Karlsruhe Institute of Technology

EFT Issues and Plans

Michael Rauch | VBSCAN year 1 mid-term meeting, 07 Feb 2018

INSTITUTE FOR THEORETICAL PHYSICS

EFT progress in WG1

- TWiki

  EFT Report 1
  https://twiki.cern.ch/twiki/bin/view/VBSCan/ShortTermTopics
- pre-meeting jointly with WG2 (June 2017)

  Indico: https://indico.cern.ch/event/647015/
- meeting in Karlsruhe after MBI (August 2017)

  Indico: https://indico.cern.ch/event/652320/
- EFT kickoff meeting (December 2017)

  Indico: https://indico.cern.ch/event/688550/
- WG1 periodic meeting (January 2018)

  Indico: https://indico.cern.ch/event/689683/

EFT progress in WG1

Discussion about various topics

- parametrization for $d = 6$ and $d = 8$ operators
- best ways to report data
- validity of the EFT approach in the high-energy region
- $\leftrightarrow$ unitarization methods
- ...

Questions from joint WG2-WG3 meeting

- Which operators most interesting?
- More info than inclusive aQGC limits?
- Include Higgs data?
- Combine 8 and 13 TeV data?

$\rightarrow$ some personal remarks during the talk
$\rightarrow$ joint Vidyo meeting in few weeks

First Steps

Effective Field Theory (EFT) as description of physics at higher energies

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

$\rightarrow$ lowest contribution from dimension-6 operators

$\rightarrow$ define framework for $d = 6$

- look at Monte Carlo codes and compare them
- choose 1 or 2 operator sets (bases) for $d = 6$ (best candidates: Warsaw, HISZ)
- identify the relevant operators (sizable tree-level interference with SM)
  - select experimentally relevant VBS process (1, possibly 2)
  - define optimal kinematic cuts for signal regions
  - can we neglect some contributions safely?
  - how far can we go?
    $\leftrightarrow$ longitudinal / transverse polarization? identify CP?
  - which input scheme? $\{\alpha, M_Z, G_F\}$, $\{M_W, M_Z, G_F\}$, ...?

Further Steps

Karlsruhe Institute of Technology

- study impact of each operator on cross section / distributions
- look for selection cuts that distinguish between operators

  $\rightarrow$ reduce number of parameters / look at subsets

  "divide and conquer"
- analysis with multiple operators at the same time
- extend to several VBS channels
- ...

Code Comparison

- several implementations available
  - SMEFTsim [Brivio, Jiang, Trott]
  - VBFNLO [MR, Zeppenfeld *et al.*]
  - Whizard [Reuter, Song; Sekulla *et al.*]
- $\rightarrow$ document codes and their features
- $\rightarrow$ compare codes and their features

$\rightarrow$ Agreement?

$\rightarrow$ Differences understood?

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 $\not{CP}$ terms
2. automatic field redefinitions to have **canonical kinetic terms**
3. automatic **parameter shifts** due to the choice of an input parameters set

Main scope:

estimate **tree-level** $|\mathcal{A}_{SM}\mathcal{A}^*_{d=6}|$ **interference** → th. accuracy $\sim$ %

* at the moment only LO, unitary gauge implementation

[Ilaria]

The SMEFTsim package

6 different frameworks implemented

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

in 2 independent, equivalent models sets (A, B) for debugging & validation

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

[Ilaria]

VBFNLO

[MR, Zeppenfeld, *et al.*]

- Implementation of D6 operators available for all VBS processes
- HISZ formulation, i.e. no operators with fermions
- both CP-even and CP-odd operators:

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right] \qquad \mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}\left[\widetilde{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right]$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger\,\widehat{W}^{\mu\nu}\,(D_\nu\Phi) \qquad \mathcal{O}_{\widetilde{W}} = (D_\mu\Phi)^\dagger\,\widetilde{W}^{\mu\nu}\,(D_\nu\Phi)$$

$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger\,\widehat{B}^{\mu\nu}\,(D_\nu\Phi) \qquad \mathcal{O}_{\widetilde{B}} = (D_\mu\Phi)^\dagger\,\widetilde{B}^{\mu\nu}\,(D_\nu\Phi)$$

$$\mathcal{O}_{WW} = \Phi^\dagger\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{\widetilde{W}W} = \Phi^\dagger\widetilde{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BB} = \Phi^\dagger\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi \qquad \mathcal{O}_{\widetilde{B}B} = \Phi^\dagger\widetilde{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{B\widetilde{W}} = \Phi^\dagger\widehat{B}_{\mu\nu}\widetilde{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{D\widetilde{W}} = \mathrm{Tr}\left[[D^\mu,\widetilde{W}^{\nu\rho}][D_\mu,\widetilde{W}_{\nu\rho}]\right]$$

(only 5 of the CP-odd operators linearly independent:

$$\mathcal{O}_{B\widetilde{W}} = -2\mathcal{O}_{\widetilde{B}} - \mathcal{O}_{\widetilde{B}B} = -2\mathcal{O}_{\widetilde{W}} - \mathcal{O}_{\widetilde{W}W} \qquad)$$

VBFNLO

[MR, Zeppenfeld, *et al.*]

- Implementation of D6 operators available for all VBS processes
- HISZ formulation, i.e. no operators with fermions
- both CP-even and CP-odd operators
- unitarization via dipole form factor

$$F = \left(1 + \frac{m^2_{\text{inv},\sum \ell}}{\Lambda^2}\right)^{-p}$$

  - $m_{\text{inv},\sum \ell}$: invariant mass of the leptons ($\sim$ boson pair)
  - Λ: characteristic scale where form factor effect becomes relevant
  - p: exponent controlling the damping

other choices easily implementable

$\rightarrow$ studies on validity range

`https://www.itp.kit.edu/vbfnlo`

6-dimensional operators

- $\mathcal{O}_6 = (\Phi^\dagger\Phi)^3$
- $\mathcal{O}_\Phi = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$
- $\mathcal{O}_T = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)$
- $\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$
- $\mathcal{O}_W = \epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
- $\mathcal{O}_{DB} = (\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\partial^\nu B_{\mu\nu})$
- $\mathcal{O}_{DW} = (\Phi^\dagger \tau^I i \overleftrightarrow{D}^\mu \Phi)(D^\nu W_{\mu\nu})^I$
- $\mathcal{O}_{D\Phi B} = i(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$
- $\mathcal{O}_{D\Phi W} = i(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)W^I_{\mu\nu}$

Features

- selected set of D6 operators
- compared to old Madgraph D6 implementation
- no field redefinitions to obtain canonical form

[Marco S.]

Code Comparison

- pick one VBS process as example

  suggestion: $pp \to e^+\nu_e\mu^+\nu_\mu$ jj (same-sign W^+W^+ production via VBS)

  - existing SM setup ($\to$ MC comparison)
  - fewer Feynman diagrams $\to$ less CPU time needed
  - largest experimental sensitivity

- restrict to a small subset of operators
  - $\mathcal{O}(3-4)$
  - representative of different features: longitudinal, transverse, CP-odd

- compare the codes numerically and understand any differences showing up

Impact of Current Limits

Investigate impact of D6 vs D8 operators on VBS

D6 input: Global Higgs and Gauge analysis of run-I data

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]

Take results and apply to vector-boson scattering

$\Rightarrow$ No contribution from $\mathcal{O}_{GG}$ and fermionic operators

$f_x/\Lambda^2[\text{TeV}^{-2}]$	LHC–Higgs + LHC–TGV + LEP–TGV Best fit	95% CL interval
f_{WW}	-0.1	$(-3.1, 3.7)$
f_{BB}	0.9	$(-3.3, 6.1)$
f_W	1.7	$(-0.98, 5.0)$
f_B	1.7	$(-11.8, 8.8)$
f_{WWW}	-0.06	$(-2.6, 2.6)$
$f_{\phi,2}$	1.3	$(-7.2, 7.5)$

For simplicity: use pos. and neg. 95% CL bound with other parameters set to zero
$\rightarrow$ slightly larger effect than true 95% CL bound

Additionally:

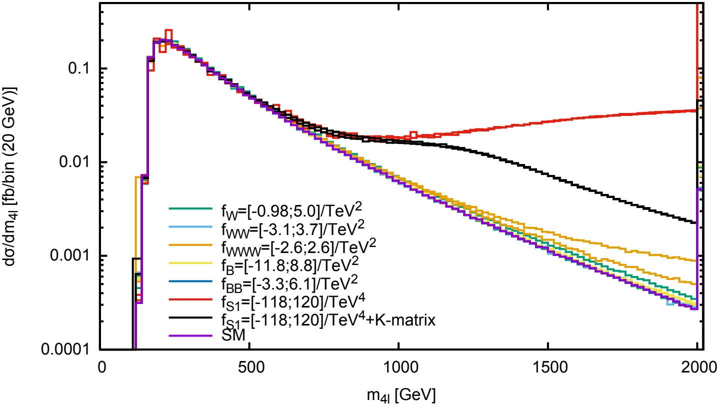
effect from dimension-8 operator $\mathcal{O}_{S,1}$

using CMS, $W^\pm W^\pm jj$, $\sqrt{S} = 8$ TeV, no unitarization [arXiv:1410.6315]

$$f_{S,1}/\Lambda^4 \in (-118, 120)\text{TeV}^{-4} \qquad (\text{for } f_{S,0}/\Lambda^4 = 0)$$

Results

Process: $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$, $\sqrt{S} = 13$ TeV, VBF cuts, NLO QCD

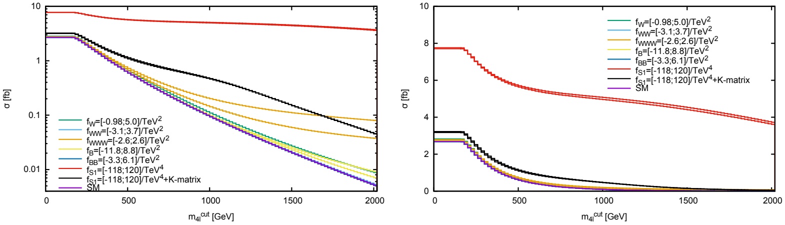


- last bin: overflow bin, $m_{4\ell} > 2000$ GeV
- effect of D6 contributions in general small; largest one by $\mathcal{O}_{WWW}$
- D8 operator dominating

Results

Process: $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$, $\sqrt{S} = 13$ TeV, VBF cuts, NLO QCD

cross section when requiring $m_{4\ell} > m_{4\ell}^{\text{cut}}$



- $\mathcal{O}_{WWW}$ contribution large only for very high $m_{4\ell} \leftrightarrow$ low event counts

  excess of 10 events for $m_{4\ell} > 1$ TeV, $\mathcal{L} = 100$ fb^{-1}, SM contrib. of 10 events
  other D6 operators below 1 event

- $\mathcal{O}_{S1}$ yielding large excess even without cuts on $m_{4\ell}$

  excess of almost 500 events for $m_{4\ell} > 1$ TeV, $\mathcal{L} = 100$ fb^{-1}
  even after unitarization excess of 37 events

Unitarization

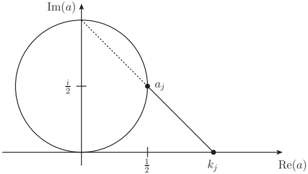
Anomalous gauge couplings spoil cancellation
$\leftrightarrow$ effects can become large $\rightarrow$ unitarity violation $\rightarrow$ unphysical

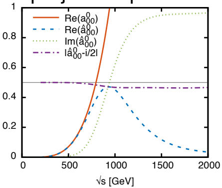
Several solutions:

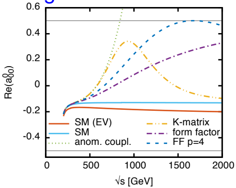
- consider only unitarity-conserving phase-space regions
  loses some information $\rightarrow$ possibly reduced sensitivity
  cut on relevant region might not be directly accessible ($m_{4\ell}$ vs. neutrinos)
- (dipole) form factor multiplying amplitudes

$$\mathcal{F}(s) = \frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n} \qquad \Lambda_{FF}^2,\ n\text{: free parameters}$$

- K-/T-matrix unitarization [Alboteanu, Kilian, Reuter, Sekulla]
  based on partial-wave analysis [Jacob, Wick]
  project amplitude back onto Argand circle

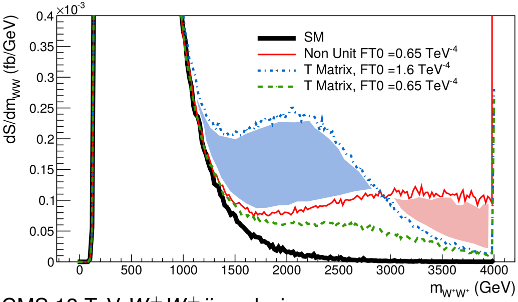






Effect on Operators

[Perez, Sekulla, Zeppenfeld]



[G. Perez]

- take recent CMS 13 TeV W^+W^+jj analysis
- re-interpret cross section in highest $m_{\ell\ell}$ bin
- non-unitarized:
  experimental bounds from high mass range → probing unitarity-violating region
- T-matrix unitarization:
  significantly lower cross section ↔ need to increase parameter to get same xs
  ↔ probing different energy range

→ differential information definitely helpful

Summary

- Comparison of different EFT codes
  - SMEFTsim [Brivio, Jiang, Trott]
  - VBFNLO [MR, Zeppenfeld *et al.*]
  - Whizard [Reuter, Song; Sekulla *et al.*]
- pick single process
- restrict to small subset of operators

  $\rightarrow$ timeline: 3-6 months

- pheno studies

We are open to suggestions for other codes!

Backup

Form of the Operators

linear EFT:

$SU(3)_c \times SU(2)_L \times U(1)_Y$ as conserved gauge groups

[Buchmüller, Wyler; Hagiwara et al; Grzadkowski et al; . . .]

building blocks:

- Higgs field Φ
- covariant derivative D^μ ($\rightarrow \partial^\mu$ when acting on singlets)
- field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$
- fermion fields ψ

$\Rightarrow$ construct all combinations which are

- Lorentz-invariant
- invariant under the gauge groups
- hermitian

Form of the Operators

Example 1:

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi$$
$$\frac{1}{2}\mathcal{O}_{\phi W} = \frac{1}{2} \mathrm{Tr}\left[\widehat{W}^{\mu\nu}\widehat{W}_{\mu\nu}\right] \Phi^\dagger \Phi$$

lead to same contribution to Feynman rules $\rightarrow$ equivalent

Example 2:

$$\partial_\mu \left(\Phi^\dagger \widehat{W}^{\mu\nu} (D_\nu \Phi)\right)$$
$$= (D_\mu \Phi)^\dagger \widehat{W}^{\mu\nu} (D_\nu \Phi) + \Phi^\dagger \left(\partial_\mu \widehat{W}^{\mu\nu}\right) (D_\nu \Phi) + \Phi^\dagger \widehat{W}^{\mu\nu} (D_\mu D_\nu \Phi)$$

total derivative in Lagrangian gives no contribution to equations of motion

$\rightarrow$ only two of the operators on right-hand side linearly independent

can use equations of motion to rewrite expressions

$\rightarrow$ 59 D6 operators (2499 for flavour non-universality) [Grzadkovski *et al.*]

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)

Alonso,Jenkins,Manohar,Trott 1312.2014

[Ilaria]

Field redefinitions

Higgs

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

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

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

Alonso,Jenkins,Manohar,Trott 1312.2014

[Ilaria]

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

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

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

[Ilaria]

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

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

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

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

[Ilaria]

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

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

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

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

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

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

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

[Ilaria]

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

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

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

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

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

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

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

[Ilaria]

SMEFTsim: implemented frameworks

6 different frameworks implemented:

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

[Ilaria]

SMEFTsim: implemented frameworks

6 different frameworks implemented:

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

---

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:

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

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

[Ilaria]

SMEFTsim: implemented frameworks

6 different frameworks implemented:

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

---

assume $U(3)^5$ symmetry + CKM only source of $\not{CP}$

- 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.:

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

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

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

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

[Ilaria]