Hands-on SMEFTsim

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What you need to have installed

follow instructions on **https://smeftsim.github.io/tutorials.html**

Part 1:

- Mathematica + FeynRules
- SMEFTsim Feynrules Source

Part 2:

- MadGraph5 v2.6+ with reweighting module, ROOT with pyROOT for python2.7 (needed for event analysis scripts)
  alternatively
  VirtualBox with `Delphes2020.vdi` Virtual Machine link

  in this case:

  ```
  sudo apt-get update
  sudo apt-get-install python-dev
  ```

  sudo pwd is `delphes`
- `SMEFTsim_U35_MwScheme_UFO` model. put it in `MAGRAPHDIR/models/`
- material: at `https://www.dropbox.com/s/nr1pm0ijxu1es5f/Material.tar` (also attached to indico)

Useful links

- SMEFTsim website `SMEFTsim.github.io`
- SMEFTsim references v1,2: Brivio,Jiang,Trott 1709.06492
  v3: Brivio 2012.11343
- FeynRules `feynrules.irmp.ucl.ac.be/`
- MadGraph support `launchpad.net/mg5amcnlo`
- Reweighting module documentation
  `cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Reweight`

Introduction

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)
→ embed all UV information

$\mathcal{O}_i$ invariant operators that form
a complete, non redundant **basis**
→ embed the IR information

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}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

8a	$(\bar{L}L)(\bar{L}L)$
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

8b	$(\bar{R}R)(\bar{R}R)$
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

8c	$(\bar{L}L)(\bar{R}R)$
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

8d	$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

	B-violating
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_{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_{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_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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

omitted

SMEFTsim

a set of models that enable
LO Monte Carlo simulations
with the complete Warsaw basis

Brivio, Jiang, Trott 1709.06492
Brivio 2012.11343
SMEFTsim.github.io

- **Purpose**: enable MC event generation in SMEFT, with a general tool that automates theory manipulations and covers all $\mathcal{L}_6$ in Warsaw basis
- **Scope**: LO predictions in the SMEFT → tree level only
  → complete predictions up to $\mathcal{O}(\Lambda^{-2})$
- Source in FeynRules, provides pre-exported UFO models
- SMEFT implemented in **10** alternative setups:

  5 flavor structures × 2 EW input schemes

- SM Higgs couplings $hgg, h\gamma\gamma, hZ\gamma$ included in $m_t \to \infty$ limit (up to $d = 7$ for gluons)
- from v3.0: allows to include linearized propagator corrections

SMEFT flavor structure: $U(3)^5$

also: Faroughy,Isidori,Wilsch,Yamamoto 2005.05366

w/o flavor assumptions $\mathcal{L}_6$ has 2499 free parameters

$O_{He,pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$ has **9** independent par.

$O_{ledq,prst} = (\bar{l}^i_p e_r)(\bar{d}_s q^i_t)$ has **162**

freedom can be reduced imposing a **symmetry**. Maximal:

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

→ only invariant contractions allowed
→ Yukawa couplings typically promoted to **spurions**:

$$Y_u \mapsto \Omega_u Y_u \Omega_q^\dagger, \quad Y_d \mapsto \Omega_d Y_d \Omega_q^\dagger, \quad Y_e \mapsto \Omega_e Y_e \Omega_l^\dagger$$

$O_{He,pr}\,\delta_{pr}$ has **1** independent par.

$O_{ledq,prst}\,(Y_e^\dagger)_{pr}(Y_d)_{st}$ has **2**

$\mathcal{L}_6 + U(3)^5$ has **85** free parameters

SMEFT flavor structure: `top`, `topU3l`

Follow standards for **top quark physics** proposed in Aguilar-Saavedra et al 1802.07237

Based on $U(2)$ symmetry in quark sector Barbieri et al. 1105.2296,1203.4218

→ 1st, 2nd gen.	(q_L, u_R, d_R)	$U(2)_q \times U(2)_u \times U(2)_d$
→ 3rd gen.	(Q_L, t_R, b_R)	no sym

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

Two alternative options for lepton sector

`top`	$[U(1)_{l+e}]^3$	→ only diagonal entries. allows $e \neq \mu \neq \tau$
`topU3l`	$U(3)_l \times U(3)_e$	→ same as $U(3)^5$ model. diagonal + $e = \mu = \tau$ imposed

SMEFT flavor structure: `top`, `topU3l`

quarks

- 4-fermion operators rotated according to recommendations. eg.

$$Q_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u) \qquad Q'_{tu} = (\bar{u}\gamma_\mu t)(\bar{t}\gamma^\mu u) \quad \longrightarrow \quad Q^{(1)}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u) \qquad Q^{(8)}_{tu} = (\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$$

$$Q_{tu} = Q^{(1)}_{tu} \qquad Q'_{tu} = \frac{1}{3}Q^{(1)}_{tu} + 2Q^{(8)}_{tu}$$

- symmetry ⇒ different Yukawa dependence between generations

$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\,\tilde{H}\; Y_u^\dagger\; u)$$

$$\mathcal{Q}_{tH} = (H^\dagger H)(\bar{Q}\,\tilde{H}\,t)$$

SMEFT flavor structure: `top`, `topU31`

quarks

- 4-fermion operators rotated according to recommendations. eg.

$$Q_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u) \qquad\qquad Q_{tu}^{(1)} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$$
$$Q'_{tu} = (\bar{u}\gamma_\mu t)(\bar{t}\gamma^\mu u) \quad \longrightarrow \quad Q_{tu}^{(8)} = (\bar{t}\,T^a\gamma_\mu t)(\bar{u}\,T^a\gamma^\mu u)$$

- symmetry $\Rightarrow$ different Yukawa dependence between generations

$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\,\tilde{H}\;Y_u^\dagger\;u)$$

$$\mathcal{Q}_{tH} = (H^\dagger H)(\bar{Q}\,\tilde{H}\,t)$$

leptons

- different Yukawa dependence and # parameters between the two models

`top`	$(\mathcal{Q}_{eH})_{pp} = (H^\dagger H)(\bar{l}_p\,H\,e_p)$	$\rightarrow$ 3 independent operators
`topU3l`	$\mathcal{Q}_{eH} = (H^\dagger H)(\bar{l}\,H\;Y_l^\dagger\;e)$	$\rightarrow$ 1 operator

SMEFTsim flavor structures: parameter counting

	`general`		`U35`		`MFV`		`top`		`topU3l`	
	all	~~CP~~	all	~~CP~~	all	~~CP~~	all	~~CP~~	all	~~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 parameter schemes

SM

(pseudo)-observables $\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$

→

analytical / MC
predictions
for any SM process

Numerical value of renormalized p determined from chosen input measurements $\mathcal{O}$:

$$p_{SM}(\mathcal{O})$$

Input parameter schemes

SMEFT

(pseudo)-observables
$\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$
EFT	$\mathbf{C_i}$

→

analytical / MC
predictions
for any SM process

One cannot find enough obs. to solve for all C_i.

→ Wilson coefficients dependence expanded around SM solutions:

$$p_{SMEFT}(\mathcal{O}, C) = p_{SM}(\mathcal{O}) + \delta p(C_i) + \ldots$$

→ different sets of $\mathcal{O}$ ⇒ different net SMEFT corrections

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

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

Input parameters for the EW sector

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ie. one chooses **3** equations among

$$\begin{aligned}
\hat{m}_Z^2 &= & [91.1876\ \text{GeV}]^2 &= \frac{\bar{v}^2}{4}(\bar{g}^2+\bar{g}'^2)\left[1+\frac{v^2 C_{HD}}{2}+\frac{2v^2\bar{g}\bar{g}'}{\bar{g}^2+\bar{g}'^2}C_{HWB}\right]\\
\hat{m}_W^2 &= & [80.387\ \text{GeV}]^2 &= \frac{\bar{v}^2\bar{g}^2}{4}\\
\hat{G}_F^2 &= & 1.1663787\times 10^{-5}\ \text{GeV}^{-2} &= \frac{1}{\sqrt{2}\bar{v}^2}\left[1+2v^2 C_{Hl}^{(3)}-v^2 C'_{ll}\right]\\
\hat{\alpha_{\rm em}}(m_Z) &= & 1/127.95 &= \frac{1}{4\pi}\frac{\bar{g}^2\bar{g}'^2}{\bar{g}^2+\bar{g}'^2}\left[1-\frac{v^2\bar{g}\bar{g}'}{\bar{g}^2+\bar{g}'^2}C_{HWB}\right]
\end{aligned}$$

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 schemes for the EW sector

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

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

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

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

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

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

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

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**

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

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

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

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

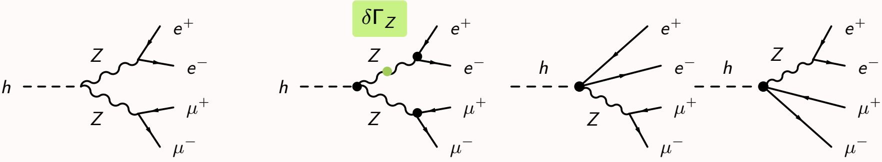
$$\bar{g}_W = \frac{e}{s_\theta}\left[1 - \frac{\Delta G_F}{\sqrt{2}}\right]$$

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

with

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

Propagator corrections



SM | SMEFT d=6

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

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

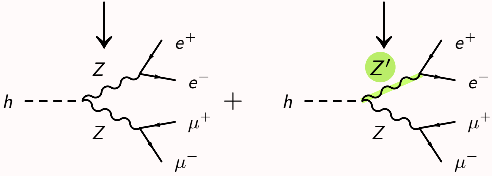
linearization usually not possible in a MC

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`

Part 1: 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.

Part 2: use in MadGraph

Setup

- if you use the Virtual Machine:
```
sudo apt-get update
sudo apt-get-install python-dev
```
sudo password is `delphes`

- download the `Material.tar` and extract:
```
tar -xvf Material.tar
```

- in `SMEFTsim_U35_MwScheme_UFO/coupling_orders.py`

  change
```
NPprop = CouplingOrder(name = 'NPprop',
expansion_order = 0,
```
  into
```
NPprop = CouplingOrder(name = 'NPprop',
expansion_order = 99,
```
  this enables propagator corrections.

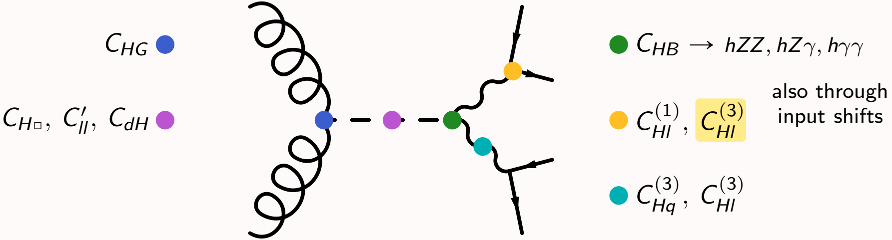
- put the restriction card `restrict_ggF41.dat` into the UFO directory

- copy the `SMEFTsim_U35_MwScheme_UFO/` dir into `MAGRAPHDIR/models/`

  the restriction has `linearPropCorrections` $= 1$. Also needed for propagators.

Exercise: $gg \to h \to e^+e^-\mu^+\mu^-$

1. generate in the SM
2. compute SMEFT corrections for some operators via reweighting: pure interference, quadratics, linear corr. from h, Z propagators
3. plot m_{12}, m_{34} to understand the impact of the different operators



1. SM $gg \to h \to e^+e^-\mu^+\mu^-$

- start Madgraph: `MADGRAPHDIR/bin/mg5_aMC`
- in MG: import model with restriction and generate process:

```
import model SMEFTsim_U35_MwScheme_UFO-ggF4l
generate g g > h SMHLOOP==1, h > e+ e- mu+ mu- SMHLOOP=0 @0 NP=0 NPprop=0
output gg_h_eemm
launch
```

- modify `param_card`: set to 0 all SMEFT parameters
- modify `run_card`: set `False = use_syst`

- `g g > h, h > ...` only generates on-shell Higgs signal
- `SMHLOOP` counts SM hgg, $hggg$, $hgggg$, $h\gamma\gamma$, $hZ\gamma$ vertices
- `NP` counts vertices with SMEFT insertions
- `NPprop` counts vertices of dummy particles carrying propagator corr.
- orders specified after `@0` apply to the entire production+decay chain. orders to the left apply only to the corresponding subprocesses.

2. SMEFT corrections to $gg \to h \to e^+e^-\mu^+\mu^-$

- The reweighting commands are already provided in the reweight cards
- They are all launched at once by the shell script. Adjust the `PROCNAME` and `RUNNAME` variables inside the script to match yours.
- Launch and approve all questions:

```
./launch_reweighting.sh
```

order specifications

any interference	`NP<=1 NP^2==1`
specific interf.	`NP<=1 NP^2==1 NPcHl1^2==1`
any square	`NP==1`
specific mixed square	`NP==1 NPcHl1^2==1 NPcHB^2==1`
propagators interf.	`NP=0 NPprop<=2 NPprop^2==2`

`NP` counts vertices in amplitude, `NP^2` counts vertices in **squared** amp.

`g g > h, h > ...` syntax does not allow amp^2 specifications.
we use `g g > h >...` instead, that generally does not restrict to on-shell.

`<=`, `=` are the same

3. Event analysis

- `gunzip gg_h_eemm/Events/run_01/unweighted_events.lhe.gz`

- analyze lhe file and create a .root with histograms

  ```
  python lhe_analyzer.py gg_h_eemm/Events/run_01/unweighted_events.lhe
  lhe_events.root
  ```

  you can visualize this in ROOT with

  ```
  root
  new TBrowser()
  ```

- create plots

  ```
  python plot_histos.py lhe_events.root
  ```

- modify `plot_histos.py` to plot different sets of lines / range

Some physics to notice

- C_{HG} and operators in the Higgs propagators only give overall rescalings
- C_{HG} correction is huge: formally **tree/loop** $\rightarrow \mathcal{O}(100)$
- difference between $C_{Hl}^{(1)}$, $C_{Hl}^{(3)}$ purely due to $C_{Hl}^{(3)}$ entering input shifts
- operators in the Z propagator only relevant for $m_{ll} \simeq m_Z$
- propagator corr. bring in new operators, that contribute to other h/Z decays, eg. C_{dH} from $h \rightarrow b\bar{b}$, $C_{Hq}^{(3)}$ from $Z \rightarrow q\bar{q}$
- $\mathcal{O}_{HB}$ modifies hZZ and introduces $hZ\gamma$ and $h\gamma\gamma$ vertices
  $\rightarrow$ spectrum significantly distorted towards low m_{ll}.
  the effect is even stronger at quadratic level.
- the square of $C_{Hl}^{(1)}$ is suppressed

Backup slides

Kinetic term normalization and field redefinitions

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

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

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

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

Calculating with non-canonically normalized kinetic terms is complicated
→ requires modifying LSZ formula

Kinetic term normalization and field redefinition: B_μ

an easier solution: redefine the fields

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

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}

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

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

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

$\to C_{HB}$ <u>only</u> remains in $C_{HB} \frac{2vh + h^2}{2} B_{\mu\nu} B^{\mu\nu}$

Kinetic term normalization and field redefinitions: h

an easier solution: redefine the fields

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

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: $\mathcal{O}_{HWB}$

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

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 $\to (Z, A)$

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

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

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

Input parameter example: m_b

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

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

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

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

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

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

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

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