Karlsruhe Institute of Technology

EFT Comparison

in collaboration with Ilaria Brivio

Michael Rauch | VBSCAN 2nd Annual Meeting, 20 Jun 2018

INSTITUTE FOR THEORETICAL PHYSICS

EFT progress in WG1

Karlsruhe Institute of Technology

- 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/

- STSM of Ilaria and MR in Milano (March 2018)

- EFT Comparison meeting in Milano (March 2018)

  Indico: https://indico.cern.ch/event/709162/

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

- 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 ~ %

* at the moment only LO, unitary gauge implementation

[Brivio]

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

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

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Pre-exported UFO files (include restriction cards)

	Set A		Set B	
	α scheme	m_W scheme	α scheme	m_W scheme
Flavor general SMEFT	SMEFTsim_A_general_alphaScheme_UFO.tar.gz	SMEFTsim_A_general_MwScheme_UFO.tar.gz	SMEFT_alpha_UFO.zip	SMEFT_mW_UFO.zip
MFV SMEFT	SMEFTsim_A_MFV_alphaScheme_UFO.tar.gz	SMEFTsim_A_MFV_MwScheme_UFO.tar.gz	SMEFT_alpha_MFV_UFO.zip	SMEFT_mW_MFV_UFO.zip
$U(3)^5$ SMEFT	SMEFTsim_A_U35_alphaScheme_UFO.tar.gz	SMEFTsim_A_U35_MwScheme_UFO.tar.gz	SMEFT_alpha_FLU_UFO.zip	SMEFT_mW_FLU_UFO.zip

[Brivio]

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:

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger\,\widehat{W}^{\mu\nu}\,(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger\,\widehat{B}^{\mu\nu}\,(D_\nu\Phi)$$
$$\mathcal{O}_{WW} = \Phi^\dagger\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi$$
$$\mathcal{O}_{BB} = \Phi^\dagger\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}\left[\widetilde{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right]$$
$$\mathcal{O}_{\widetilde{W}} = (D_\mu\Phi)^\dagger\,\widetilde{W}^{\mu\nu}\,(D_\nu\Phi)$$
$$\mathcal{O}_{\widetilde{B}} = (D_\mu\Phi)^\dagger\,\widetilde{B}^{\mu\nu}\,(D_\nu\Phi)$$
$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger\widetilde{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi$$
$$\mathcal{O}_{\widetilde{B}B} = \Phi^\dagger\widetilde{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi$$
$$\mathcal{O}_{B\widetilde{W}} = \Phi^\dagger\widehat{B}_{\mu\nu}\widetilde{W}^{\mu\nu}\Phi$$
$$\mathcal{O}_{D\widetilde{W}} = \mathrm{Tr}\left[[D^\mu,\widetilde{W}^{\nu\rho}][D_\mu,\widetilde{W}_{\nu\rho}]\right]$$

(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

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

Features

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

[Sekulla]

Code Comparison

- started late March between MG5_aMC + SMEFTsim and VBFNLO

SMEFTsim	VBFNLO
complete $d = 6$ Warsaw basis	$d = 6$ HISZ basis $d = 8$ Éboli basis
tree-level EFT	tree-level EFT
$\{ M_W, M_Z, G_F \}$ input	$\{ M_W, M_Z, G_F \}$ input
can compute separately contributions of different order in anomalous coupling	computes squared matrix element with all powers of operator insertions
computes matrix elements using pure EFT expansion	allows unitarization of cross sections by different methods

Testing Setup: Diboson W^+Z

First test with simpler process:

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

- $\sqrt{s} = 13$ TeV, LO
- $\mu_F = 91.188$ GeV, PDF `PDF4LHC15_nlo_mc_pdfas`
- generic cuts:

$$p_{T,\text{miss}} > 20 \text{ GeV} \qquad p_{T,\ell} > 20 \text{ GeV} \qquad R_{\ell\ell} > 0.4 \qquad m_{\ell\ell} > 15 \text{ GeV}$$

- parameters:

$$M_W = 80.387 \text{ GeV} \quad M_Z = 91.1876 \text{ GeV} \quad G_F = 1.166379 \cdot 10^{-5} \text{ GeV}^{-2}$$
$$m_t = 173.2 \text{ GeV} \quad m_b = 4.18 \text{ GeV} \quad m_{u,d,c,s,e,\mu} = 0$$

  widths autocalculated by codes (LO)
  $\to$ manually switch off NLO QCD corrections to $W, Z \to q\bar{q}$ in VBFNLO
- statistics: MG5_aMC 10^5 events, VBFNLO 2^{26} MC points, 6 iterations

Diboson W^+Z Results

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

code	integrated c.s.
MG5_aMC	27.30 ± 0.03 fb
VBFNLO	27.24 ± 0.01 fb

Anomalous couplings:

- SM $+ \frac{c_W}{\mathrm{TeV}^2} \epsilon_{ijk} W^{i,\mu}{}_{\nu} W^{j,\nu}{}_{\rho} W^{k,\rho}{}_{\mu}$
- with up to 2 c insertions in $\mathcal{A} \to$ include c^4 terms in $|\mathcal{A}|^2$
- corresponds to $\mathcal{O}_{WWW} = \frac{f_{WWW}}{\Lambda^2} \mathrm{Tr}[\widehat{W}^{\mu}{}_{\nu} \widehat{W}^{\nu}{}_{\rho} \widehat{W}^{\rho}{}_{\mu}]$ in VBFNLO
- relation: $\frac{c_W}{\mathrm{TeV}^2} = \frac{g^3}{4} \frac{f_{WWW}}{\Lambda^2}$
- example: $c_W = 1$

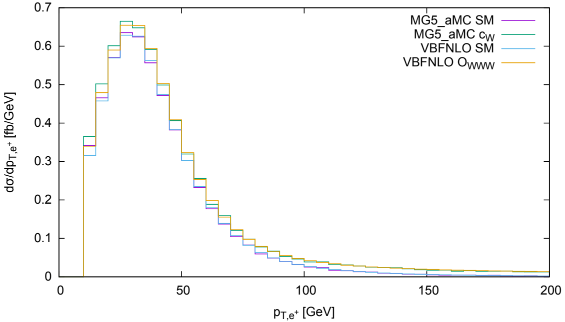
code	integrated c.s.
MG5_aMC + SMEFTsim	32.80 ± 0.03 fb
VBFNLO	32.78 ± 0.01 fb

$\to$ good agreement

Diboson W^+Z Results

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

→ Distributions:

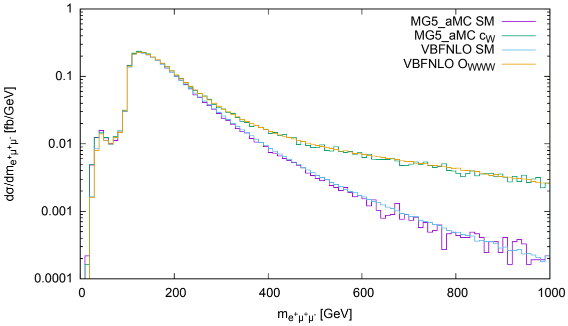


→ good agreement within statistical uncertainties

Diboson W^+Z Results

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

→ Distributions:



→ good agreement in all tested distributions

→ continue with VBS

VBS Process same-sign W^+W^+jj

VBS process:

$$pp \to e^+\nu_e\mu^+\nu_\mu jj$$

- $\sqrt{s} = 13$ TeV, LO
- $\mu_F = 91.188$ GeV, PDF `PDF4LHC15_nlo_mc_pdfas`
- generic cuts:

$$p_{T,j} > 20\text{ GeV} \quad |\eta_j| < 4.5 \quad m_{jj} > 500\text{ GeV} \quad |\Delta\eta_{jj}| > 2.5$$
$$p_{T,\ell} > 20\text{ GeV} \quad |\eta_\ell| < 2.5 \quad m_{\ell\ell} > 15\text{ GeV} \quad p_{T,\text{miss}} > 40\text{ GeV}$$
$$R_{\ell j} > 0.3 \quad R_{\ell\ell} > 0.3$$

- statistics: MG5_aMC 10^4 events, VBFNLO 2^{26} MC points, 6 iterations

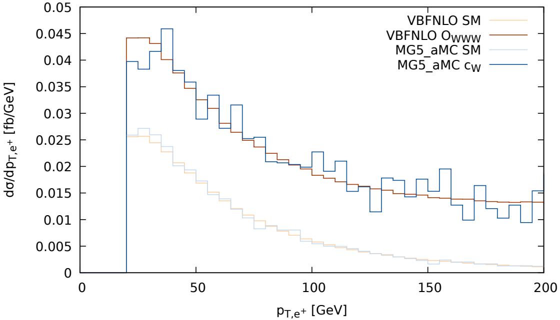
code	SM	$\mathcal{O}_{WWW}$	$\mathcal{O}_{WWW}$ (NP=1)
MG5_aMC + SMEFTsim	1.602 ± 0.003 fb	40.36 ± 0.01 fb	2.854 ± 0.004 fb
VBFNLO	1.5928 ± 0.0005 fb	36.89 ± 0.02 fb	—

$\to$ good agreement in SM case, more statistics needed for anomalous couplings

VBS Process same-sign W^+W^+jj

$$pp \to e^+\nu_e\mu^+\nu_\mu jj$$

→ Distributions:

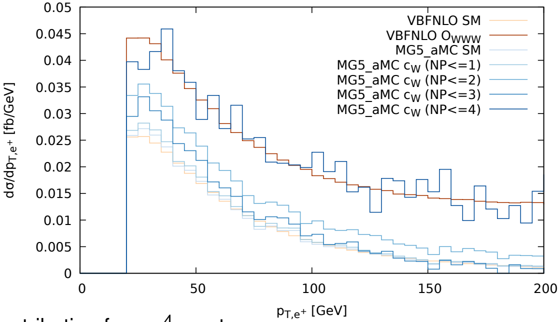


→ good agreement

VBS Process same-sign W^+W^+jj

$$pp \to e^+\nu_e\mu^+\nu_\mu jj$$

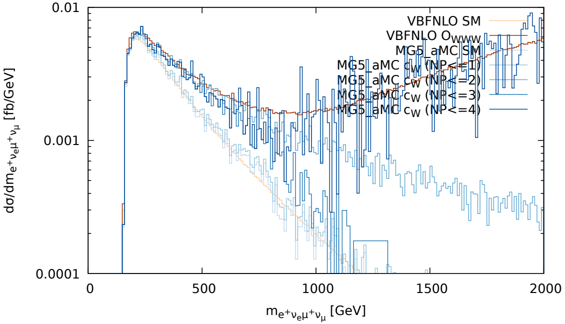
can use feature of MG5_aMC + SMEFTsim:
break down insertion of anomalous coupling to different orders
$\to$ handle on EFT expansion



- largest contribution from c_W^4 part
- $\leftrightarrow$ leading term should be linear
- $\leftrightarrow$ large anomalous coupling chosen

VBS Process same-sign W^+W^+jj

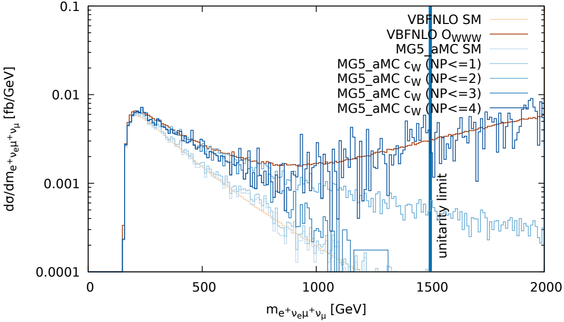
$$pp \to e^+\nu_e\mu^+\nu_\mu jj$$



- anomalous coupling shows large growth at large $m_{4\ell}$ values
- eventually violation of unitarity
  (break-down of expansion, neglected terms in series become equally relevant)

VBS Process same-sign W^+W^+jj

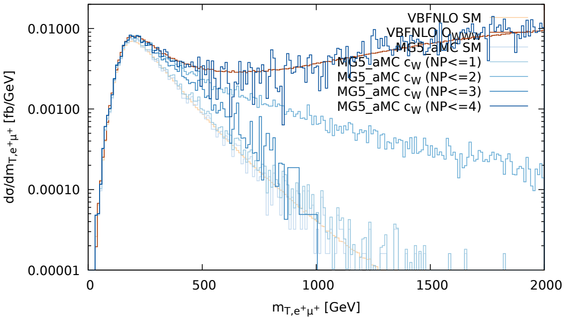
$$pp \to e^+\nu_e\mu^+\nu_\mu jj$$



- limit of tree-level unitarity in $2 \to 2$ scattering process via partial-wave analysis
- calculated with VBFNLO formfactor tool
- violated for $m_{4\ell} \gtrsim 1.5$ TeV

VBS Process same-sign W^+W^+jj

$$pp \to e^+ \nu_e \mu^+ \nu_\mu jj$$



$$m_{T,e^+\mu^+} = \sqrt{\left(p_{e^+} + p_{\mu^+} + p_{T,\text{miss}}\right)^2} \qquad \text{(four-vector sum, } p^2_{T,\text{miss}} \overset{!}{=} 0\text{)}$$

Summary

- comparison of different EFT codes
- first tests successful with
  - SMEFTsim (with MG5_aMC) [Brivio, Jiang, Trott]
  - VBFNLO [MR, Zeppenfeld *et al.*]
- interesting physics aspects already appearing (linear vs. all insertions)
- extend to more operators

  $\stackrel{?}{\rightarrow}$ also look at Higgs EFT (different expansion)
- pheno studies
- include other codes
  - Whizard [Reuter, Song; Sekulla *et al.*]
  - Sherpa + SMEFTsim ? [Gomez-Ambrosio]

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 ($\to \partial^\mu$ 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:

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

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

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:

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

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

[Brivio]

Field redefinitions

Higgs

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

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

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

Alonso,Jenkins,Manohar,Trott 1312.2014

Shifts from input parameters

SM case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar{\theta}}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

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

$$\rightarrow$$

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

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

[Brivio]

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

[Brivio]

Shifts from input parameters

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

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

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

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

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

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

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

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

[Brivio]

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

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

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

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

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

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

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

[Brivio]

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

[Brivio]

SMEFTsim: implemented frameworks

6 different frameworks implemented:

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

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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:

$$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_r \gamma^\mu u_s)\, \delta_{rs}$$
$$\mathcal{Q}_{eB} = B_{\mu\nu}(\bar{l}_r H \sigma^{\mu\nu} e_s)\, (\mathbf{Y_l})_{rs}$$

[Brivio]

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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.:

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

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

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

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

[Brivio]

Unitarization

Anomalous gauge couplings spoil cancellation
↔ effects can become large → unitarity violation → unphysical

Several solutions:

- consider only unitarity-conserving phase-space regions
  loses some information → 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