The SMEFTsim package

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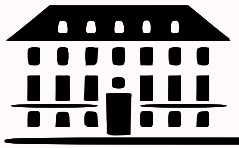
feynrules.irmp.ucl.ac.be/wiki/SMEFT

Brivio, Jiang, Trott JHEP 1712 (2017) 070

arXiv: 1709.06492



The Niels Bohr International Academy

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):

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

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

C_i free parameters (Wilson coefficients)

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

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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
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$(\bar{L}R)(\bar{R}L)$ 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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

More than a parameterization

the complete SMEFT Lagrangian, truncated at a given order,
is always* **a self-consistent QFT** and
a valid description of Nature

* assuming nearly-decoupled BSM matching SM sym + fields and evaluating at $E \ll \Lambda$

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- allows systematic one-loop improvement, RG evolution ...
- avoids inconsistencies / basis dependence

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- allows long-term, extensible analysis plan
- common framework for LHC and lower E experiments

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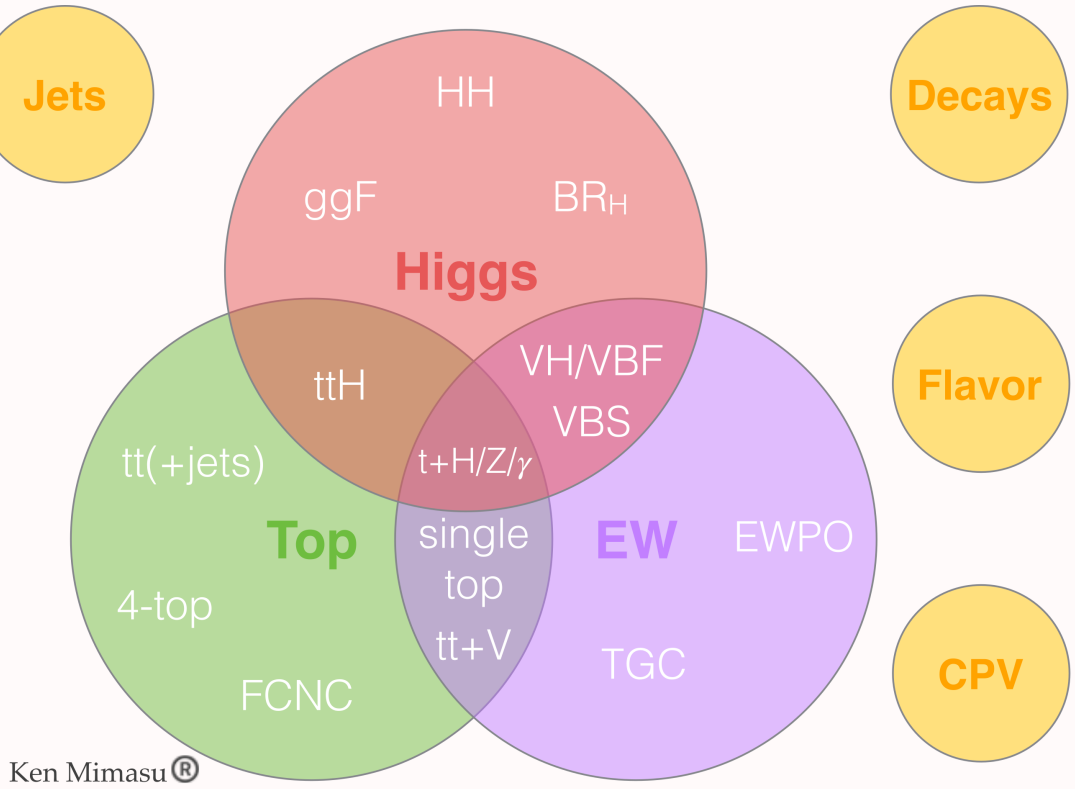
- individual processes necessarily have blind directions
- combination of different processes / sectors required



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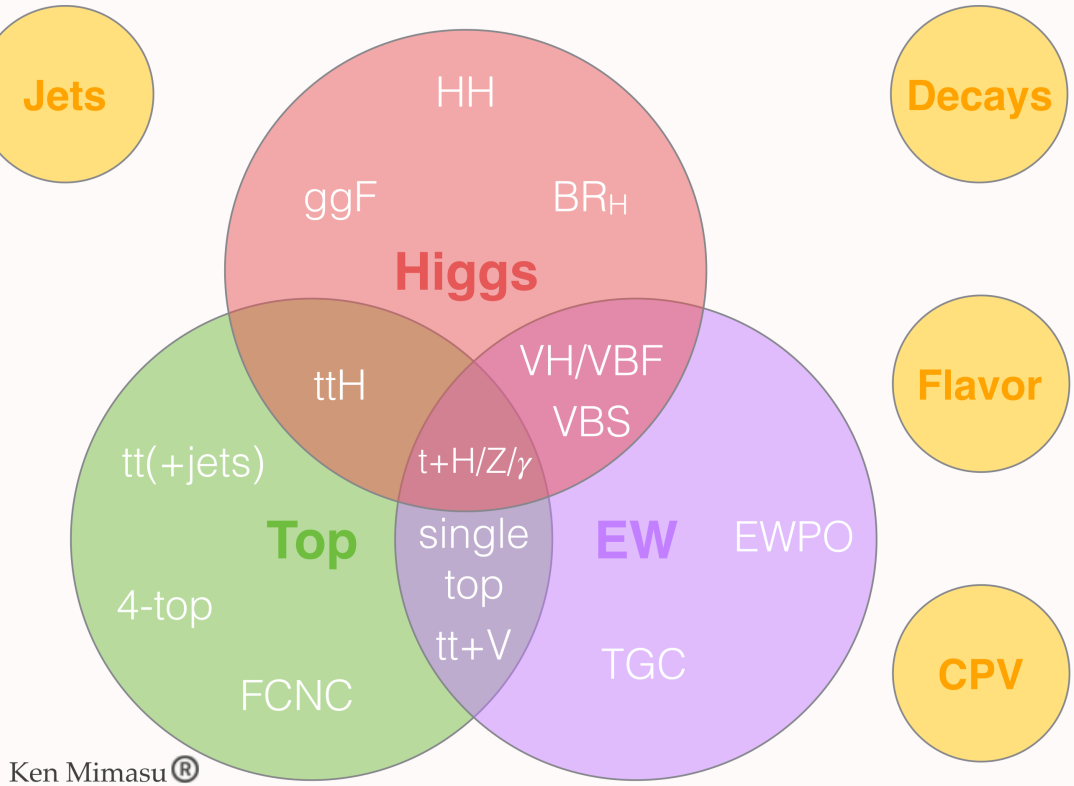


SMEFTsim is designed to enable global analyses

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**

⇝ backup

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

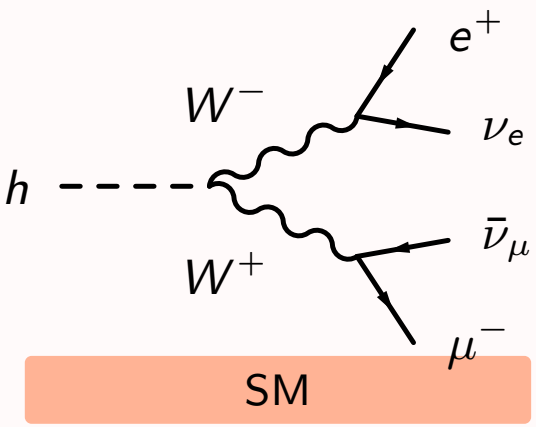
Main scope:

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

NLO not supported.

SMEFTsim – scope

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



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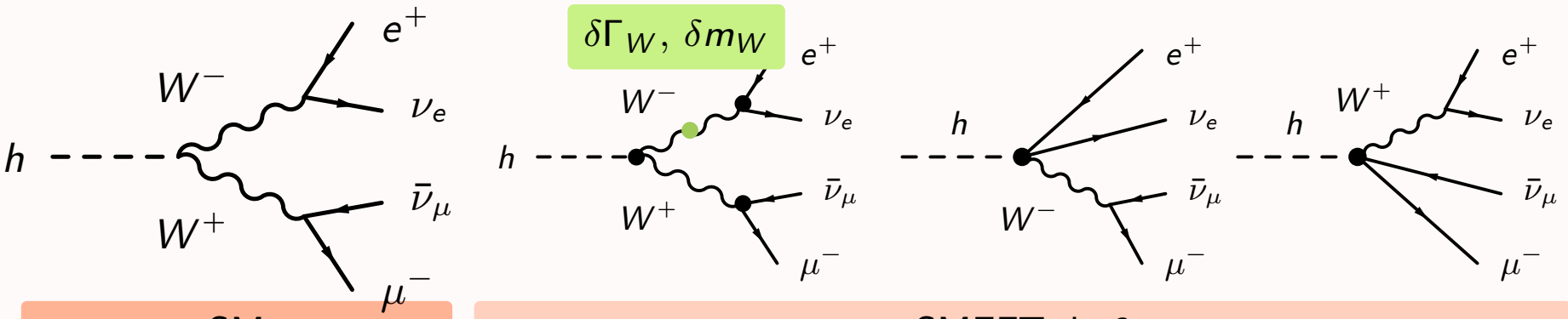

SM | SMEFT d=6

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

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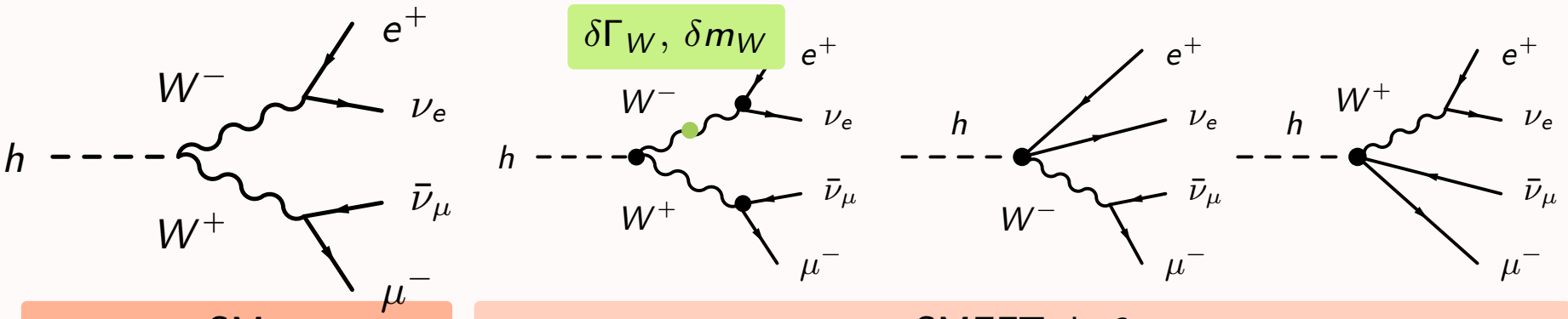

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$$\mathrm{Br}(h \to 2\ell 2\nu) = \mathrm{Br}(h \to 2\ell 2\nu)_{SM} \left[1 + \frac{\delta\Gamma_{h\to 2\ell 2\nu}}{\Gamma_{h\to 2\ell 2\nu, SM}} - \frac{\delta\Gamma_H}{\Gamma_{H,SM}} \right]$$

SMEFTsim – scope

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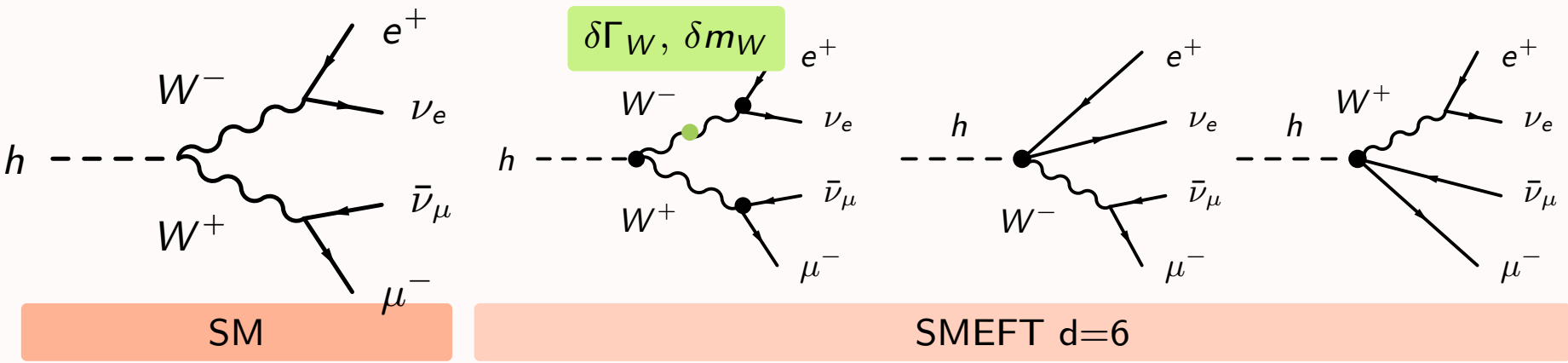

most accurate SM prediction

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SMEFTsim – scope

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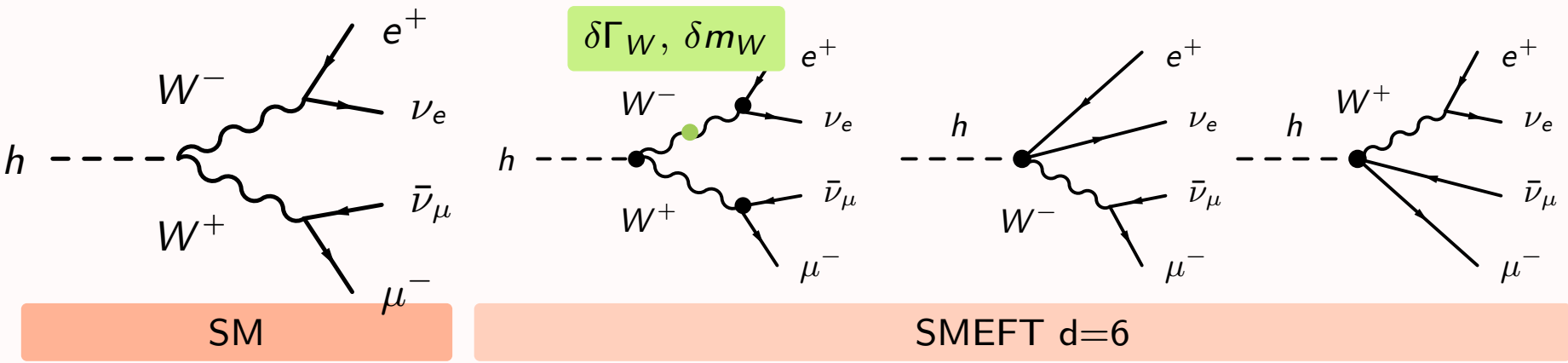

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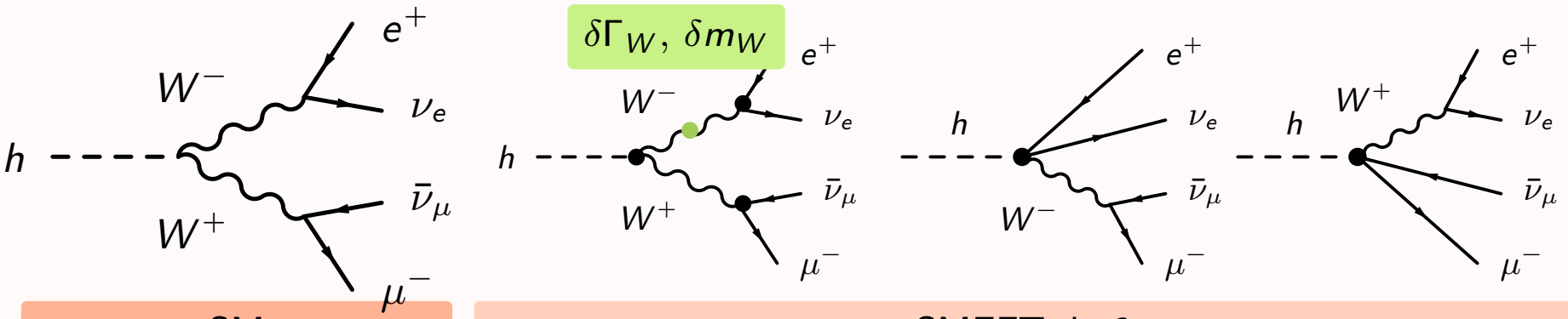

most accurate SM prediction

estimate @tree with MG5 + SMEFTsim (or analytically)

Brivio, Corbett, Trott 1906.06949

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

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 input obs. definitions to get:

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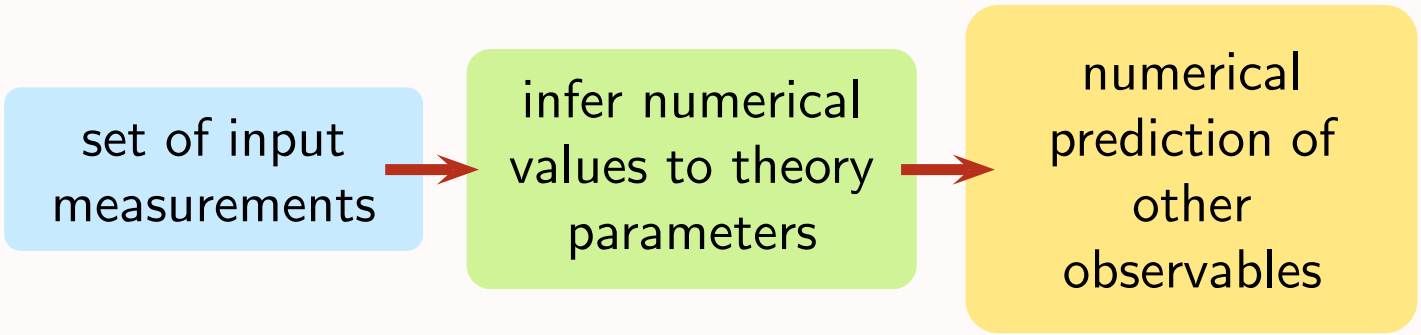

SM:

analytic calculations
Monte Carlo generation
...

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

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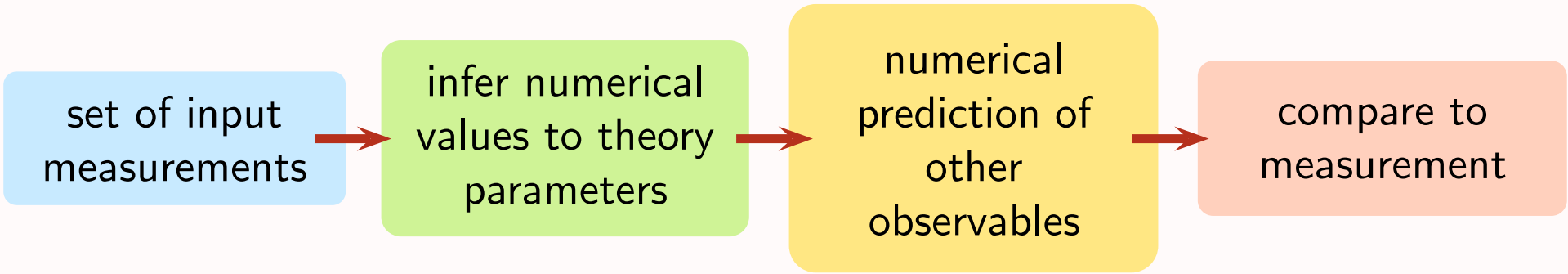


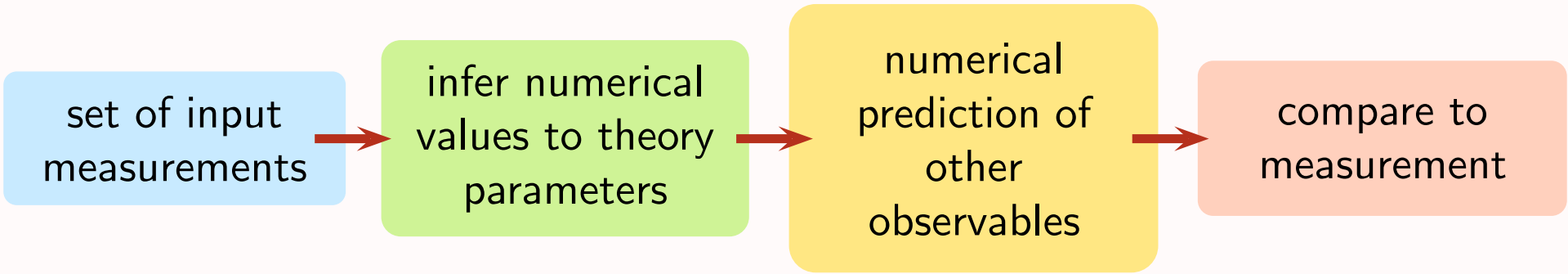
SM:

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

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

Shifts from input parameters

when testing a theory:



SMEFT:

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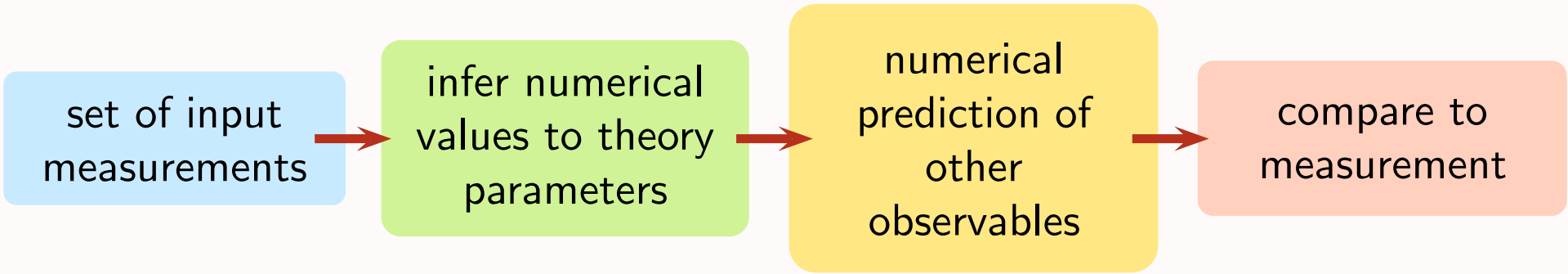

SMEFT:

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 schemes for the EW sector

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

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

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

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

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

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

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

with

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

Input schemes for the EW sector

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

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

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

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

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

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

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

with

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

SMEFTsim - further specifications

- **SM** Higgs couplings HGG, $H\gamma\gamma$, $HZ\gamma$ included
  oh-shell loop functions $I(m_t, m_W)$ hard coded in the couplings
  interaction order `SMHLOOP`

- 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` / `NP^2==2`

- restriction cards: `SMlimit`, `massless`, `CPconserving`,
  `TopEFT`: top physics flavor assumptions (see later)

- validation has been extensive and is always ongoing ⇝ backup

- `Mathematica` notebook for analytic Feynman rules also available

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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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

SMEFTsim - available flavor assumptions

- Flavor general

---

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:

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

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

$$\mathcal{Q}_{ll} = (\bar{\ell}_r \gamma^\mu \ell_s)(\bar{\ell}_m \gamma_\mu \ell_n) \quad \delta_{rs}\delta_{mn} \text{ or } \delta_{rn}\delta_{ms} \rightarrow C_{ll}, C'_{ll}$$

SMEFTsim - available flavor assumptions

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

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

- $C_i \in \mathbb{R}$

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.:

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

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

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

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

SMEFT for top physics

Common standards were proposed in the LPCC note: Aguilar-Saavedra et al 1802.07237

Main points:

- Warsaw basis
- focus on operators containing the top quark (exception: O_{Hb} included)
- specific flavor assumptions

  Baseline:

  quarks $\rightarrow$ 1st, 2nd gen. (q_L, u_R, d_R) $U(2)_q \times U(2)_u \times U(2)_d$

  $\rightarrow$ 3rd gen. (Q_L, t_R, b_R) no sym

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

  leptons $[U(1)_{l+e}]^3$

Implemented in `dim6top`, by G. Durieux and C. Zhang

SMEFT for top physics

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- specific flavor assumptions

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quarks $\rightarrow$ 1st, 2nd gen. (q_L, u_R, d_R) $U(2)_q \times U(2)_u \times U(2)_d$

$\rightarrow$ 3rd gen. (Q_L, t_R, b_R) no sym

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

leptons $[U(1)_{l+e}]^3$

57 param. + **16** ~~CP~~ phases in operators with **top**

[excl. leptons: 34 + 8 ~~CP~~]

Implemented in `dim6top`, by G. Durieux

SMEFT for top physics

Example from Brivio,Bruggisser,Maltoni,Moutafis,Plehn,Vryonidou,Westhoff,Zhang 1910.03606 ⇝ Eleni's talk

$$O^1_{\phi Q} = (\phi^\dagger\, i \overleftrightarrow{D_\mu}\, \phi)(\bar{Q}\gamma^\mu Q) \qquad {}^\ddagger O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\, \widetilde{\phi}\, B_{\mu\nu}$$

$$O^3_{\phi Q} = (\phi^\dagger\, i \overleftrightarrow{D^I_\mu}\, \phi)(\bar{Q}\gamma^\mu \tau^I Q) \qquad {}^\ddagger O_{tW} = (\bar{Q}\sigma^{\mu\nu} t)\, \tau^I \widetilde{\phi}\, W^I_{\mu\nu}$$

$$O_{\phi t} = (\phi^\dagger\, i \overleftrightarrow{D_\mu}\, \phi)(\bar{t}\gamma^\mu t) \qquad {}^\ddagger O_{bW} = (\bar{Q}\sigma^{\mu\nu} b)\, \tau^I \phi\, W^I_{\mu\nu}$$

$${}^\ddagger O_{\phi tb} = (\widetilde{\phi}^\dagger i D_\mu \phi)(\bar{t}\gamma^\mu b) \qquad {}^\ddagger O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\, \widetilde{\phi}\, G^A_{\mu\nu}\,.$$

$$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i) \qquad O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i \gamma^\mu q_i)$$

$$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i) \qquad O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i \gamma^\mu \tau^I q_i)$$

$$O^8_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i) \qquad O^1_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}_i \gamma^\mu u_i)$$

$$O^8_{td} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i \gamma_\mu T^A d_i) \qquad O^1_{td} = (\bar{t}\gamma^\mu t)(\bar{d}_i \gamma_\mu d_i)\,;$$

$$O^8_{Qu} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i \gamma_\mu T^A u_i) \qquad O^1_{Qu} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i \gamma_\mu u_i)$$

$$O^8_{Qd} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i \gamma_\mu T^A d_i) \qquad O^1_{Qd} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i \gamma_\mu d_i)$$

$$O^8_{tq} = (\bar{q}_i \gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t) \qquad O^1_{tq} = (\bar{q}_i \gamma^\mu q_i)(\bar{t}\gamma_\mu t)\,;$$

22 op. + O_{tH} + 11 with 4-heavy q. + 23 with leptons

SMEFT for top physics in SMEFTsim

currently this flavor assumption is not implemented directly

→ can be reproduced with restriction cards on the `general` version

e.g.

`cuG33`	`ctG`	`cqq13333`	$\frac{\texttt{cQQ1}}{2} + \frac{\texttt{cQQ8}}{24}$
`cuW33`	`ctW`	`cqq1i33i`	$\frac{\texttt{cQq81}}{4} + \frac{3\,\texttt{cQq83}}{4}$
		`cqq1ii33`	$\texttt{cQq11} - \frac{\texttt{cQq81}}{6}$
`cuu3333`	`ctt1`	`cqq33333`	$\frac{\texttt{cQQ8}}{8}$
`cuui33i`	$\frac{\texttt{ctu8}}{2}$	`cqq3i33i`	$\frac{\texttt{cQq81}}{4} - \frac{\texttt{cQq83}}{4}$
`cuuii33`	$\texttt{ctu1} - \frac{\texttt{ctu8}}{6}$	`cqq3ii33`	$\texttt{cQq13} - \frac{\texttt{cQq83}}{6}$

the complete mapping is available, in both directions

SMEFT for top physics in SMEFTsim

currently this flavor assumption is not implemented directly

→ can be reproduced with restriction cards on the `general` version

e.g.

`cuG33`	`ctG`
`cuW33`	`ctW`
`cuu3333`	`ctt1`
`cuui33i`	$\frac{\texttt{ctu8}}{2}$
`cuuii33`	$\texttt{ctu1} - \frac{\texttt{ctu8}}{6}$

`cqq13333`	$\frac{\texttt{cQQ1}}{2} + \frac{\texttt{cQQ8}}{24}$
`cqq1i33i`	$\frac{\texttt{cQq81}}{4} + \frac{3\,\texttt{cQq83}}{4}$
`cqq1ii33`	$\texttt{cQq11} - \frac{\texttt{cQq81}}{6}$
`cqq33333`	$\frac{\texttt{cQQ8}}{8}$
`cqq3i33i`	$\frac{\texttt{cQq81}}{4} - \frac{\texttt{cQq83}}{4}$
`cqq3ii33`	$\texttt{cQq13} - \frac{\texttt{cQq83}}{6}$

the complete mapping is available, in both directions

NEW VERSION coming, with direct top flavor implementation

→ contains a **complete basis** (top + all the rest)

→ 15 bosonic d.o.f. + (**179** abs + **49** ~~CP~~ phases) in fermionic op.

SMEFTsim - What's next?

Main direction of improvement: optimize for signal generation for LHC

- **new flavor scheme** to match with top physics

  Top note 1802.07237

- include all vertices, with up to 6 legs
- interaction orders for individual operators
- linearization of propagator corrections
- more user friendly: public **FAQ / manual**
- open to suggestions!

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:

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

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

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

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

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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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	-	-
	12	692 740. 9950.4	690 240. 9319.7	-	-	-	-
	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 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 × 10² 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 × 10²		−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 × 10²		−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 × 10²									
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 × 10²	71	40	75					
c_{tq}^8	ctq8	13	8.2	27	2.6 × 10²	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 × 10²	22	11	18	−3.8 × 10²		−7.9 × 10²	−6.1 × 10²	−4.6 × 10²
$c_{Qq}^{1,1}$	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 × 10²					−68
$c_{\varphi Q}^-$	cpQM	−0.063	1	−41	−0.76	−1 × 10²	−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 × 10²	1.2 × 10²	2.2 × 10²	1.2 × 10²	1.3 × 10²
$c_{\varphi t}$	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 × 10²
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 × 10²	2.5 × 10²	3.8 × 10²	2.4 × 10²	3.1 × 10²	2.4 × 10²	8.4 × 10²		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 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		91	−0.5	−0.27					
c_{Qt}^1	cQt1	−0.15	−5.6	1×10^2		−0..	−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	16	0.56					
c_{tt}^1	ctt1			-1.8×10^2									
c_{tb}^1	ctb1	−0.0095	0.46	−0.059		−0.02	−0.02	−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	4×10^{-15}		-6.4×10^{-15}	-5.2×10^{-15}	-4.1×10^{-15}
$c_{Qq}^{1,8}$	cQq81												
c_{tq}^8	ctq8												
c_{Qu}^8	cQu8												
c_{tu}^8	ctu8												
c_{Qd}^8	cQd8												
c_{td}^8	ctd8												
$c_{Qq}^{3,1}$	cQq13	3.3	3	3.8	1.1 × 10	22	11	18	3.8 × 10		7.9 × 10	0.1 × 10	4.8 × 10
$c_{Qq}^{1,1}$	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					
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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		

12 top processes

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

SMEFTsim validation

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

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

Top 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 × 10² 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 × 10²		−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 × 10²		−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 × 10²									
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 × 10²	71	40	75					
c_{tq}^8	ctq8	13		27	2.6 × 10²	62	51	74					
c_{Qu}^8	cQu8												
c_{tu}^8	ctu8												
c_{Qd}^8	cQd8												
c_{td}^8	ctd8												
$c_{Qq}^{3,1}$	cQq13												
$c_{Qq}^{1,1}$	cQq11												
c_{tq}^1	ctq1												
c_{Qu}^1	cQu1												
c_{tu}^1	ctu1												
c_{Qd}^1	cQd1												
c_{td}^1	ctd1												
$c_{t\varphi}$	ctp												
$c_{\varphi Q}^-$	cpQM												
$c_{\varphi Q}^3$	cpQ3												
$c_{\varphi t}$	cpt												
$c_{\varphi tb}$	cptb												
c_{tW}	ctW												
c_{tZ}	ctZ												
c_{bW}	cbW												
c_{tG}	ctG												
$c_{t\varphi}^I$	ctpI												
$c_{\varphi tb}^I$	cptbI												
c_{tW}^I	ctWI												
c_{tZ}^I	ctZI												
c_{bW}^I	cbWI												
c_{tG}^I	ctGI												
$c_{Ql}^{3(1)}$	cQl31												
$c_{Ql}^{-(1)}$	cQlM1												
$c_{Qe}^{(1)}$	cQe1					−1.5					−0.39		
$c_{tl}^{(1)}$	ctl1				−0.0023	−3.6					−0.036		
$c_{te}^{(1)}$	cte1					−6.7					0.064		

12 top processes

~ 50 coefficients

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

$$
\begin{array}{ll|ll}
c_{QQ}^1 & \equiv 2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)} & c_{QQ}^8 & \equiv 8C_{qq}^{3(3333)} \\
c_{Qt}^1 & \equiv C_{qu}^{1(3333)} & c_{Qt}^8 & \equiv C_{qu}^{8(3333)} \\
\hline
c_{Qq}^{3,1} & \equiv C_{qq}^{3(ii33)} + \frac{1}{6}(C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}) & c_{Qq}^{3,8} & \equiv C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)} \\
c_{Qq}^{1,1} & \equiv C_{qq}^{1(ii33)} + \frac{1}{6}C_{qq}^{1(i33i)} + \frac{1}{2}C_{qq}^{3(i33i)} & c_{Qq}^{1,8} & \equiv C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)} \\
\hline
c_{t\varphi}^{[I]} & \equiv \underset{Re}{[Im]}\{C_{uH}^{(33)}\} & c_{Hq}^- & \equiv C_{Hq}^{1(33)} - C_{Hq}^{3(33)} \\
c_{HQ}^3 & \equiv C_{Hq}^{3(33)} & c_{Ht} & \equiv C_{Hu}^{(33)}
\end{array}
$$

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 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												
$c_{Qq}^{1,8}$	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				
$c_{Qq}^{1,1}$	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	2		
$c_{\varphi t}$	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					
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		
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$c_{te}^{(1)}$	cte1					−6.7					0.064		

12 top processes

~ 50 coefficients

both interference and quadratic terms

↓

1200+ numbers compared

SMEFTsim validation

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Top note: Aguilar-Saavedra et al. 1802.07237

3. Validation against `VBFNLO`

Arnold et al. 0811.4559,1107.4038, Baglio et al 1404.3940

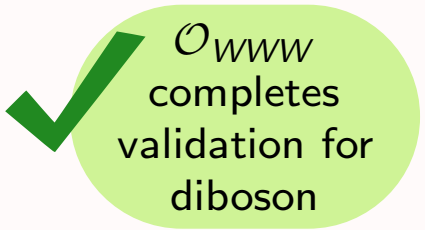
VBSCan Thessaloniki Workshop summary 1906.11332

`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



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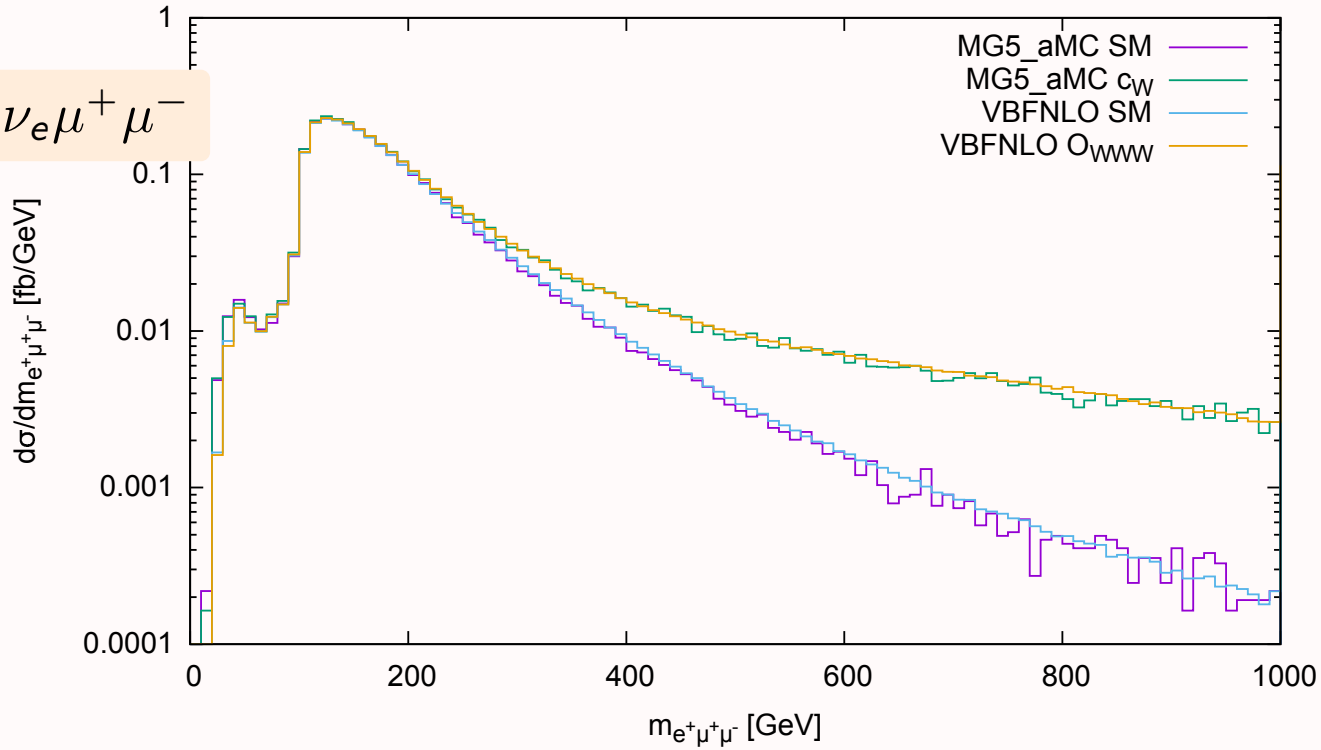
VBSCan Thessaloniki Workshop summary 1906.11332

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



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VBSCan Thessaloniki Workshop summary 1906.11332

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

SMEFT MC validation group, CERN-LPCC-2019-02

SMEFTsim validation

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2. Validation against `dim6top`

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

Top 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 1906.11332

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

SMEFT MC validation group, CERN-LPCC-2019-02

5. Validation against analytic expressions

Brivio,Trott SMEFT review 1706.08945
Brivio,Corbett,Trott 1906.06949
Brivio,Hays,Smith,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
...
```

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