VBS & SMEFT

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VBS Can

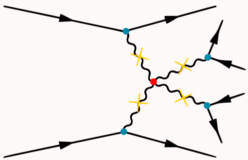
Plan

1. intro & remarks on the SM EFT:

motivation for a **global analysis**

2. VBS in the SM EFT – focus on dimension 6

- **relevant operators** in the Warsaw basis [qualitative considerations]
- what can/should VBS be combined with?



☛ for more quantitative and specific studies, see the next talk by Raquel+Kristin

The SMEFT

fundamental assumptions:

- new physics nearly decoupled: $\Lambda \gg (v, E)$
- at the accessible scale: **SM** fields + symmetries

☛ a Taylor expansion in canonical dimensions (v/Λ or E/Λ):

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

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

C_i free parameters (Wilson coefficients)

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

Constructing a basis

SM fields + symmetries

↓

<u>all</u> the allowed invariant structures at dimension d

Constructing a basis

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remove terms that give equivalent physics (redundant at S-matrix level) via

- **integration by parts**

  e.g. $\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) = -(H^\dagger H)\,\Box\,(H^\dagger H)$

- **equations of motion (EOM)**

  e.g. $(H^\dagger H)(\bar\psi_L i\not{D}\psi_L) \sim (H^\dagger H)(\bar\psi_L H\psi_R)$

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a basis

=

minimal set of independent operators (parameters)
for the most general classification of BSM effects

Some remarks

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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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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

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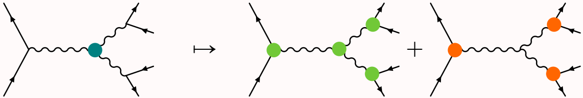
$$W^a_{\mu\nu} D^\mu H^\dagger \sigma^a D^\nu H \quad \overset{EOM}{\mapsto} \quad \mathcal{Q}_{HW},\ \mathcal{Q}_{HWB},\ \mathcal{Q}^{(3)}_{Hq},\ \mathcal{Q}^{(3)}_{Hl} + \text{Higgs ops.}$$



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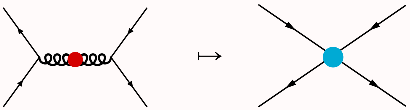
$$D_\mu G^{a\mu\nu} D^\rho G^a_{\rho\nu} \quad \overset{EOM}{\mapsto} \quad (\bar{q} T^a q + \bar{u} T^a u + \bar{d} T^a d)^2$$



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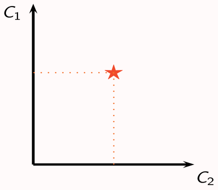

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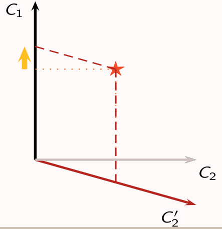

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☛ a **global analysis** is strongly motivated and ultimately needed!

VBS in the SMEFT – preliminary considerations

Here the SMEFT analysis will focus only on the **leading** SMEFT contributions:

tree level | dimension 6 | SM-SMEFT interference

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EFT expansion:

$$\Delta O_{SMEFT} = \frac{C_i^{(6)}}{\Lambda^2}a_i + \frac{C_i^{(6)}C_j^{(6)}}{\Lambda^4}b_{ij} + \frac{C_i^{(8)}}{\Lambda^4}c_i + \mathcal{O}(\Lambda^{-6})$$

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subleading terms

- quadratic d6 + linear d8 corrections to Lag. param. (unknown!)
- vertex corrections:
  $\mathcal{A}^{(6)}\times\mathcal{A}^{(6)}$ (1 ins.)
  $\mathcal{A}_{SM}\times\mathcal{A}^{(6)}$ (2 ins.)
  $\mathcal{A}_{SM}\times\mathcal{A}^{(8)}$ (1 ins.)

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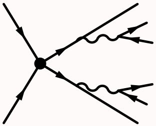


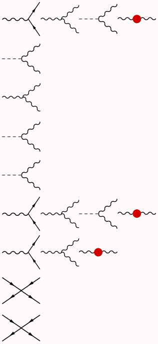
4-fermion operators: relevant only with 4 left-handed quarks

→ others can be neglected

Minimal set of operators relevant for VBS

With the above assumptions, in the Warsaw basis:

$$\mathcal{Q}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$$
$$\mathcal{Q}_{H\Box} = (H^\dagger H)(H^\dagger \Box H)$$
$$\mathcal{Q}_{W} = \varepsilon_{ijk} W^i_{\mu\nu} W^{j\nu\rho} W^{k\mu}_{\rho}$$
$$\mathcal{Q}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$$
$$\mathcal{Q}_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}'_{ll} = (\bar{l}\gamma_\mu l')(\bar{l}'\gamma^\mu l)$$
$$\mathcal{Q}^{(1)}_{qq} = (\bar{q}\gamma_\mu q)(\bar{q}'\gamma^\mu q')$$
$$\mathcal{Q}^{(1)\prime}_{qq} = (\bar{q}\gamma_\mu q')(\bar{q}'\gamma^\mu q)$$



$$\mathcal{Q}^{(1)}_{Hl} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$$
$$\mathcal{Q}^{(3)}_{Hl} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$$
$$\mathcal{Q}^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
$$\mathcal{Q}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$$
$$\mathcal{Q}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$
$$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$
$$\mathcal{Q}^{(3)}_{qq} = (\bar{q}\sigma^i\gamma_\mu q)(\bar{q}'\sigma^i\gamma^\mu q')$$
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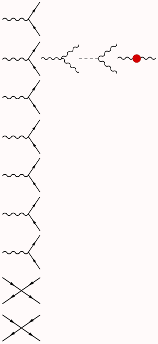

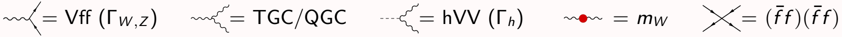

18 parameters

⇝ see talk by **Raquel+Kristin**

ZZ case: Gomez-Ambrosio 1809.04189

Combining VBS with. . .

VBS alone can constrain only **combinations** of coefficients (still meaningful!)
Combination with other measurements is needed to break further degeneracies.

 = Vff ($\Gamma_{W,Z}$)  = TGC/QGC  = hVV (Γ_h)  = m_W  = $(\bar{f}f)(\bar{f}f)$

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. . . **Higgs** production and decay  (∼ **13**/18 parameters)

step 0: κ parametrization (2 param.) $\leftrightarrow$

$$\begin{cases} \kappa_Z = 1 + \left(C_{H\Box} - C_{Hl}^{(3)} + \frac{C'_{ll}}{2}\right) + \frac{C_{HD}}{4} \\ \kappa_W = 1 + \left(C_{H\Box} - C_{Hl}^{(3)} + \frac{C'_{ll}}{2}\right) - \frac{C_{HD}}{4} \\ C_{HW},\ C_{HB},\ C_{HWB} \to 0 \end{cases}$$

next steps:
– reintroduce C_{HW}, C_{HB}, C_{HWB} → kin. dependence
– include effects in Vff vertices

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. . . Higgs production and decay  (~ **13**/18 parameters)

. . . diboson  (~ **11**/18 parameters)

TGC and QGC are completely correlated at dimension 6
⇒ interesting interplay

! including corrections of other classes (Vff, hVV, 4f) makes the comparison less obvious

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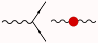
. . . Drell-Yan  ($\sim$ **10**/18 parameters)

clean handle on Vff and m_W operators.

can be also compared to LEP data

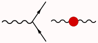
Combining VBS with...

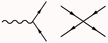
VBS alone can constrain only **combinations** of coefficients (still meaningful!)
Combination with other measurements is needed to break further degeneracies.

 = Vff ($\Gamma_{W,Z}$)  = TGC/QGC  = hVV (Γ_h)  = m_W  = $(\bar{f}f)(\bar{f}f)$

...Higgs production and decay  (~ **13**/18 parameters)

...diboson  (~ **11**/18 parameters)

...Drell-Yan  (~ **10**/18 parameters)

...dijet  (~ **12**/18 parameters)

pure quark currents in Vff and 4-fermion

- ! QCD loops in the SMEFT can be relevant
- ! large # operators contributing vs. poor flavor/charge sensitivity
- ! can have EFT validity issues and/or very large th. unc. at high E

Summary & take-home

- The **SMEFT** is a well-defined, general framework for BSM effects

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- It is worth using its full power with a truly global analysis
  - most general BSM characterization (assuming SM sym + fields)
  - universal parameterization for data interpretation

Summary & take-home

- The **SMEFT** is a well-defined, general framework for BSM effects
- It is worth using its full power with a truly global analysis
  - most general BSM characterization (assuming SM sym + fields)
  - universal parameterization for data interpretation
- VBS receives leading SMEFT corrections at dimension 6
  - qualitatively $\sim$ **18** operators in the most minimal case.

    The exact number can vary depending on selected channel / distributions

    $\rightsquigarrow$ see talk by **Raquel+Kristin**
  - VBS alone can only constrain linear combinations of coefficients. Combining with other channels in required to break degeneracies: e.g. **Higgs, diboson, Drell-Yan, dijet. . .**

Summary & take-home

- The **SMEFT** is a well-defined, general framework for BSM effects

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  - most general BSM characterization (assuming SM sym + fields)
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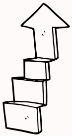
  - VBS alone can only constrain linear combinations of coefficients. Combining with other channels in required to break degeneracies: e.g. **Higgs, diboson, Drell-Yan, dijet. . .**

- lots to do! Sequential steps to include more and more terms



Backup slides

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

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

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

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

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

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

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

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

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

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

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
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

Authors

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NBIA and Discovery Center, Niels Bohr Institute, University of Copenhagen

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

Implemented frameworks

We implemented 6 different frameworks:

3 flavor structures $\begin{cases} \text{general} \\ U(3)^5 \text{ symmetric} \\ \text{linear MFV} \end{cases}$ $\times$ 2 input schemes $\begin{cases} \hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f \\ \hat{m}_W, \hat{m}_Z, \hat{G}_f \end{cases}$

Implemented frameworks

We implemented 6 different frameworks:

3 flavor structures	general $U(3)^5$ symmetric linear MFV	$\times$	2 input schemes	$\hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f$ $\hat{m}_W, \hat{m}_Z, \hat{G}_f$

completely general flavor indices:

2499 parameters including all complex phases

Implemented frameworks

We implemented 6 different frameworks:

3	flavor structures	general $U(3)^5$ symmetric linear MFV	$\times$	2	input schemes	$\hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f$ $\hat{m}_W, \hat{m}_Z, \hat{G}_f$

---

assume an **exact flavor symmetry**

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

under which: $\psi \mapsto U_\psi \psi$ for $\psi = \{u, d, q, l, e\}$

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

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

- flavor indices contractions are fixed by the symmetry → less parameters

Examples:

$$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_r \gamma^\mu u_s)\, \delta_{\bf rs}$$

$$\mathcal{Q}_{eB} = B_{\mu\nu}(\bar{l}_r H \sigma^{\mu\nu} e_s)\, (\mathbf{Y_l})_{\bf rs}$$

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---

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

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

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

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

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

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

SMEFTsim 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]	[illegible]W12	692 740. 9950.4	690 240. 9319.7	-	-	-	-
[illegible]	[illegible]12	706 050. 9205.5	706 050. 9205.5				

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

xsec [pb]
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]

		$pp \to t\bar t$	$pp \to t\bar t\, b\bar b$	$pp \to t\bar t\, t\bar t$	$pp \to t\bar t\, e^+\nu$	$pp \to t\bar t\, e^+e^-$	$pp \to t\bar t\,\gamma$	$pp \to t\bar t\, h$	$pp \to tj$	$pp \to t\, e^-\bar\nu$	$pp \to tj\, e^+e^-$	$pp \to tj\,\gamma$	$pp \to tj\, h$
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		[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	[illegible]		-6.4×10^{-15}	-5.2×10^{-15}	-4.1×10^{-15}
$c^{1,8}_{Qq}$	cQq81	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{tq}	ctq8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{Qu}	cQu8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{tu}	ctu8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{Qd}	cQd8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
c^8_{td}	ctd8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$c^{3,1}_{Qq}$	cQq13	[illegible]	[illegible]	[illegible]	[illegible]	[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					
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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					−68
$c^-_{\varphi Q}$	cpQM	−0.063	1	−41	−0.76	-1×10^2	−0.13	−0.29			21		
$c^3_{\varphi Q}$	cpQ3	0.68	22	0.065	0.46	3.7	1.5	1.8	1.2×10^2	1.2×10^2	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			
$c^I_{t\varphi}$	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

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

SMEFTsim validation

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

2. Validation against `dim6top`

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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												
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}	ctq1												
c^1_{Qu}	cQu1												
c^1_{tu}	ctu1												
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}	$\equiv 2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$	c^8_{QQ}	$\equiv 8C^{3(3333)}_{qq}$
c^1_{Qt}	$\equiv C^{1(3333)}_{qu}$	c^8_{Qt}	$\equiv C^{8(3333)}_{qu}$
$c^{3,1}_{Qq}$	$\equiv C^{3(ii33)}_{qq} + \frac{1}{6}\left(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}\right)$	$c^{3,8}_{Qq}$	$\equiv C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
$c^{1,1}_{Qq}$	$\equiv C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$	$c^{1,8}_{Qq}$	$\equiv C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
$c^{[I]}_{t\varphi}$	$\equiv {}^{[Im]}_{Re}\{C^{(33)}_{uH}\}$	c^-_{Hq}	$\equiv C^{1(33)}_{Hq} - C^{3(33)}_{Hq}$
c^3_{HQ}	$\equiv C^{3(33)}_{Hq}$	c_{Ht}	$\equiv C^{(33)}_{Hu}$

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12 top processes

$\sim$ 50 coefficients

both interference and quadratic terms
↓
1200+ numbers compared

$\sigma(\text{int.})/\sigma(\text{SM})$ 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		[illegible]		
$c_{Qq}^{1,1}$	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					
$c_{\varphi Q}^{-}$	cpQM	−0.063	1	−41	−0.76	-1×10^2	−0.13	−0.29					
$c_{\varphi Q}^{3}$	cpQ3	0.68	22	0.065	0.46	3.7	1.5	1.8	1.2×10^2	1.2×10^2	[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			
$c_{t\varphi}^{I}$	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		
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   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

SMEFTsim validation

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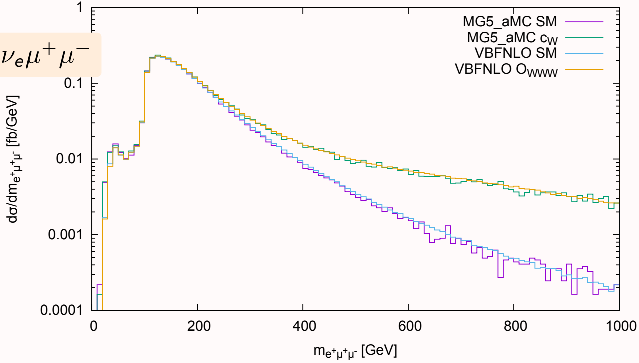
$pp \to e^+\nu_e\mu^+\mu^-$



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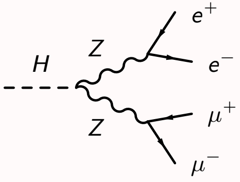
Brivio,Trott SMEFT review 1706.08945
Brivio,Hays,Trott,Žemaitytė, in preparation.

Example



	theory	MG interf.	MG full xs
cHW	−0.757133	−0.77948	−0.778724
cHB	−0.217121	−0.223247	−0.223151
cHWB	0.308271	0.295226	0.317418
cHbox	2.	1.99882	2.00469
cHD	0.167224	0.164264	0.170457
cHe	−3.5239	−1.72758	−1.72691
cHl1	4.38291	2.15039	2.14801
cHl3	−1.61513	−3.85776	−3.86201
cll1	2.99835	2.99884	3.00731

$\sigma(\text{int.})/\sigma(\text{SM})$ for $\bar{C}_i = C_i(v/\Lambda)^2 = 1$

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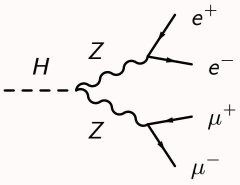

dominant diag. contribution analytically known

MG5: `h > e+ e- mu+ mu- / a`

pure int.

full xsec, linearized

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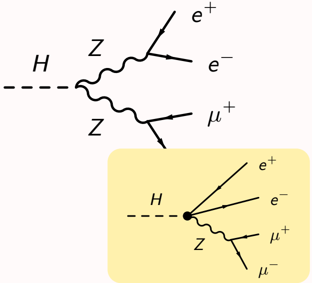

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```
z > e+ e-                   z > u u~
w+ > l+ vl                  w+ > uq dq~

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
...
```

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5. Further validation still in progress!