The SM EFT
- a global approach -

Ilaria Brivio

Institut für Theoretische Physik,
Universität Heidelberg

work mostly developed at the
Niels Bohr Institute, University of Copenhagen
with M. Trott and T. Corbett

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):

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

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

C_i free parameters (Wilson coefficients)

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

The SMEFT – recent developments

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

The SMEFT – recent developments

B cons. $\mathbf{N_f = 1 \rightarrow}$ **2** **76** **22** **895**

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

$\mathbf{N_f = 3 \rightarrow}$ **12** **2499** **948** **36971**

- # of parameters known for all orders

Lehman 1410.4193
Lehman,Martin 1510.00372
Henning,Lu,Melia,Murayama 1512.03433

The SMEFT – recent developments

Weinberg PRL43(1979)1566

Lehman 1410.4193
Henning,Lu,Melia,Murayama 1512.03433

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

Leung,Love,Rao Z.Ph.C31(1986)433
Buchmüller,Wyler Nucl.Phys.B268(1986)621
Grzadkowski et al 1008.4884

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$

The SMEFT – recent developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$
- efficient matching techniques developed: CDE/UOLEA

$\rightsquigarrow$ Benjamin's talk

Henning,Lu,Murayama 1412.1837,1604.01019
del Aguila,Kunszt,Santiago 1602.00126
Drozd,Ellis,Quevillon,You 1512.03003
Ellis,Quevillon,You,Zhang 1604.02445,1706.07765
Fuentes-Martin,Portoles,Ruiz-Femenia 1607.02142
Zhang 1610.00710

The SMEFT – recent developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$
- efficient matching techniques developed: CDE/UOLEA

$\rightsquigarrow$ Benjamin's talk

- relation with the amplitude method

Shadmi,Weiss 1809.09644
Henning,Melia 1901.06747,1902.06754,1902.06747
Ma,Shu,Xiao 1902.06752

The SMEFT – recent developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$
- efficient matching techniques developed: CDE/UOLEA

$\rightsquigarrow$ Benjamin's talk

- relation with the amplitude method

$\mathcal{L}_6$: leading deviations from SM

- complete RGE available

Alonso,Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014
Grojean,Jenkins,Manohar,Trott 1301.2588
Alonso,Chang,Jenkins,Manohar,Shotwell 1405.0486
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706

The SMEFT – recent developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

⇝ Benjamin's talk

$\mathcal{L}_6$: leading deviations from SM

- complete RGE available
- many tree-level calculations of Higgs / EW / flavor observables

The SMEFT – recent developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$
- efficient matching techniques developed: CDE/UOLEA

⇝ Benjamin's talk

- relation with the amplitude method

$\mathcal{L}_6$: leading deviations from SM

- complete RGE available
- many tree-level calculations of Higgs / EW / flavor observables
- 1-loop results available for selected processes

⇝ Ben's talk

Pruna,Signer 1408.3565
Hartmann,(Shepherd),Trott 1505.02646,1507.03568,1611.09879
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Gauld,Pecjak,Scott 1512.02508, Dawson,Giardino 1801.01136
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460
Dedes,Paraskevas,Rosiek,Suxho,Trifyllis 1805.00302 ...

The SMEFT – recent developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$
- efficient matching techniques developed: CDE/UOLEA

⇝ Benjamin's talk

- relation with the amplitude method

$\mathcal{L}_6$: leading deviations from SM

- complete RGE available
- many tree-level calculations of Higgs / EW / flavor observables
- 1-loop results available for selected processes

⇝ Ben's talk

- formulation in R_ξ gauge

Dedes, Materkowska, Paraskevas, Rosiek, Suxho 1704.03888
Helset, Paraskevas, Trott 1803.08001

The SMEFT – recent developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$
- efficient matching techniques developed: CDE/UOLEA ⇝ Benjamin's talk
- relation with the amplitude method

$\mathcal{L}_6$: leading deviations from SM

- complete RGE available
- many tree-level calculations of Higgs / EW / flavor observables
- 1-loop results available for selected processes ⇝ Ben's talk
- formulation in R_ξ gauge
- various tools available for numerical analysis ⇝ SMEFT-Tools
  [MC generation, analytic calculation, fitting, matching, RGE running...]

The Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

More than a parameterization

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

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

More than a parameterization

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

- model-independent (within assumptions)
- allows systematic one-loop improvement, RG evolution ...

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

More than a parameterization

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

- model-independent (within assumptions)
- allows systematic one-loop improvement , RG evolution ...

- a general, systematic probe of new physics
- a universal language for data interpretation

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

A global approach

global $=$ **all** operators contributing to measured processes are retained *a priori*.
only selection criterion: physical impact.

A global approach

global = **all** operators contributing to measured processes are retained *a priori*.
only selection criterion: physical impact.

- goal: rather than putting constraints on specific anomalous interactions,
  measure the parameters of the SMEFT as a well-defined, self-consistent theory

A global approach

global $=$ **all** operators contributing to measured processes are retained *a priori*.
only selection criterion: physical impact.

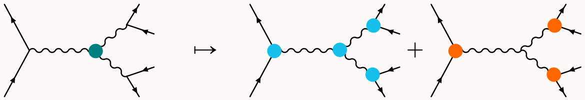
- goal: rather than putting constraints on specific anomalous interactions, **measure** the parameters of the SMEFT as a well-defined, self-consistent theory
- other selection criteria (e.g. correspondence with **anomalous couplings** / classification in **sectors**) are basis dependent

A global approach

global = **all** operators contributing to measured processes are retained *a priori*. only selection criterion: physical impact.

- goal: rather than putting constraints on specific anomalous interactions, **measure** the parameters of the SMEFT as a well-defined, self-consistent theory
- other selection criteria (e.g. correspondence with **anomalous couplings** / classification in **sectors**) are basis dependent

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

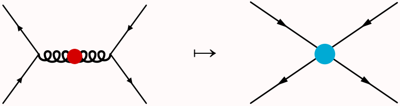


A global approach

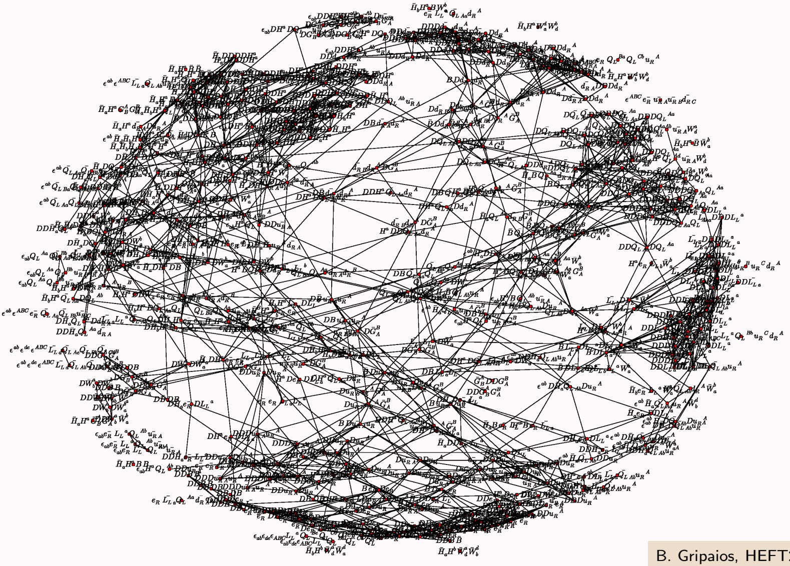
global = **all** operators contributing to measured processes are retained *a priori*.
only selection criterion: physical impact.

- goal: rather than putting constraints on specific anomalous interactions, **measure** the parameters of the SMEFT as a well-defined, self-consistent theory
- other selection criteria (e.g. correspondence with **anomalous couplings** / classification in **sectors**) are basis dependent

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



The need for a global analysis



B. Gripaios, HEFT2018

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 $\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) \to$ theo. accuracy $\gtrsim 1\%$

NLO not supported.

The SMEFTsim package

6 different implementations available

Brivio, Jiang, Trott 1709.06492

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

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

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

Authors

Ilaria Brivio, Yun Jiang and Michael Trott

ilaria.brivio@nbi.ku.dk, yunjiang@nbi.ku.dk, michael.trott@cern.ch

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

How many relevant parameters?

How many relevant parameters?

Depends on choices of low energy symmetries. e.g. flavor

How many relevant parameters?

Depends on choices of low energy symmetries. e.g. flavor

observables

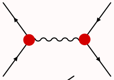
Focusing on **interference** $\mathcal{A}_{SM}\mathcal{A}_6^*$ (assume subdominant quadratic terms)

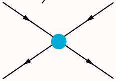
Selection due to SM kinematics / symmetries in the presence of:

- resonances in SM
- FCNCs op.
- dipole op. (interf. $\sim m_f$)
- ...

ψ^4 operators generally **suppressed** wrt. "pole operators" by

$$\left(\frac{\Gamma_B m_B}{v^2}\right)^n \sim \begin{array}{ll} 1/300 & (Z,W) \\ 1/10^6 & (h) \end{array}$$

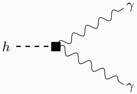




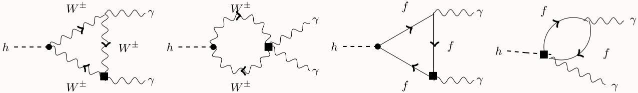
How many relevant parameters?

Depends on choices of
- low energy symmetries. e.g. flavor
- observables
- SMEFT accuracy

loop order



$C_{HW}\,,\ C_{HB}\,,\ C_{HWB}$



$+\ C_{W}\,,\ C_{HD}\,,\ C_{eW}\,,$
$C_{eB}\,,\ C_{uW}\,,\ C_{uB}\,,\ C_{dW}\,,$
$C_{dB}\,,\ C_{eH}\,,\ C_{uH}\,,\ C_{dH}$

Hartmann,Trott 1505.02646,1507.03568
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Dedes,Paraskevas,Rosiek,Suxho,Trifyllis 1805.00302

EFT order

$+$ dimension 8 $+\ \ldots$

How many relevant parameters?

Depends on choices of low energy symmetries. e.g. flavor

observables

SMEFT accuracy

---

resonant-dominated (**pole**) observables **@LO**

	total $N_f = 3$	WZH pole obs.
general	2499	~ 46
MFV	~ 108	~ 30
$U(3)^5$	~ 70	~ 24

Brivio,Jiang,Trott 1709.06492

How many relevant parameters?

Depends on choices of low energy symmetries. e.g. flavor

observables

SMEFT accuracy

---

resonant-dominated (**pole**) observables **@LO** → off-shell regions of parameter space (tails)

↓

NLO*

*NLO QCD corrections can be significant!

EW + Higgs - mostly pole obs. → 23 parameters

Brivio,Hays,Smith,Trott,Žemaitytė in preparation

Z,W couplings

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

$$\begin{aligned}
\mathcal{Q}_{HD} &= (D_\mu H^\dagger H)(H^\dagger D^\mu H)\\
\mathcal{Q}_{HWB} &= (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{Hl}^{(3)} &= (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)\\
\mathcal{Q}'_{ll} &= (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)
\end{aligned}$$

input quantities

Bhabha scattering

$$\begin{aligned}
\mathcal{Q}_{ee} &= (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{le} &= (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{ll} &= (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)
\end{aligned}$$

$$\begin{aligned}
\mathcal{Q}_{Hbox} &= (H^\dagger H)\,\square\,(H^\dagger H)\\
\mathcal{Q}_{HG} &= (H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}\\
\mathcal{Q}_{HB} &= (H^\dagger H)B_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{HW} &= (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}\\
\mathcal{Q}_{uH} &= (H^\dagger H)(\bar{q}\tilde{H}u)\\
\mathcal{Q}_{dH} &= (H^\dagger H)(\bar{q}Hd)\\
\mathcal{Q}_{eH} &= (H^\dagger H)(\bar{l}He)\\
\mathcal{Q}_{G} &= \varepsilon_{abc}G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho\\
\mathcal{Q}_{uG} &= (\bar{q}\sigma^{\mu\nu}T^a\tilde{H}u)G^a_{\mu\nu}
\end{aligned}$$

H processes

$$\mathcal{Q}_W = \varepsilon_{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

TGC

Application: global fits

large number of global SMEFT fits in the literature,
with different observable and operator sets.

examples:

EW

- Berthier,Trott 1508.05060
- Berthier,Bjørn,Trott 1606.06693
- Brivio,Trott 1701.06424

Higgs + EW

- Butter,Éboli,Gonzalez-Fraile,Gonzalez-Garcia, Plehn,Rauch 1604.03105
- Ellis,Murphy,Sanz,You 1803.03252
- da Silva,Alves,Rosa,Éboli,Gonzalez-Garcia 1812.01009
- Biekötter,Corbett,Plehn 1812.07587
- Brivio,Hays,Smith,Trott,Žemaitytė in preparation

⇝ Anke's talk

top sector

- Hartland,Maltoni,Nocera,Rojo,Slade,Vryonidou,Zhang 1901.05965
- Brivio,Bruggisser,Maltoni,Moutafis,Plehn,Vryonidou, Westhoff,Zerwas,Zhang in preparation

⇝ Sebastian's talk

⇝ Rhea's talk

An important observable: the Higgs width

a crucial observable for the Higgs sector

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

$\Rightarrow$ Higgs measurements can be factored into

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

An important observable: the Higgs width

a crucial observable for the Higgs sector

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

$\Rightarrow$ Higgs measurements can be factored into

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

SMEFT: probe separately production and decay

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

An important observable: the Higgs width

a crucial observable for the Higgs sector

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

$\Rightarrow$ Higgs measurements can be factored into

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

SMEFT: probe separately production and decay 👍

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

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

The Higgs width in the SMEFT

Analytic calculation of the inclusive Γ_H:

Brivio,Corbett,Trott 1906.06949

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

The Higgs width in the SMEFT

Analytic calculation of the inclusive Γ_H:

Brivio, Corbett, Trott 1906.06949

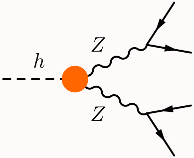
- LO in the EFT: up to Λ^{-2}.
- **tree level**.
  SM couplings $H\gamma\gamma, HZ\gamma, Hgg$ included for $H \to f\bar{f}\gamma \,/\, \gamma\gamma \,/\, gg$.
- Warsaw basis with $\mathbf{U(3)^5}$ **flavor symmetry**
- EW input scheme: $\{m_Z, m_W, G_F\}$
- full calculation for $h \to 4f$: narrow width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

Why analytic?

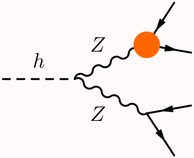
- control over different contributions
- easier to linearize in $\delta\Gamma_V, \delta m_V$
- more stable than MC for the massless fermions case with γ diagrams
- calculation can be **automated** once and for all
  $\to$ much faster than running MC every time

H → 4f in the SMEFT

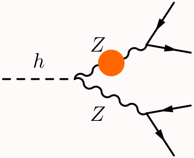
① corrections to SM diagrams



$\propto g_{\mu\nu}$ (SM-like)
$\propto g_{\mu\nu} p \cdot q - p_\nu q_\mu$



$\delta g_L, \delta g_R$

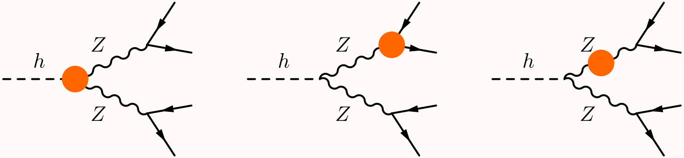


$$\frac{-i m_Z \delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

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

H → 4f in the SMEFT

① corrections to SM diagrams

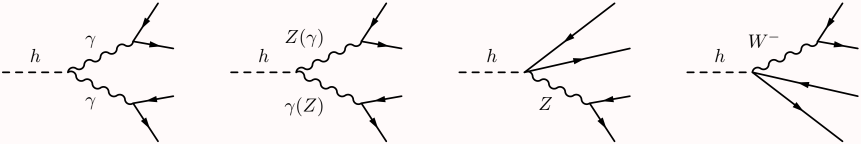


$\propto g_{\mu\nu}$ (SM-like)
$\propto g_{\mu\nu} p \cdot q - p_\nu q_\mu$

$\delta g_L, \delta g_R$

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

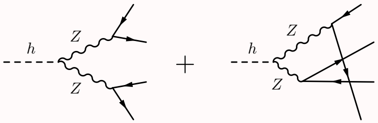
② genuine SMEFT diagrams



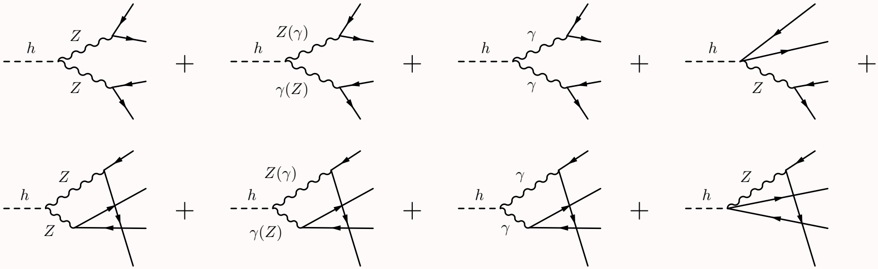
H → 4f in the SMEFT - complexity

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

SM

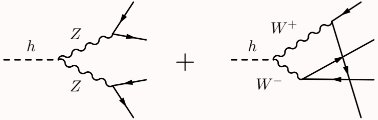


interfering with

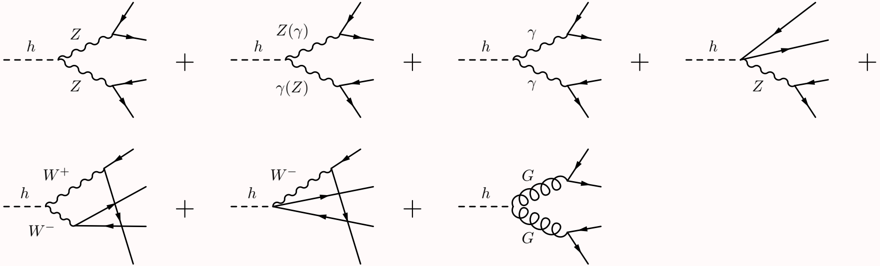


$h \to \bar{u}\, u\, \bar{d}\, d$

SM



interfering with



$H \to 4f$ - results

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

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

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

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

$H \to 4f$ - results

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

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

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

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

Impact of photon diagrams

☛ main contribution missed in the narrow width approx.

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

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

The total Higgs width in the SMEFT

putting together all the main contributions* we obtain

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

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

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

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

Summary & take-home

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

Summary & take-home

- The **SMEFT** is a well-defined, general framework for BSM searches
- 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 searches
- 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
- SMEFTsim is a powerful tool specifically designed for this purpose @LO

Summary & take-home

- The **SMEFT** is a well-defined, general framework for BSM searches
- 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
- SMEFTsim is a powerful tool specifically designed for this purpose @LO
- the Higgs inclusive width has been computed at LO in the SMEFT, including relevant, previously neglected contributions

Backup slides

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

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

$$\rightarrow$$

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

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

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

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

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

$$\alpha_{\rm em} = \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2}\left[1+\bar{v}^2 C_{HWB}\frac{\bar{g}_2^3/\bar{g}_1}{\bar{g}_1^2+\bar{g}_2^2}\right]$$
$$m_Z = \frac{\bar{g}_2\bar{v}}{2c_{\bar{\theta}}} + \delta m_Z(C_i)$$
$$G_f = \frac{1}{\sqrt{2}\bar{v}^2} + \delta G_f(C_i)$$

$\rightarrow$

$$\hat{v}^2 = \frac{1}{\sqrt{2}G_f}$$
$$\sin\hat{\theta}^2 = \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_f m_Z^2}}\right)$$
$$\hat{g}_1 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}}$$
$$\hat{g}_2 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}}$$

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

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

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

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

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

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

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

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

Shifts from input parameters

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

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

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

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

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

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

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

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

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

---

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:

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

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

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 $\begin{cases} \hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f \\ \hat{m}_W, \hat{m}_Z, \hat{G}_f \end{cases}$

---

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.:

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

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

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

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