												
c_{tW}	ctW	0.98	1	-34	13	1.1	69	9.4	84	-76	45	50	9.1×10^2
c_{tZ}	ctZ	-0.54	0.028	27	-0.048	-3.6	-55	-4.3			-10	-6	
c_{bW}	cbW												
c_{tG}	ctG	2.7×10^2	2.5×10^2	3.8×10^2	2.4×10^2	3.1×10^2	2.4×10^2	8.4×10^2		59			
$c_{t\varphi}^{I}$	ctpI		-7.3×10^{-7}	0.045	-0.00064	-0.00029		0.045					-0.21
$c_{\varphi tb}^{I}$	cptbI												
c_{tW}^{I}	ctWI	4.8×10^{-6}	0.032	-1.6	-0.19	0.29	0.91	0.031	1.6×10^{-16}	-1.4	0.47	0.022	-0.13
c_{tZ}^{I}	ctZI	-1.4×10^{-6}	0.1	-1.2	0.0098	3.2	-0.56	-0.057			-0.87	0.67	
c_{bW}^{I}	cbWI												
c_{tG}^{I}	ctGI	-0.00098	0.48	0.66	0.031	-0.7	0.019	-2.4		0.4			
$c_{Ql}^{3(1)}$	cQl31				0.011	0.06				4.1	6		
$c_{Ql}^{-(1)}$	cQlM1				-0.0062	-9.8					2.2		
$c_{Qe}^{(1)}$	cQe1					-1.5					-0.39		
$c_{tl}^{(1)}$	ctl1				-0.0023	-3.6					-0.036		
$c_{te}^{(1)}$	cte1					-6.7					0.064		

SMEFTsim validation

1. Internal validation: 2 independent versions (A, B)

2. Validation against `dim6top`

feynrules.irmp.ucl.ac.be/wiki/dim6top – G.Durieux,C.Zhang

Top WG note: Aguilar-Saavedra et al. 1802.07237

$\sigma(\text{int.})/\sigma(\text{SM})$ for $C_i = 1$, $\Lambda = 1$ TeV [permille]

		$pp \to t\bar{t}$	$pp \to t\bar{t}\,b\bar{b}$	$pp \to t\bar{t}\,t\bar{t}$	$pp \to t\bar{t}\,e^+\nu$	$pp \to t\bar{t}\,e^+e^-$	$pp \to t\bar{t}\,\gamma$	$pp \to t\bar{t}\,h$
SM	sm	5.2×10^2 pb	1.9 pb	0.0098 pb	0.02 pb	0.016 pb	1.4 pb	0.4 pb
c^1_{QQ}	cQQ1	−0.25	−1.9	-1×10^2		−1.6	−0.67	−0.71
c^8_{QQ}	cQQ8	−0.16	−3.2	−34		[illegible]	−0.5	−0.27
c^1_{Qt}	cQt1	−0.15	−5.6	1×10^2		[illegible]	−0.19	−0.55
c^8_{Qt}	cQt8	−0.053	−1.8	−41		−0.18	−0.095	−0.15
c^1_{Qb}	cQb1	−0.0055	0.72	−0.052		−0.015	−0.007	−0.026
c^8_{Qb}	cQb8	0.14	3.9	0.12		0.35	[illegible]	0.56
c^1_{tt}	ctt1			-1.8×10^2				
c^1_{tb}	ctb1	−0.0095	0.46	−0.059		−0.02	[illegible]	−0.039
c^8_{tb}	ctb8	0.13	3.5	0.11		0.26	0.31	0.56
c^1_{QtQb}	cQtQb1							
c^8_{QtQb}	cQtQb8							
c^{1I}_{QtQb}	cQtQb1I							
c^{8I}_{QtQb}	cQtQb8I							
$c^{3,8}_{Qq}$	cQq83	2.7	−0.11	4.7	−85	−20	8.5	15
$c^{1,8}_{Qq}$	cQq81	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{tq}	ctq8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{Qu}	cQu8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{tu}	ctu8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{Qd}	cQd8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{td}	ctd8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$c^{3,1}_{Qq}$	cQq13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$c^{1,1}_{Qq}$	cQq11	0.94	−1.4	−7.7	−5.9	−5	3	5.4
c^1_{tq}	ctq1	0.65	2.4	−7.9	8.7	0.84	3.7	4.8
c^1_{Qu}	cQu1	0.57	1.5	−5.2		1.5	2.9	4.3
c^1_{tu}	ctu1	1.1	−0.29	−3.8		2.3	3.3	6.6
c^1_{Qd}	cQd1	−0.19	0.55	−4		−0.66	−0.3	−1.4
c^1_{td}	ctd1	−0.37	−1.3	−5		−0.91	−1.3	−2.1
$c_{t\varphi}$	ctp		−0.00035	−9.1	−0.034	−0.0093		-1.2×10^2
$c^-_{\varphi Q}$	cpQM	−0.063	1	−41	−0.76	-1×10^2	−0.13	−0.29
$c^3_{\varphi Q}$	cpQ3	0.68	22	0.065	0.46	3.7	1.5	1.8
$c_{\varphi t}$	cpt	−0.024	2.8	42	−0.36	68	−0.058	−0.16
$c_{\varphi tb}$	cptb							
c_{tW}	ctW	0.98	1	−34	13	1.1	69	9.4
c_{tZ}	ctZ	−0.54	0.028	27	−0.048	−3.6	−55	−4.3
c_{bW}	cbW							
c_{tG}	ctG	2.7×10^2	2.5×10^2	3.8×10^2	2.4×10^2	3.1×10^2	2.4×10^2	8.4×10^2
$c^I_{t\varphi}$	ctpI		-7.3×10^{-7}	0.045	−0.00064	−0.00029		0.045
$c^I_{\varphi tb}$	cptbI							
c^I_{tW}	ctWI	4.8×10^{-6}	0.032	−1.6	−0.19	0.29	0.91	0.031
c^I_{tZ}	ctZI	-1.4×10^{-6}	0.1	−1.2	0.0098	3.2	−0.56	−0.057
c^I_{bW}	cbWI							
c^I_{tG}	ctGI	−0.00098	0.48	0.66	0.031	−0.7	0.019	−2.4
$c^{3(1)}_{Ql}$	cQl31				0.011	0.06		
$c^{-(1)}_{Ql}$	cQlM1				−0.0062	−9.8		
$c^{(1)}_{Qe}$	cQe1					−1.5		
$c^{(1)}_{tl}$	ctl1				−0.0023	−3.6		
$c^{(1)}_{te}$	cte1					−6.7		

		$pp \to tj$	$pp \to t\,e^-\bar{\nu}$	$pp \to tj\,e^+e^-$	$pp \to tj\,\gamma$	$pp \to tj\,h$
SM	sm	55 pb	2.5 pb	0.0054 pb	0.39 pb	0.016 pb
$c^{3,8}_{Qq}$	cQq83	[illegible]		-6.4×10^{-15}	-5.2×10^{-15}	-4.1×10^{-15}
$c^{3,1}_{Qq}$	cQq13	[illegible]		[illegible]	[illegible]	[illegible]
$c_{t\varphi}$	ctp					−68
$c^-_{\varphi Q}$	cpQM			21		
$c^3_{\varphi Q}$	cpQ3	1.2×10^2	1.2×10^2	2.2×10^2	1.2×10^2	1.3×10^2
$c_{\varphi t}$	cpt			5.2		
c_{tW}	ctW	84	−76	45	50	9.1×10^2
c_{tZ}	ctZ			−10	−6	
c_{tG}	ctG		59			
$c^I_{t\varphi}$	ctpI					−0.21
c^I_{tW}	ctWI	1.6×10^{-16}	−1.4	0.47	0.022	−0.13
c^I_{tZ}	ctZI			−0.87	0.67	
c^I_{tG}	ctGI		0.4			
$c^{3(1)}_{Ql}$	cQl31		4.1	6		
$c^{-(1)}_{Ql}$	cQlM1			2.2		
$c^{(1)}_{Qe}$	cQe1			−0.39		
$c^{(1)}_{tl}$	ctl1			−0.036		
$c^{(1)}_{te}$	cte1			0.064		

12 top processes

$pp \to t\bar{t}$	$pp \to t\bar{t}\,b\bar{b}$	$pp \to t\bar{t}\,t\bar{t}$	$pp \to t\bar{t}\,e^+\nu$	$pp \to t\bar{t}\,e^+e^-$	$pp \to t\bar{t}\,\gamma$
$pp \to t\bar{t}\,h$	$pp \to tj$	$pp \to t\,e^-\bar{\nu}$	$pp \to tj\,e^+e^-$	$pp \to tj\,\gamma$	$pp \to tj\,h$

SMEFTsim validation

1. Internal validation: 2 independent versions (A, B)

2. Validation against `dim6top`

feynrules.irmp.ucl.ac.be/wiki/dim6top – G.Durieux,C.Zhang

Top WG note: Aguilar-Saavedra et al. 1802.07237

$\sigma(\text{int.})/\sigma(\text{SM})$ for $C_i = 1$, $\Lambda = 1$ TeV [permille]

		$pp \to t\bar{t}$	$pp \to t\bar{t}\,b\bar{b}$	$pp \to t\bar{t}\,t\bar{t}$	$pp \to t\bar{t}\,e^+\nu$	$pp \to t\bar{t}\,e^+e^-$	$pp \to t\bar{t}\,\gamma$	$pp \to t\bar{t}\,h$	$pp \to tj$	$pp \to t\,e^-\bar{\nu}$	$pp \to tj\,e^+e^-$	$pp \to tj\,\gamma$	$pp \to tj\,h$
SM	sm	5.2×10^2 pb	1.9 pb	0.0098 pb	0.02 pb	0.016 pb	1.4 pb	0.4 pb	55 pb	2.5 pb	0.0054 pb	0.39 pb	0.016 pb
c^{1}_{QQ}	cQQ1	−0.25	−1.9	-1×10^2		−1.6	−0.67	−0.71					
c^{8}_{QQ}	cQQ8	−0.16	−3.2	−34		−0.91	−0.5	−0.27					
c^{1}_{Qt}	cQt1	−0.15	−5.6	1×10^2		−0.76	−0.19	−0.55					
c^{8}_{Qt}	cQt8	−0.053	−1.8	−41		−0.18	−0.095	−0.15					
c^{1}_{Qb}	cQb1	−0.0055	0.72	−0.052		−0.015	−0.007	−0.026					
c^{8}_{Qb}	cQb8	0.14	3.9	0.12		0.35	0.16	0.56					
c^{1}_{tt}	ctt1			-1.8×10^2									
c^{1}_{tb}	ctb1	−0.0095	0.46	−0.059		−0.02	−0.026	−0.039					
c^{8}_{tb}	ctb8	0.13	3.5	0.11		0.26	0.31	0.56					
c^{1}_{QtQb}	cQtQb1												
c^{8}_{QtQb}	cQtQb8												
c^{1I}_{QtQb}	cQtQb1I												
c^{8I}_{QtQb}	cQtQb8I												
$c^{3,8}_{Qq}$	cQq83	2.7	−0.11	4.7	−85	−20	8.5	15	-3.4×10^{-15}		-6.4×10^{-15}	-5.2×10^{-15}	-4.1×10^{-15}
$c^{1,8}_{Qq}$	cQq81	12	7.1	25	2.6×10^2	71	40	75					
c^{8}_{tq}	ctq8	13	[illegible]	[illegible]	2.6×10^2	[illegible]	[illegible]	[illegible]					
c^{8}_{Qu}	cQu8												
c^{8}_{tu}	ctu8												
c^{8}_{Qd}	cQd8												
c^{8}_{td}	ctd8												
$c^{3,1}_{Qq}$	cQq13												
$c^{1,1}_{Qq}$	cQq11												
c^{1}_{tq}	[illegible]												
c^{1}_{Qu}	[illegible]												
c^{1}_{tu}	ctu[illegible]												
c^{1}_{Qd}	cQd1												
c^{1}_{td}	ctd1												
$c_{t\varphi}$	ctp												
$c^{-}_{\varphi Q}$	cpQM												
$c^{3}_{\varphi Q}$	cpQ3												
$c_{\varphi t}$	cpt												
$c_{\varphi tb}$	cptb												
c_{tW}	ctW												
c_{tZ}	ctZ												
c_{bW}	cbW												
c_{tG}	ctG												
$c^{I}_{t\varphi}$	ctpI												
$c^{I}_{\varphi tb}$	cptbI												
c^{I}_{tW}	ctWI												
c^{I}_{tZ}	ctZI												
c^{I}_{bW}	cbWI												
c^{I}_{tG}	ctGI												
$c^{3(1)}_{Ql}$	cQl31												
$c^{-(1)}_{Ql}$	cQlM1												
$c^{(1)}_{Qe}$	cQe1					−1.5					−0.39		
$c^{(1)}_{tl}$	ctl1				−0.0023	−3.6					−0.036		
$c^{(1)}_{te}$	cte1					−6.7					0.064		

12 top processes

$\sim$ 50 coefficients

Warsaw basis with specific flavor assumption. e.g.:

$$c^{1}_{QQ} \equiv 2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq} \qquad c^{8}_{QQ} \equiv 8C^{3(3333)}_{qq}$$

$$c^{1}_{Qt} \equiv C^{1(3333)}_{qu} \qquad c^{8}_{Qt} \equiv C^{8(3333)}_{qu}$$

$$c^{3,1}_{Qq} \equiv C^{3(ii33)}_{qq} + \frac{1}{6}\left(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}\right) \qquad c^{3,8}_{Qq} \equiv C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$$

$$c^{1,1}_{Qq} \equiv C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq} \qquad c^{1,8}_{Qq} \equiv C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$$

$$c^{[I]}_{t\varphi} \equiv {}^{[Im]}_{Re}\{C^{(33)}_{uH}\} \qquad c^{-}_{Hq} \equiv C^{1(33)}_{Hq} - C^{3(33)}_{Hq}$$

$$c^{3}_{HQ} \equiv C^{3(33)}_{Hq} \qquad c_{Ht} \equiv C^{(33)}_{Hu}$$

SMEFTsim validation

1. Internal validation: 2 independent versions (A, B)

2. Validation against `dim6top`

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Top WG note: Aguilar-Saavedra et al. 1802.07237

$\sigma(\text{int.})/\sigma(\text{SM})$ for $C_i = 1$, $\Lambda = 1$ TeV [permille]

		$pp \to t\bar{t}$	$pp \to t\bar{t}\,b\bar{b}$	$pp \to t\bar{t}\,t\bar{t}$	$pp \to t\bar{t}\,e^+\nu$	$pp \to t\bar{t}\,e^+e^-$	$pp \to t\bar{t}\,\gamma$	$pp \to t\bar{t}\,h$	$pp \to tj$	$pp \to t\,e^-\bar{\nu}$	$pp \to tj\,e^+e^-$	$pp \to tj\,\gamma$	$pp \to tj\,h$
SM	sm	5.2×10^2 pb	1.9 pb	0.0098 pb	0.02 pb	0.016 pb	1.4 pb	0.4 pb	55 pb	2.5 pb	0.0054 pb	0.39 pb	0.016 pb
c^1_{QQ}	cQQ1	−0.25	−1.9	-1×10^2		−1.6	−0.67	−0.71					
c^8_{QQ}	cQQ8	−0.16	−3.2	−34		−0.91	−0.5	−0.27					
c^1_{Qt}	cQt1	−0.15	−5.6	1×10^2		−0.76	−0.19	−0.55					
c^8_{Qt}	cQt8	−0.053	−1.8	−41		−0.18	−0.095	−0.15					
c^1_{Qb}	cQb1	−0.0055	0.72	−0.052		−0.015	−0.007	−0.026					
c^8_{Qb}	cQb8	0.14	3.9	0.12		0.35	0.16	0.56					
c^1_{tt}	ctt1			-1.8×10^2									
c^1_{tb}	ctb1	−0.0095	0.46	−0.059		−0.02	−0.026	−0.039					
c^8_{tb}	ctb8	0.13	3.5	0.11		0.26	0.31	0.56					
c^1_{QtQb}	cQtQb1												
c^8_{QtQb}	cQtQb8												
c^{1I}_{QtQb}	cQtQb1I												
c^{8I}_{QtQb}	cQtQb8I												
$c^{3,8}_{Qq}$	cQq83	2.7	−0.11	4.7	−85	−20	8.5	15	-3.4×10^{-15}		-6.4×10^{-15}	-5.2×10^{-15}	-4.1×10^{-15}
$c^{1,8}_{Qq}$	cQq81	12	7.1	25	2.6×10^2	71	40	75					
c^8_{tq}	ctq8	13	8.2	27	2.6×10^2	62	51	74					
c^8_{Qu}	cQu8	7.4	4.4	18		21	41	44					
c^8_{tu}	ctu8	7.4	3	16		14	22	45					
c^8_{Qd}	cQd8	5	3	11		17	7.3	29					
c^8_{td}	ctd8	5	2.1	10		12	10	28					
$c^{3,1}_{Qq}$	cQq13	3.3	3	5.8	1.1×10^2	22	11	18	-3.8×10^2		[illegible]		
$c^{1,1}_{Qq}$	cQq11	0.94	−1.4	−7.7	−5.9	−5	3	5.4					
c^1_{tq}	ctq1	0.65	2.4	−7.9	8.7	0.84	3.7	4.8					
c^1_{Qu}	cQu1	0.57	1.5	−5.2		1.5	2.9	4.3					
c^1_{tu}	ctu1	1.1	−0.29	−3.8		2.3	3.3	6.6					
c^1_{Qd}	cQd1	−0.19	0.55	−4		−0.66	−0.3	−1.4					
c^1_{td}	ctd1	−0.37	−1.3	−5		−0.91	−1.3	−2.1					
$c_{t\varphi}$	ctp		−0.00035	−9.1	−0.034	−0.0093		-1.2×10^2					
$c^-_{\varphi Q}$	cpQM	−0.063	1	−41	−0.76	-1×10^2	−0.13	−0.29					
$c^3_{\varphi Q}$	cpQ3	0.68	22	0.065	0.46	3.7	1.5	1.8	1.2×10^2	1.2×10^2	[illegible]		
$c_{\varphi t}$	cpt	−0.024	2.8	42	−0.36	68	−0.058	−0.16					
$c_{\varphi tb}$	cptb												
c_{tW}	ctW	0.98	1	−34	13	1.1	69	9.4	84	−76			
c_{tZ}	ctZ	−0.54	0.028	27	−0.048	−3.6	−55	−4.3			[illegible]	[illegible]	
c_{bW}	cbW												
c_{tG}	ctG	2.7×10^2	2.5×10^2	3.8×10^2	2.4×10^2	3.1×10^2	2.4×10^2	8.4×10^2		59			
$c^I_{t\varphi}$	ctpI		-7.3×10^{-7}	0.045	−0.00064	−0.00029		0.045					−0.21
$c^I_{\varphi tb}$	cptbI												
c^I_{tW}	ctWI	4.8×10^{-6}	0.032	−1.6	−0.19	0.29	0.91	0.031	1.6×10^{-16}	−1.4	0.47	0.022	−0.13
c^I_{tZ}	ctZI	-1.4×10^{-6}	0.1	−1.2	0.0098	3.2	−0.56	−0.057			−0.87	0.67	
c^I_{bW}	cbWI												
c^I_{tG}	ctGI	−0.00098	0.48	0.66	0.031	−0.7	0.019	−2.4		0.4			
$c^{3(1)}_{Ql}$	cQl31				0.011	0.06				4.1	6		
$c^{-(1)}_{Ql}$	cQlM1				−0.0062	−9.8					2.2		
$c^{(1)}_{Qe}$	cQe1					−1.5					−0.39		
$c^{(1)}_{tl}$	ctl1				−0.0023	−3.6					−0.036		
$c^{(1)}_{te}$	cte1					−6.7					0.064		

12 top processes

$\sim$ 50 coefficients

both interference and quadratic terms
$\downarrow$
1200+ numbers compared

SMEFTsim validation

1. Internal validation: 2 independent versions (A, B)

2. Validation against `dim6top`

   feynrules.irmp.ucl.ac.be/wiki/dim6top – G.Durieux,C.Zhang
   Top WG note: Aguilar-Saavedra et al. 1802.07237

3. Validation against `VBFNLO`

   Arnold et al. 0811.4559,1107.4038, Baglio et al 1404.3940
   VBSCan Thessaloniki Workshop summary. To appear.

`VBFNLO` has hard coded matrix elements for selected EW processes
uses HISZ basis→ could validate $O_{WWW} = \varepsilon_{ijk} W_\nu^{i\mu} W_\rho^{j\nu} W_\mu^{k\rho}$

checked: $pp \to e^+\nu_e\mu^+\mu^-$ and $pp \to e^+\nu_e\mu^+\nu_\mu jj$

LO, compared σ_{SM} + distributions

✔ $\mathcal{O}_{WWW}$ completes validation for diboson

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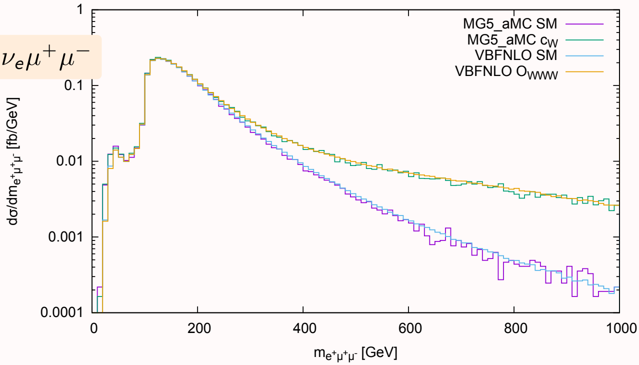
   VBSCan Thessaloniki Workshop summary. To appear.

$pp \to e^+\nu_e\mu^+\mu^-$



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3. Validation against `VBFNLO`

Arnold et al. 0811.4559,1107.4038, Baglio et al 1404.3940
VBSCan Thessaloniki Workshop summary. To appear.

4. Validation against `dim6top` and `SMEFT@NLO` using dedicated `MadGraph5` plugin

SMEFT MC validation group, CERN-LPCC-XXXX

SMEFTsim validation

1. Internal validation: 2 independent versions (A, B)

2. Validation against `dim6top`

   feynrules.irmp.ucl.ac.be/wiki/dim6top – G.Durieux,C.Zhang
   Top WG note: Aguilar-Saavedra et al. 1802.07237

3. Validation against `VBFNLO`

   Arnold et al. 0811.4559,1107.4038, Baglio et al 1404.3940
   VBSCan Thessaloniki Workshop summary. To appear.

4. Validation against `dim6top` and `SMEFT@NLO` using dedicated `MadGraph5` plugin

   SMEFT MC validation group, CERN-LPCC-XXXX

5. Validation against analytic expressions

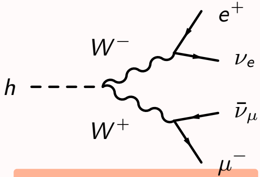
   Brivio,Trott SMEFT review 1706.08945
   Brivio,Corbett,Trott, to appear.
   Brivio,Hays,Trott,Žemaitytė, in preparation.

```
z > e+ e-                     z > u u~
w+ > l+ vl                    w+ > uq dq~

h > a a                       h > z a
h > b b                       h > ta+ ta-
h > e+ e- mu+ mu- / a         h > e+ ve mu- vm
p p > z h / a                 g g > h
p p > w+ h                    p p > w- h
...
```

SMEFTsim – practical use

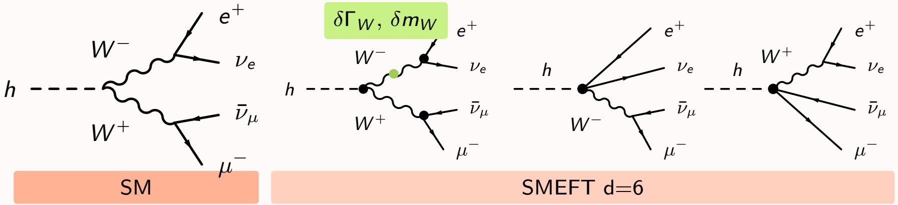
Example: SMEFT corrections to $\text{Br}(h \to e^+\nu_e\mu^-\bar{\nu}_\mu)$



SM

SMEFTsim – practical use

Example: SMEFT corrections to $\mathrm{Br}(h \to e^+ \nu_e \mu^- \bar{\nu}_\mu)$



- only 1 operator insertion / diagram. All corrections linearized.
- pick m_W as input parameter $\to \delta m_W = 0$

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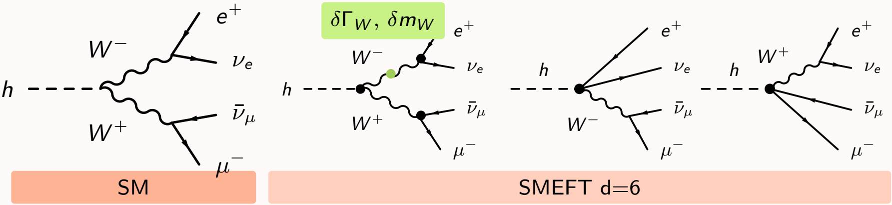

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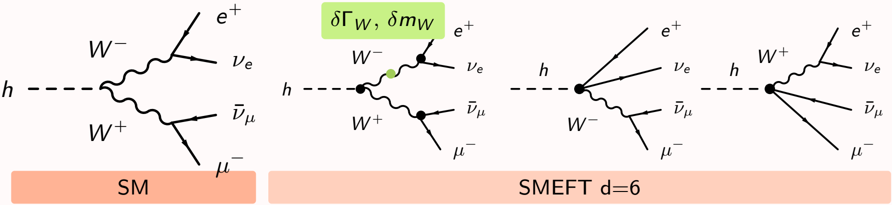
$$\mathrm{Br}(h \to 2\ell 2\nu) = \mathrm{Br}(h \to 2\ell 2\nu)_{SM}\left[1 + \frac{\delta\Gamma_{h\to 2\ell 2\nu}}{\Gamma_{h\to 2\ell 2\nu,SM}} - \frac{\delta\Gamma_H}{\Gamma_{H,SM}}\right]$$

SMEFTsim – practical use

Example: SMEFT corrections to $\mathrm{Br}(h \to e^+ \nu_e \mu^- \bar{\nu}_\mu)$



most accurate SM prediction

$$\mathrm{Br}(h \to 2\ell 2\nu) = \mathrm{Br}(h \to 2\ell 2\nu)_{SM} \left[1 + \frac{\delta\Gamma_{h\to 2\ell 2\nu}}{\Gamma_{h\to 2\ell 2\nu, SM}} - \frac{\delta\Gamma_H}{\Gamma_{H,SM}} \right]$$

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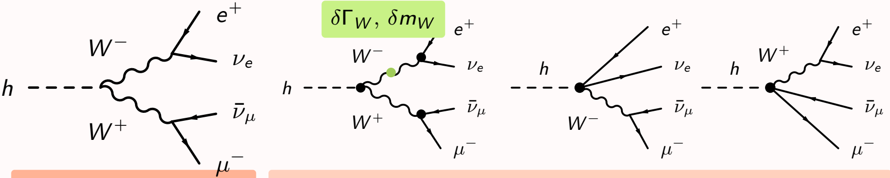

SM

SMEFT d=6

most accurate
SM prediction

$$\mathrm{Br}(h\to 2\ell 2\nu) = \mathrm{Br}(h\to 2\ell 2\nu)_{SM}\left[1+\frac{\delta\Gamma_{h\to 2\ell 2\nu}}{\Gamma_{h\to 2\ell 2\nu,SM}} - \frac{\delta\Gamma_H}{\Gamma_{H,SM}}\right]$$

SMEFTsim – practical use

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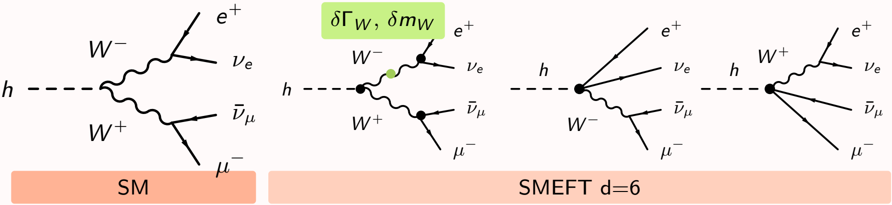

most accurate SM prediction

estimate with `MG5 + SMEFTsim` or analytically

$$\mathrm{Br}(h \to 2\ell 2\nu) = \mathrm{Br}(h \to 2\ell 2\nu)_{SM} \left[1 + \frac{\delta\Gamma_{h\to 2\ell 2\nu}}{\Gamma_{h\to 2\ell 2\nu, SM}} - \frac{\delta\Gamma_H}{\Gamma_{H,SM}} \right]$$

SMEFTsim – practical use

estimating $\delta\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e,SM}$

1.
```
import model SMEFTsim_A_U35_MwScheme_UFO-massless
```

SMEFTsim – practical use

estimating $\delta\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e,SM}$

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```
generate h > e+ ve mu- vm~  NP<=1 (NP^2==1)
```

`NP<=1` fixes max 1 op. insertion / diagram

with `NP^2==1`: interference only

SMEFTsim – practical use

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   – fix W width to SM value

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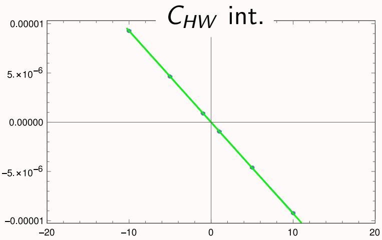
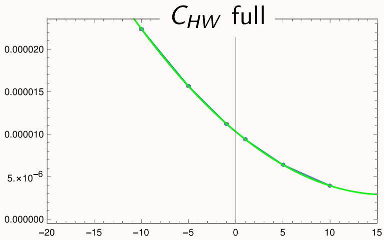
4.
```
launch
```

SMEFTsim – practical use

estimating $\delta\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e,SM}$

- estimate full $\Gamma(h\to W^+\mu^-\bar{\nu}_\mu)$ in SM limit
- estimate pure interference contribution with one C_i turned on ($\times 5$ values)
  $\to$ linear interpolation $x_i + y_i\,C_i \to$ extract y_i
- estimate full $\Gamma(h\to W^+\mu^-\bar{\nu}_\mu)$ with one C_i turned on ($\times 5$ values)
  $\to$ quadratic interpolation $x_i + y_i\,C_i + z_i\,C_i^2 \to$ extract y_i





SMEFTsim – practical use

estimating $\delta\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar{\nu}_\mu\nu_e,SM}$

normalization:

$\bar{C}_i = C_i\left(\frac{v^2}{\Lambda^2}\right)$

	theory	MG interf	MG full xs
CHW	-1.48743	-1.48844	-1.48002
CHbox	2.	1.99786	2.00819
CHD	-0.5	-0.499802	-0.495254
CHl3	-3.76422	-3.77082	-3.76292
Cll1	3.	2.99626	2.99819

$y_i/\Gamma_{h\to e^+\nu_e\mu^-\bar{\nu}_\mu,SM}$ from pure interference

$y_i/\Gamma_{h\to e^+\nu_e\mu^-\bar{\nu}_\mu,SM}$ from linearized full width

$\delta\Gamma_W$ omitted here

SMEFTsim – practical use

estimating $\delta\Gamma_{h\to e^+\mu^-\bar\nu_\mu\nu_e}/\Gamma_{h\to e^+\mu^-\bar\nu_\mu\nu_e,SM}$

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✔ two SMEFTsim columns are consistent

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✓ validated with theory

✓ two SMEFTsim columns are consistent

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analytic calculation!

Brivio,Corbett,Trott to appear

$\delta\Gamma_W$ omitted here

The Higgs width in the SMEFT - analytically

Analytic calculation of the inclusive Γ_H on the way: Brivio,Corbett,Trott, to appear

- LO in the EFT: up to Λ^{-2}.
- **tree level**.
  SM couplings $H\gamma\gamma, HZ\gamma, Hgg$ included for $H \to f\bar{f}\gamma$ / $\gamma\gamma$ / gg.
- Warsaw basis with $\mathbf{U(3)^5}$ **flavor symmetry**
- EW input scheme: $\{m_Z, m_W, G_F\}$
- full calculation for $h \to 4f$: narrow width approximation for W, Z avoided

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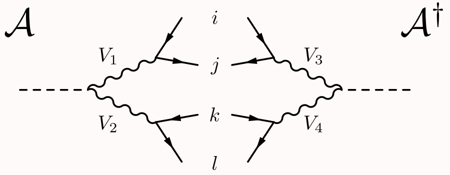
Why analytic?

- allows to separate contributions
- easier to linearize in $\delta\Gamma_V, \delta m_V$
- more stable for the massless fermions case with γ diagrams
- calculation can be **automated** once and for all
  $\to$ much faster than running MC every time

wait for the next **tool**!

H → 4f - analytic calculation

automated with general decomposition:



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

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

- $\mathcal{F}$ computed for every $\{V\}$ set.
  numerical integration of phase space: Vegas in Mathematica.
  cross-check: 2 independent parameterizations of phase space, RAMBO.
  agreement w. SMEFTsim to better than 1% in all channels ✓

$H \to 4f$ - results

Example: $H \to e^+e^-\mu^+\mu^-$ $\qquad m_i, m_j, m_k, m_l = 0$

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

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}_{Hl}^{(1)}$	$\bar{C}_{Hl}^{(3)}$	$\bar{C}_{He}$	$\bar{C}_{Hq}^{(1)}$	$\bar{C}_{Hq}^{(3)}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
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

$H \to 4f$ - results

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	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}^{(1)}_{Hl}$	$\bar{C}^{(3)}_{Hl}$	$\bar{C}_{He}$	$\bar{C}^{(1)}_{Hq}$	$\bar{C}^{(3)}_{Hq}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
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A	γ diagrams
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Impact of photon diagrams

☛ main contribution missed in the narrow width approx.

turns out to be a $\mathcal{O}(1-250)\%$ 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

The total Higgs width in the SMEFT

putting together all the main contributions* we obtain

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

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

$$\begin{aligned}\frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,SM}^{\rm tot}} = &- 1.50\, C_{HB} - 1.21\, C_{HW} + 1.21\, C_{HWB} + 50.6\, C_{HG}\\ &+ 1.83\, C_{H\Box} - 0.43\, C_{HD} + 1.17\, C'_{ll}\\ &- 0.06\,|C_{uH}| - 1.16\,|C_{dH}| - 0.13\,|C_{eH}|\\ &+ 0.002\, C_{Hq}^{(1)} + 0.06\, C_{Hq}^{(3)} + 0.001\, C_{Hu} - 0.0007\, C_{Hd}\\ &- 0.0009\, C_{Hl}^{(1)} - 2.32\, C_{Hl}^{(3)} - 0.0006\, C_{He}\end{aligned}$$

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

PRELIMINARY

SMEFTsim - What's next?

Main direction of improvement: optimize for signal generation for LHC

- **new flavor scheme** $U(2)^5$ to match with top physics
- include vertices with up to 6 legs
- interaction orders for individual operators
- improve treatment of propagator corrections
- more user friendly: public **FAQ / manual**
- open to suggestions!

Backup slides

The Warsaw basis

Gzadkowski,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

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

Numerical inputs chosen

Input parameters	Value	Ref.	
$\hat{\alpha}_{ew}(m_Z)$		$1/127.950$	PDG 2016, 1203.5425
$\hat{m}_W$	GeV	80.365 ± 0.016	TeVatron: 1307.7627
$\hat{m}_Z$	GeV	91.1876 ± 0.0021	PDG 2016, hep-ex/0509008,1203.5425
$\hat{G}_F$	GeV^{-2}	$1.1663787(6) \times 10^{-5}$	PDG 2016, 1203.5425
$\hat{m}_h$	GeV	$125.09 \pm 0.21 \pm 0.11$	1503.07589
$\hat{\alpha}_s(m_Z)$	GeV	0.1185 ± 0.0011	PDG 2016
$\hat{m}_e$	GeV	$0.5109989461(31) \times 10^{-3}$	PDG 2016
$\hat{m}_\mu$	GeV	$105.6583745(24) \times 10^{-3}$	PDG 2016
$\hat{m}_\tau$	GeV	1.77686 ± 0.00012	PDG 2016
$\hat{m}_u$	GeV	$2.2^{+0.6}_{-0.4} \times 10^{-3}$	PDG 2016
$\hat{m}_c$	GeV	1.28 ± 0.03	PDG 2016
$\hat{m}_t$	GeV	$173.21 \pm 0.51 \pm 0.71$	PDG 2016
$\hat{m}_d$	GeV	$4.7^{+0.5}_{-0.4} \times 10^{-3}$	PDG 2016
$\hat{m}_s$	GeV	$0.096^{+0.008}_{-0.004}$	PDG 2016
$\hat{m}_b$	GeV	$4.18^{+0.04}_{-0.03}$	PDG 2016
CKM: λ		0.22506	PDG 2016
A		0.811	PDG 2016
ρ		0.124	PDG 2016
η		0.356	PDG 2016

Field redefinitions

Gauge bosons

$$\mathcal{L}_{\rm SMEFT} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} +$$
$$+ C_{HB}(H^\dagger H)B_{\mu\nu}B^{\mu\nu} + C_{HW}(H^\dagger H)W^I_{\mu\nu}W^{I\mu\nu} + C_{HWB}(H^\dagger\sigma^I H)W^I_{\mu\nu}B^{\mu\nu}$$
$$+ C_{HG}(H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}$$

to have **canonically normalized kinetic terms** we need to

1. redefine fields and couplings keeping (gV_μ) unchanged:

$$\begin{aligned} \mathcal{B}_\mu &\to B_\mu(1 + C_{HB}v^2) & g_1 &\to g_1(1 - C_{HB}v^2) \\ \mathcal{W}^I_\mu &\to W^I_\mu(1 + C_{HW}v^2) & g_2 &\to g_2(1 - C_{HW}v^2) \\ \mathcal{G}^a_\mu &\to G^a_\mu(1 + C_{HG}v^2) & g_s &\to g_s(1 - C_{HG}v^2) \end{aligned}$$

2. correct the rotation to mass eigenstates:

$$\begin{pmatrix} \mathcal{W}^3_\mu \\ \mathcal{B}_\mu \end{pmatrix} = \begin{pmatrix} 1 & -v^2 C_{HWB}/2 \\ -v^2 C_{HWB}/2 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

(equivalent to a shift of the Weinberg angle)

Grinstein,Wise Phys.Lett.B265(1991)326
Alonso,Jenkins,Manohar,Trott 1312.2014

Field redefinitions

Higgs

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{2} D_\mu H^\dagger D^\mu H + C_{H\Box}(H^\dagger H)(H^\dagger \Box H) + C_{HD}(H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$$

to have a canonically normalized kinetic term, in unitary gauge, we need to replace

$$h \to h\left(1 + v^2 C_{H\Box} - \frac{v^2}{4} C_{HD}\right)$$

Grinstein,Wise Phys.Lett.B265(1991)326
Alonso,Jenkins,Manohar,Trott 1312.2014