Monte Carlo SMEFT predictions for the LHC

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SMEFT @ LHC

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

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

- odd dimensions typically neglected because of L/B violation
- leading effects expected at dim 6 → main focus of this talk
- dim 8 (increasingly) studied as subleading / uncertainty on dim 6

Plan of the talk

1. An overview of Monte Carlo predictions for SMEFT @LHC ⇝ **Ken**'s talk
2. More details about `SMEFTsim`
   [generalities + updates since last SMEFT-Tools]

IB,Jiang,Trott 1709.06492, IB 2012.11343
`smeftsim.github.io`

SMEFT corrections to LHC processes

$$\int d\Phi \quad \int \text{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

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could PDF fits absorb SMEFT away?

- SMEFT effects within unc. for Run I-II
- can be sizeable for HL-LHC pred.

Carrazza et al 1905.05215
Greljo et al. 2104.02723
Iranipour,Ubiali 2201.07240

$\varepsilon \cdot A$

acceptances for SM and SMEFT differ if Lorentz structure changes

ATLAS 2004.03447
ATLAS-CONF-2020-053
ATL-PHYS-PUB-2022-037

EFT impact can depend on jet def.

Haisch et al 2204.00663

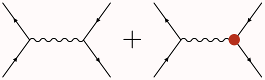
ME-PS matching has to include soft/collinear em. from EFT

Goldouzian et al 2012.06872
Haisch et al 2204.00663

SMEFT corrections to LHC processes

$$\int d\Phi \quad \int \mathrm{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

$$A_{SMEFT} = A_{SM} + \sum_i \left(C_i^{(6)}/\Lambda^2 \right) A_i$$



$$|A_{SMEFT}|^2 = |A_{SM}|^2 + \sum_i \frac{C_i^{(6)}}{\Lambda^2} 2Re\left(A_{SM} A_i^\dagger\right) + \sum_{i,j} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} |A_i A_j^\dagger|$$

$\times$ (SM K-factor)

interference/linear

quadratics

- A_{SMEFT} typically computed up to 1-loop in QCD / EW
- $\int d\Phi \int \mathrm{PDFs}\, |A_{SMEFT}|^2$

  can be computed with **Monte Carlo gen.** up to 1-loop in QCD

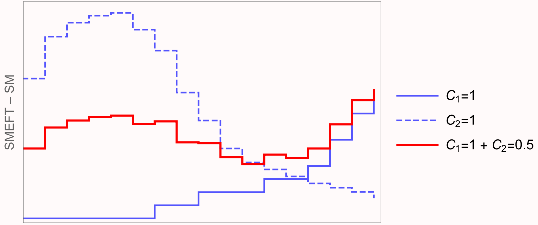
MC simulations for SMEFT

Most used: MadGraph5_aMC@NLO

- maximal flexibility in terms of processes
- interaction orders syntax facilitates **morphing**
- offers an integrated **reweighting** module — Gainer et al. 1404.7129, Mattelaer 1607.00763
- supports polarized matrix elements — Buarque-Franzosi,Mattelaer,Ruiz,Shil 1912.01725
- recent updates (from 2.9.0) — Mattelaer, Ostrolenk 2102.00773
  optimized **phase space integrator** + new algorithm for amplitude evaluation
  → faster and more agile for EFT, when several diagrams are 0

Morphing of EFT signal

@ LHC one is typically interested in kinematic distributions
→ final shape is a superposition of SMEFT effects depending on C_k



the parameterization has to be **polynomial** in C_k in each bin:

$$n^i(C_1, C_2) = n^i_{SM} + C_1\, a^i_1 + C_2\, a^i_2\, (+C_1^2\, b^i_1 + C_2^2\, b^i_2 + C_1 C_2\, b^i_{12})$$

→ morphing = **determine n^i_{SM}, a^i_k, (b^i_k, b^i_{kl}) for each bin i**

→ for N coeff. requires: $(1+N)$ event generations for SM + interferences
$N(N+1)/2$ for quadratics

much more efficient than evaluating n_i on N-dimensional grid!

Reweighting procedure

1. simulate a process in a certain setup (A) $\rightarrow$ unweighted events
2. "convert" to a different model/parameter space point (B) by scaling **weight** W event by event

$$W_B = \frac{|A_B|^2}{|A_A|^2} W_A$$

- ✔ re-use event samples: much **faster** than re-generating
- ✔ relation between W_B from W_A has arbitrary **numerical precision**
- ✔ **smaller stat. uncertainties** in ratios/sums/diffs of SM(EFT) components

$$\text{two indep. sim.} \rightarrow \quad \sigma\left[\frac{n(B)}{n(A)}\right] = \sqrt{\sigma\left[n(B)\right]^2 + \sigma\left[n(A)\right]^2}$$

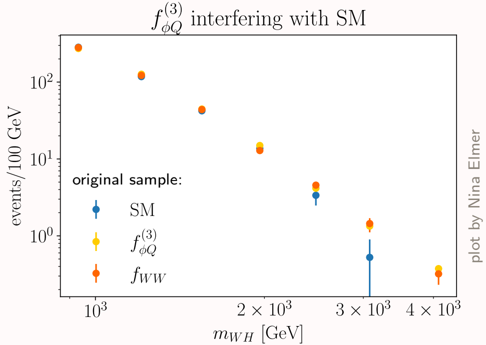
$$n(B) \text{ from rwgt of } n(A) \rightarrow \quad \sigma\left[\frac{n(B)}{n(A)}\right] = 0 \quad \text{[fully correlated]}$$

essentially recycling phase-space integration, re-evaluating only matrix element

Reweighting procedure – caveats

⚠ **phase space sampling** has to be adequate for both A and B

⚠ too small statistics in a given bin can lead to large over/under-estimations



→ SM sample missing statistics in 3 highest bins

→ statistics is important to integrate properly over non-shown variables

⚠ MG5 uses **dynamical phase sp. integration**: adapts to process, doesn't "factorize" dependence reduced with large # events (smaller stat error)

UFO models for SMEFT

most used:

SMEFTsim IB,Jiang,Trott 1709.06492, IB 2012.11343

- only tree level
- full Warsaw basis (incl ~~CP~~) in various flavor version
- full dependence on m_ψ, CKM, leading spurions

SMEFT@NLO Degrande,Durieux,Maltoni,Mimasu,Vryonidou,Zhang 2008.11743 ⇝ Ken's talk

- up to 1-loop QCD
- full Warsaw basis with CP and $U(3)_d \times U(2)_u \times U(2)_q \times U(1)^3_{l+e}$
- 5-flavor scheme $(m_b = 0 = y_b, V_{CKM} = \mathbb{1})$

dim6top Durieux,Zhang 1802.07237

- only tree level, same flavor sym as in SMEFT@NLO + expl. breakings
- only top operators, including FCNC

more with alternative operator sets/bases (also dim8) in FeynRules database

validation protocol Durieux et al 1906.12310

based on dedicated MG5 module that performs single-event comparisons

→ extensive cross-comparisons performed for SMEFTsim, SMEFT@NLO, dim6top

Simulations with other Monte Carlo generators

- **Sherpa** ⇝ more talks at indico.cern.ch/event/971724/

  supports UFO and interaction order specifications Höche,Kuttimalai,Schumann,Siegert 1412.6478

- **POWHEG-BOX**

  hard-coded matrix elements. some processes available in SMEFT NLO QCD:
  - EW Higgs production — Mimasu,Sanz,Williams 1512.02572
  - diboson — Baglio,Dawson,(Homiller,Lewis) 1812.00214, 1909.11576
  - $\ell\ell$ Drell Yan up to dim 8 — Alioli,Dekens,Girard,Mereghetti 1804.07407; Alioli,Boughezal,Mereghetti,Petriello 2003.11615
  - HH — Heinrich,Jang,Scyboz 2204.13045

  MG5 – POWHEG-BOX interface Nason,Oleari,Rocco,Zaro 2008.06364

  ME produced by MG up to NLO QCD → run in POWHEG

- **JHUGen**: H production + $H \to 4\ell, \tau\tau$, on- and off-shell Gritsan,Roskes,Sarica,Schulze, Xiao,Zhou 2002.09888

  anomalous couplings mapped to SMEFT: Warsaw, Higgs b. (via JHUGenLexicon)
  LO, reweighting possible (via MELA)

- **VBFNLO**

  hard-coded matrix elements. EW+QCD diboson, triboson, VBS, VBF for H,Z,W,γ
  anomalous couplings mapped to SMEFT: HISZ basis dim 6 + Éboli basis dim 8

  Hagiwara et al PRD48(1993)2182, Éboli et al hep-ph/0009262

SMEFTsim

What is SMEFTsim?

- **Purpose**: enable MC event generation in SMEFT, with a general tool that automates theory manipulations and implements all $\mathcal{L}_6$ in Warsaw basis
- **Scope**: complete tree-level $\mathcal{O}(\Lambda^{-2})$ predictions, in unitary gauge
- consists of **FeynRules model + 10 UFOs** (pre-exported)

`general` `MFV` `U35` `top` `topU3l`

$\times$

$\{\alpha_{\rm em}, m_Z, G_F\}$ $\{m_W, m_Z, G_F\}$

- original version: IB,Jiang,Trott 1709.06492 [already presented at SMEFT-Tools 2019!]
- since dec 2020:
  - ★ a version 3.x, with a few new features. I'll mark those with a ★
  - ★ a dedicated github website and repository smeftsim.github.io
  - ★ a bible-manual with answers to anything you could possibly ask IB 2012.11343

(yes, there are a lot of conversion tables) (yes, there's even a logo: SMEFTsim)

Flavor in SMEFTsim

- all operators defined in the **up basis**

$$Y_d \equiv Y_d^{(d)} V^\dagger\,, \quad Y_u \equiv Y_u^{(d)}\,, \quad Y_l \equiv Y_l^{(d)}$$

- CKM implemented using Wolfenstein parameterization
- symmetries can be imposed:
  - ✔ much fewer free parameters
  - ✔ LHC cannot distinguish all quark flavors anyway
  - ✔ FV/FUV/FCNC are not a primary target
  - ✔ implement a possible "flavor power counting"

Bordone,Catà,Feldmann 1910.02641
Faroughy,Isidori,Wilsch,Yamamoto 2005.05366
Greljo,Palavrić,Thomsen 2203.09561

→ directly hard-coded into 5 alternative `SMEFTsim` versions

`general` no symmetry → 

`top` $U(2)_q \times U(2)_u \times U(2)_d \times U(1)^3_{l+e}$

`topU3l` $U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e$

`MFV` $U(3)^5$ + extra spurion insertions $-$ ~~CP~~

`U35` $U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

Flavor in SMEFTsim: U35 and MFV

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

U35 includes symmetric contractions + **leading spurion** insertions with yukawas

$$(Q_{He})_{pr} = (\bar{e}_p \gamma_\mu e_r)(H^\dagger i \overleftrightarrow{D} H) \quad \to C_{He}\, \delta_{pr}$$

$$(Q_{dH})_{pr} = (\bar{q}_p H d_r)(H^\dagger H) \quad \to C_{dH}\, (Y_d^\dagger)_{pr}$$

$$(Q_{uu})_{prst} = (\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t) \quad \to C_{uu}\, \delta_{pr}\delta_{st} + C'_{uu}\, \delta_{pt}\delta_{sr}$$

$$(Q_{ledq})_{prst} = (\bar{l}^j_p e_r)(\bar{d}_s q^j_t) \quad \to C_{ledq}\, (Y_l^\dagger)_{pr}(Y_d)_{st}$$

Flavor in SMEFTsim: `U35` and `MFV`

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

MFV → drops all explicit ~~CP~~ terms (only CKM phase remains) and
→ retains spurions up to $\mathcal{O}(Y_l, Y_u^3, Y_d^3)$ ★

$$(Q_{He})_{pr} = (\bar{e}_p \gamma_\mu e_r)(H^\dagger i \overleftrightarrow{D} H) \quad \to C_{He}\, \delta_{pr}$$

$$(Q_{dH})_{pr} = (\bar{q}_p H d_r)(H^\dagger H) \quad \to C_{dH}^{(0)} (Y_d^\dagger)_{pr} + (\Delta^u C_{dH})(Y_u^\dagger Y_u Y_d)_{pr} + (\Delta^d C_{dH})(Y_d^\dagger Y_d Y_d)_{pr}$$

$$(Q_{uu})_{prst} = (\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t) \quad \to C_{uu}^{(0)}\, \delta_{pr}\delta_{st} + C_{uu}^{\prime(0)}\, \delta_{pt}\delta_{sr} + (\Delta C_{uu})(Y_u Y_u^\dagger)_{pr}\delta_{st} + (\Delta C_{uu}^\prime)(Y_u Y_u^\dagger)_{pt}\delta_{sr}$$

$$(Q_{ledq})_{prst} = (\bar{l}_p^j e_r)(\bar{d}_s q_t^j) \quad \to C_{ledq}^{(0)} (Y_l^\dagger)_{pr} (Y_d)_{st} + (Y_l^\dagger)_{pr}\Big[(\Delta^u C_{ledq})(Y_d Y_u^\dagger Y_u)_{st} + (\Delta^d C_{ledq})(Y_d Y_d^\dagger Y_d)_{st}\Big]$$

Flavor in SMEFTsim: `top` and `topU3l`

Aguilar-Saavedra et al 1802.07237

topU3l $U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e$

leptons: same as `U35`

quarks: split light and heavy fields (q_L, u_R, d_R) + (Q_L, t_R, b_R)

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

→ no FV currents

→ spurions needed in $(\bar{q}u), (\bar{q}d)$ currents but not in $(\bar{Q}t), (\bar{Q}b)$

top $U(2)_q \times U(2)_u \times U(2)_d \times U(1)^3_{l+e}$

quarks: same as `topU3l`

leptons: → LFV forbidden $(Z\bar{e}\mu = 0)$

→ LFUV allowed $(Z\bar{e}e \neq Z\bar{\mu}\mu)$

→ L and R transform under same $U(1) \Rightarrow$ no spurions needed in $(\bar{l}e)$

SMEFTsim flavor structures: parameter counting

	general		U35		MFV		top		topU3l	
	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$
$\mathcal{L}_6^{(1)}$	4	2	4	2	2	-	4	2	4	2
$\mathcal{L}_6^{(2,3)}$	3	-	3	-	3	-	3	-	3	-
$\mathcal{L}_6^{(4)}$	8	4	8	4	4	-	8	4	8	4
$\mathcal{L}_6^{(5)}$	54	27	6	3	7	-	14	7	10	5
$\mathcal{L}_6^{(6)}$	144	72	16	8	20	-	36	18	28	14
$\mathcal{L}_6^{(7)}$	81	30	9	1	14	-	21	2	15	2
$\mathcal{L}_6^{(8a)}$	297	126	8	-	10	-	31	-	16	-
$\mathcal{L}_6^{(8b)}$	450	195	9	-	19	-	40	2	27	2
$\mathcal{L}_6^{(8c)}$	648	288	8	-	28	-	54	4	31	4
$\mathcal{L}_6^{(8d)}$	810	405	14	7	13	-	64	32	40	20
tot	2499	1149	85	25	120	-	275	71	182	53

Input parameters for the EW sector

the **EW sector** has 3 independent parameters

$$\{v,\, g,\, g'\}$$

that are fixed by **3** input measurements, usually chosen among

$$\{m_Z,\, m_W,\, G_F,\, \alpha_{\rm em}\}$$

ie. one chooses **3** equations among

$$\hat{m}_Z^2 = \quad [91.1876 \text{ GeV}]^2 = \frac{\bar{v}^2}{4}(\bar{g}^2+\bar{g}'^2)\left[1+\frac{v^2 C_{HD}}{2}+\frac{2v^2\bar{g}\bar{g}'}{\bar{g}^2+\bar{g}'^2}C_{HWB}\right]$$

$$\hat{m}_W^2 = \quad [80.387 \text{ GeV}]^2 = \frac{\bar{v}^2\bar{g}^2}{4}$$

$$\hat{G}_F^2 = \quad 1.1663787\times 10^{-5} \text{ GeV}^{-2} = \frac{1}{\sqrt{2}\bar{v}^2}\left[1+2v^2 C_{Hl}^{(3)} - v^2 C'_{ll}\right]$$

$$\hat{\alpha_{\rm em}}(m_Z) = \quad 1/127.95 = \frac{1}{4\pi}\frac{\bar{g}^2\bar{g}'^2}{\bar{g}^2+\bar{g}'^2}\left[1-\frac{v^2\bar{g}\bar{g}'}{\bar{g}^2+\bar{g}'^2}C_{HWB}\right]$$

solves in $\{\bar{v},\bar{g},\bar{g}'\}$ and **replaces** the solution $\bar{x}\to\hat{x}(1+\delta x/x)$ in $\mathcal{L}_{SM}$

Input parameters for the EW sector

the **EW sector** has 3 independent parameters

$$\{v,\, g,\, g'\}$$

that are fixed by **3** input measurements, usually chosen among

$$\{m_Z,\, m_W,\, G_F,\, \alpha_{\rm em}\}$$

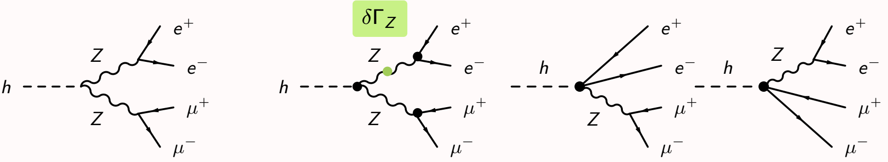
- SMEFTsim implements two alternative options:

$$\{\alpha_{\rm em}, m_Z, G_F\} \qquad \{m_W, m_Z, G_F\}$$

- **Higgs and fermion masses** also used as inputs
  to define scalar potential parameters and Yukawa couplings
- no input scheme introduced for **CKM**

  Descotes-Genon,Falkowski,Fedele,González-Alonso,Virto 1812.08163

Propagator corrections



SM | SMEFT d=6

$$m_Z \equiv m_Z^{SM}, \quad \Gamma_Z = \Gamma_Z^{SM} + \delta\Gamma_Z$$

$$\mathcal{A} \propto \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z} = \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \left[1 - \frac{i m_Z}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \delta\Gamma_Z \right] + \mathcal{O}(\delta\Gamma_Z^2)$$

- relevant when particle nearly on-shell
- in narrow-width approx, corresponds to correction to Γ_{tot} in BR

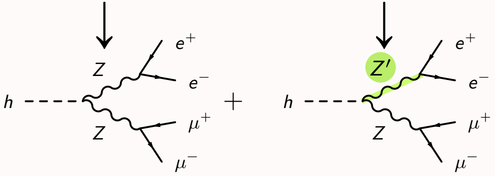
linearization usually not possible in a MC

only options: → include $(\Gamma_Z^{SM} + \delta\Gamma_Z)$ at the denominator

→ analytic treatment Brivio,Corbett,Trott 1906.06949

Propagator corrections in SMEFTsim ⭐

$$\mathcal{A} \propto \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z} = \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \left[1 - \frac{i m_Z}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \delta\Gamma_Z \right] + \mathcal{O}(\delta\Gamma_Z^2)$$



Dummy fields W', Z', h', t' are added whose propagator is **the pure linearized shift**

Gröber, Mattelaer, Mimasu – Les Houches 2017 1803.10379

Insertions controlled by interaction order `NPprop` in dummy vertices
→ e.g. interference piece `NPprop<=2 NPprop^2==2`

What about loop-generated Higgs couplings?

SMEFTsim is a purely LO UFO model. cannot do $gg \to h, h \to \gamma\gamma \dots$ in SM
$\to$ cannot compute interference terms?!

$\to$ implemented as point-vertices in $m_t \to \infty$ limit [ok for Higgs prod+decay]

γ $$\mathcal{L} = \frac{e^2}{8\pi^2} f_{\gamma\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}\right)\mathcal{O}_{\gamma\gamma} + \frac{e^2}{4\pi^2} f_{Z\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}, \frac{m_Z^2}{4m_W^2}\right)\mathcal{O}_{Z\gamma}$$

two relevant $d = 5$ operators:

$$\mathcal{O}_{\gamma\gamma}^{(1)} = A_{\mu\nu}A^{\mu\nu}\frac{h}{v}\,, \qquad \mathcal{O}_{Z\gamma}^{(1)} = Z_{\mu\nu}A^{\mu\nu}\frac{h}{v}\,,$$

$f_{\gamma\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}\right)$, $f_{Z\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}, \frac{m_Z^2}{4m_W^2}\right)$ computed to order m_t^{-2}, m_W^{-6}.

What about loop-generated Higgs couplings?

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$\to$ cannot compute interference terms?!

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G $$\mathcal{L} = \frac{g_s^2}{48\pi^2}\left[O_{gg}^{(1)} - \frac{7}{60m_t^2}\mathcal{O}_{gg}^{(2)} + \frac{g}{5m_t^2}\mathcal{O}_{gg}^{(3)} + \frac{1}{30m_t^2}\mathcal{O}_{gg}^{(4)} + \frac{3}{5m_t^2}\mathcal{O}_{gg}^{(5)}\right]$$

complete basis of HG operators up to $d = 7$: "top-EFT"

Neill 0908.1573
Harlander,Neumann 1309.2225
Dawson,Lewis,Zeng 1409.6299

$$\mathcal{O}_{gg}^{(1)} = G_{\mu\nu}^a G^{a\mu\nu}\frac{h}{v},$$

$$\mathcal{O}_{gg}^{(2)} = D_\sigma G_{\mu\nu}^a D^\sigma G^{a\mu\nu}\frac{h}{v}, \quad \mathcal{O}_{gg}^{(3)} = f_{abc}G_\mu^{a\nu}G_\nu^{b\sigma}G_\sigma^{c\mu}\frac{h}{v},$$

$$\mathcal{O}_{gg}^{(4)} = D^\mu G_{\mu\nu}^a D_\sigma G^{a\sigma\nu}\frac{h}{v}, \quad \mathcal{O}_{gg}^{(5)} = G^{a\mu\nu}D_\nu D^\sigma G_{\sigma\mu}^a\frac{h}{v}.$$

$\to$ complete basis for hg^2, hg^3, hg^4 vertices at $\mathcal{O}(m_t^{-2})$

$\to$ full momentum dependence: Higgs can be off-shell.

SMEFTsim: use in Mathematica

SMEFT Feynman Rules

A Mathematica notebook with more examples in the GitHub repository:

```
SMEFTsim_Mathematica_notebooks/SMEFTsim_usage_examples.nb
```

Instructions

- load Feynrules

```
$FeynRulesPath = SetDirectory[``FEYNRULESPATH''];
<< FeynRules`;
```

- load SMEFTsim. Flavor and Scheme must be defined first!

```
SetDirectory[``SMEFTSIM_FR_PATH''];
Flavor = U35;
Scheme = MwScheme;
LoadModel[``SMEFTsim_main.fr'']
```

accepted flavors: `general, U35, MFV, top, topU3l`

accepted schemes: `alphaScheme, MwScheme`

only the selected combination is loaded.
information about other options cannot be accessed.

Obtaining Feynman rules

- hVV vertices

```
frHVV = FeynmanRules[LHiggs + LSMloop + L6cl4, MaxParticles -> 3,
    Contains -> H];
```

- Zff vertices

```
frZfer = FeynmanRules[LFermions + L6cl7, MaxParticles -> 3,
    Contains -> Z];
```

- all vertices from **bosonic op.** eg. $\mathcal{O}_{HB}$

```
OHB // FeynmanRules
```

- all vertices from **fermionic op.** eg. $\mathcal{O}_{Hl}^{(1)}$

```
Select[L6cl7, !FreeQ[#, cHl1] &] // FeynmanRules
```

or

```
OHl1[1,1] // FeynmanRules
```

specifying flavor indices

- all FR are given in **input scheme-independent** form, containing `dg1, dgw, dGf...`.
  go to scheme-specific notation applying replacements:

`.//MwShifts` or `.//alphaShifts`

Available variables and functions

- `LGauge`. Gauge boson kin. terms.
- `LHiggs`. Higgs boson kin. term (incl hVV, $hhVV$)
- `LFermions`. Fermions kin. terms
- `LSMloop`. SM Higgs couplings to $hgg(ggg), h\gamma\gamma, hZ\gamma$
- `L6cl1, ...L6cl7`. Operators of class 1...7
- `L6cl8a, ...L6cl8d`. Operators of class 8a ...8d

- `WCsimplify`. Collects the Wilson coefficients in an expression one by one.
- `SMlimit`. Returns the SM limit of an expression.
- `relativeVariation`. Returns an expression normalized to its SM part

- `MwShifts`. Input shifts replacements for $\{m_W, m_Z, G_F\}$ scheme.
- `alphaShifts`. Input shifts replacements for $\{\alpha_{\rm em}, m_Z, G_F\}$ scheme.

NEW: Interactive Feynman rules tool

- can be downloaded from Notebook Archive
- imports files used to export UFOs → guaranteed correspondence with UFOs
- full dependence on flavor indices, spurions, CKM, CP-odd parameters, masses etc → can be useful for analytics

[DEMO]

SMEFTsim: use in MadGraph

Restriction cards

Interaction orders

Propagator corrections

Example applications

VBS with propagators
ATLAS?

Summary

-

Backup slides

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

1	X^3	2	φ^6 and $\varphi^4 D^2$ 3		$\psi^2\varphi^3$ 5
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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

4	$X^2\varphi^2$	6	$\psi^2 X\varphi$		$\psi^2\varphi^2 D$ 7
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

The Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

8a	$(\bar{L}L)(\bar{L}L)$	8b	$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$ 8c
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

The Warsaw basis

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8a	$(\bar{L}L)(\bar{L}L)$	8b	$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$ 8c
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

omitted

Input schemes for the EW sector

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

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

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

Kinetic term normalization and field redefinitions

Some $d = 6$ operators give corrections to **kinetic terms**

e.g. $C_{HB}\,(H^\dagger H) B_{\mu\nu} B^{\mu\nu} \xrightarrow{\text{unitary g.}} C_{HB}\dfrac{v^2}{2} B_{\mu\nu} B^{\mu\nu} + C_{HB}\dfrac{2vh + h^2}{2} B_{\mu\nu} B^{\mu\nu}$

$$C_{HD}\,(H^\dagger D_\mu H)(D^\mu H^\dagger H) \xrightarrow{\text{unitary g.}} C_{HD}\frac{v^2}{4}\partial_\mu h \partial^\mu h + \dots$$

$$C_{H\Box}\,(H^\dagger H) D_\mu D^\mu (H^\dagger H) \xrightarrow{\text{unitary g.}} C_{H\Box}\left[\frac{v^2}{2}\partial_\mu h \partial^\mu h + \frac{3}{2} v^2 h \partial_\mu \partial^\mu h\right] + \dots$$
$$= -C_{H\Box}\,\partial_\mu h \partial^\mu h + \dots$$

Calculating with non-canonically normalized kinetic terms is complicated
$\rightarrow$ requires modifying LSZ formula

Kinetic term normalization and field redefinition: B_μ

an easier solution: redefine the fields

eg. B_μ $\quad \mathcal{L}_{\rm SMEFT} \supset -\frac{1}{4} B_{\mu\nu} B^{\mu\nu}\left[1 - 2v^2 C_{HB}\right]$

replace everywhere $\begin{cases} B_\mu \to B_\mu \left[1 + v^2 C_{HB}\right] \\ g' \to g' \left[1 - v^2 C_{HB}\right] \end{cases}$ and expand linearly in C_{HB}

$$\to -\frac{1}{4} B_{\mu\nu} B^{\mu\nu}\left[1 - 2v^2 C_{HB}\right]\left[1 + 2v^2 C_{HB}\right] = -\mathbf{\frac{1}{4}} B_{\mu\nu} B^{\mu\nu} + \mathcal{O}(C_{HB}^2)$$

$\to D_\mu \sim g' B_\mu$ unchanged up to $\mathcal{O}(C_{HB}^2)$

$\to \mathcal{L}_6$ unchanged up to $\mathcal{O}(C_{HB}^2)$

$\to C_{HB}$ only remains in $C_{HB} \dfrac{2vh + h^2}{2} B_{\mu\nu} B^{\mu\nu}$

Kinetic term normalization and field redefinitions: h

an easier solution: redefine the fields

eg. h $\mathcal{L}_{\rm SMEFT} \supset \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \frac{v^2}{2} C_{HD} - 2v^2 C_{H\Box}\right] = \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \Delta_h\right]$

replace everywhere $h \to h\left[1 - \frac{v^2}{4} C_{HD} + v^2 C_{H\Box}\right]$, expand linearly in $C_{HD},\ C_{H\Box}$

$$\to \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \Delta_h\right]\left[1 - \Delta_h\right] \quad = \quad \mathbf{\frac{1}{2}}\partial_\mu h \partial^\mu h + \mathcal{O}(\Delta_h^2)$$

$\to \mathcal{L}_6$ unchanged up to $\mathcal{O}(\Delta_h^2)$

$\to$ **SM Higgs couplings**: $h^3, h^4, hVV, hhVV, h\bar\psi\psi$

with n h-legs are rescaled by $[1 - n\,\Delta_h]$

A special kinetic term correction: $\mathcal{O}_{HWB}$

$$C_{HWB}\,(H^\dagger W_{\mu\nu} H) B^{\mu\nu} \xrightarrow{\text{unitary g.}} -C_{HWB}\frac{v^2}{2} W^3_{\mu\nu} B^{\mu\nu} + \dots$$

introduces a **kinetic mixing** between $W^3, B \longrightarrow$ needs to be diagonalized!

3 subsequent operations:

(1) normalize kin. term for B C_{HB} and W^i C_{HW}

(2) rotate to diagonalize kin. term in (W^3, B) C_{HWB}

(3) rotate to diagonalize mass term $\rightarrow (Z, A)$

doing **(2)**, **(3)** it at once:

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} 1 & -v^2 C_{HWB}/2 \\ -v^2 C_{HWB}/2 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

$\rightarrow$ correction to the **Weinberg angle** $\rightarrow$ enters **SM γ, Z couplings**

Input parameter example: m_b

assuming $U(3)^5 \to \mathcal{O}_{dH} = (H^\dagger H)(\bar{q}_L Y_D^\dagger H^\dagger d_R) \quad \to \quad$ take the b terms:

$$\mathcal{L}_{\rm SMEFT} \supset -\frac{\bar{y}_b \bar{v}}{\sqrt{2}}\left[1-\frac{v^2}{2}C_{dH}\right]\bar{b}_L b_R - \frac{\bar{y}_b}{\sqrt{2}}\left[1-\frac{3v^2}{2}C_{dH}\right] h\bar{b}_L b_R + \text{h.c.}$$

$$= -\frac{\bar{y}_b \hat{v}}{\sqrt{2}}\left[1-\frac{v^2}{2}C_{dH}+\frac{\Delta G_F}{\sqrt{2}}\right]\bar{b}_L b_R - \frac{\bar{y}_b}{\sqrt{2}}\left[1-\frac{3v^2}{2}C_{dH}\right] h\bar{b}_L b_R + \text{h.c.}$$

measured as $\hat{m}_b$

$$\to \bar{y}_b = \hat{m}_b \frac{\sqrt{2}}{\hat{v}}\left[1+\frac{v^2}{2}C_{dH}-\frac{\Delta G_F}{\sqrt{2}}\right]$$

replacing $\bar{y}_b$ back in $\mathcal{L}$:

$$\mathcal{L}_{\rm SMEFT} \supset -\hat{m}_b \bar{b}_L b_R - \frac{\hat{m}_b}{\hat{v}}\left[1-v^2 C_{dH}-\frac{\Delta G_F}{\sqrt{2}}\right] h\bar{b}_L b_R + \text{h.c.}$$

correction to Yukawa coupling

Input parameter example: m_b

assuming $U(3)^5 \to \mathcal{O}_{dH} = (H^\dagger H)(\bar{q}_L Y_D^\dagger H^\dagger d_R) \quad \to$ take the b terms:

$$\mathcal{L}_{\rm SMEFT} \supset -\frac{\bar{y}_b \bar{v}}{\sqrt{2}}\left[1 - \frac{v^2}{2} C_{dH}\right] \bar{b}_L b_R - \frac{\bar{y}_b}{\sqrt{2}}\left[1 - \frac{3v^2}{2} C_{dH}\right] h\bar{b}_L b_R + \text{h.c.}$$

$$= \underbrace{-\frac{\bar{y}_b \hat{v}}{\sqrt{2}}\left[1 - \frac{v^2}{2} C_{dH} + \frac{\Delta G_F}{\sqrt{2}}\right]}_{\text{measured as } \hat{m}_b} \bar{b}_L b_R - \frac{\bar{y}_b}{\sqrt{2}}\left[1 - \frac{3v^2}{2} C_{dH}\right] h\bar{b}_L b_R + \text{h.c.}$$

$$\to \bar{y}_b = \hat{m}_b \frac{\sqrt{2}}{\hat{v}}\left[1 + \frac{v^2}{2} C_{dH} - \frac{\Delta G_F}{\sqrt{2}}\right]$$

replacing $\bar{y}_b$ back in $\mathcal{L}$:

$$\mathcal{L}_{\rm SMEFT} \supset -\hat{m}_b \bar{b}_L b_R - \frac{\hat{m}_b}{\hat{v}}\left[1 - v^2 C_{dH} - \frac{\Delta G_F}{\sqrt{2}}\right] h\bar{b}_L b_R + \text{h.c.}$$

correction to Yukawa coupling