SMEFT calculations for LHC

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check out also talks at EFT WG meeting:
indico.cern.ch/event/971724/

The SMEFT Lagrangian

relevant for LHC

leading corrections

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \boxed{\sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)}} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \boxed{\sum_i \frac{C_i^{(8)}}{\Lambda^4} O_i^{(8)}} + \dots$$

SMEFT predictions require making theory choices:

- **operator basis**
  most used: Warsaw basis — Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884
  basis translation tools available — Falkowski et al 1508.05895, Aebischer et al 1712.05298
- **flavor structure**
  most used: $U(3)^5$ (MFV) or $U(2)$ for top — Bordone,Catà,Feldmann 1910.02641; Faroughy,Isidori,Wilsch,Yamamoto 2005.05366; Brivio(Jiang,Trott) 1709.06492, 2012.11343
- CP, B violation?
- **input parameters for the EW sector**: 3 among $\{\alpha_{em}, G_F, m_Z, m_W\}$
  most used: $\{G_F, m_Z, m_W\}$ to avoid SMEFT corrections to m_W

LHC processes in the SMEFT

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

LHC processes in the SMEFT

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

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

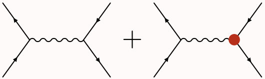
$\varepsilon \cdot \boxed{A}$ ATLAS HIGG-2018-28
ATLAS-CONF-2020-053

acceptances for SM and SMEFT differ if Lorentz structure changes

LHC processes in the SMEFT

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

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



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

$\times$ (SM K-factor)

- A_{SMEFT} computed up to 1-loop in QCD / EW
- quadratics
  - same EFT order as SM-$O^{(8)}$ interference
  - introduce more EFT parameters
  - generally improve fit convergence (ensure $\sigma > 0$)
  - included for convergence check

Most used: simulations with MadGraph5_aMC@NLO

- generation automated for any process up to NLO QCD
- interaction orders syntax allows to isolate polynomial terms
  → morphing of SMEFT signal.

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

- reweighting module very much used — Gainer et al. 1404.7129, Mattelaer 1607.00763

  $\sigma(A) \to \sigma(B)$ changing each event's weight: $W_B = \dfrac{|A_B|^2}{|A_A|^2} W_A$

  → re-use event samples: much faster than re-generating
  → smaller stat. uncertainties in ratios/sums/diffs of SM(EFT) components

- recent updates (from 2.9.0) — Mattelaer, Ostrolenk 2102.00773
  optimized **phase space integrator** + new algorithm for **amplitude** evaluation
  → much faster and more agile for EFT, when several diagrams are 0

- supports polarized matrix elements — Buarque-Franzosi,Mattelaer,Ruiz,Shil 1912.01725

UFO models

most used in Warsaw basis:

SMEFTsim

Brivio,Jiang,Trott 1709.06492
Brivio 2012.11343

- only LO
- full Warsaw basis. CP even + odd, includes all m_f and y_f
- 5 flavor structures $\times$ 2 EW input schemes
  general, $U(3)^5$, MFV, $U(2)^3 \times U(3)^2$, $U(2)^3 \times U(1)^3_{l+e}$
  $\{G_F, m_Z, \alpha_{em}\}$, $\{G_F, m_Z, m_W\}$
- includes $hgg(g)$, $h\gamma\gamma$, $hZ\gamma$ SM interactions in $m_t \to \infty$ limit
- includes *linear* SMEFT corrections in propagators $(\delta m, \delta\Gamma)$ of top, Higgs and EW bosons

SMEFT@NLO

Degrande,Durieux,Maltoni, Mimasu,Vryonidou 2008.11743

- allows NLO QCD
- only CP even, 5 flavor scheme (only $m_t, y_t \neq 0$)
- flavor structure: $U(3)_d \times U(2)_u \times U(2)_q \times U(1)^3_{l+e}$
- EW inputs: $\{G_F, m_Z, m_W\}$

both follow validation protocol Durieux et al 1906.12310

other UFOs in FR database:
`dim6top` Durieux,Zhang 1802.07237
HEL Alloul,Fuks,Sanz 1310.5150 . . .

Simulations with other Monte Carlo generators

- **Sherpa**
  also 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

  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

- ...

Analytical predictions

Apart from usual advantages
(exact results and cancellations, better results in "hard" corners of phase space...)

SMEFT analytic computations are currently necessary for

- NLO EW in SMEFT
- including properly RG running of SMEFT parameters
- including properly propagator corrections beyond LO
- going beyond dimension 6

Going beyond dimension 6

Passarino(David) 1901.04177,2009.00127
Hays,Martin,Sanz,Setford 1808.00442
Alioli et al 2003.11615. . .

$d = 8$ predictions useful in order to

- estimate uncertainties on $d = 6$
- understand series convergence, also in relation to specific UV models
- study interplay between SMEFT and loop expansions
- compare to HEFT

complete **bases** now available Li,Ren,Shu,Xiao,Yu 2005.00008, Murphy 2005.00059

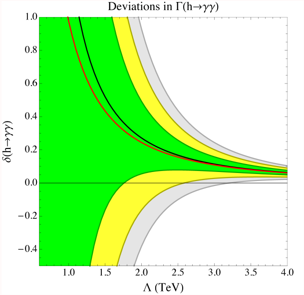
caveat: $\dfrac{d=6}{d=8} \sim \dfrac{\Lambda^2}{v^2(E^2)}$ undetermined in EFT → extra assumptions required

"geoSMEFT" (Corbett,Hays),Helset,(Martin),Trott 1909.08470, 2001.01453, 2007.00565, 2102.02819

2, 3 point functions: [few structures] $\times (H^\dagger H)^n$

→ can be written **at all orders** in EFT

→ full results up to $\mathcal{O}(\Lambda^{-4})$ for
2-body h, Z decays + EWPO



NLO calculations

NLO predictions useful in order to

- improve predictions **accuracy** and **uncertainty** estimates
- improve **interpretation** if deviations are observed
- have sensitivity to operators that only enter at loop level

✅ R_ξ gauge, Ward identities, BFM Dedes et al 1704.03888, Quadri 2102.10656, Trott et al 1803.08001,1909.08470,2010.08451

✅ Feynman rules in R_ξ gauge automated Dedes et al 1704.03888,1904.03204, Corbett 2010.15852

✅ RGE running automated (Celis),Fuentes-Martin,(Ruiz-Femenia),Vicente,Virto 1704.04504,2010.16341, Aebischer,Kumar,Straub 1804.05033

a few processes available at NLO EW at $d = 6$

$\mu \to e\gamma$	Pruna,Signer 1408.3565
$h \to \gamma\gamma$	Hartmann,Trott 1505.02646,1507.03568, Passarino et al 1505.03706, Dedes et al 1805.00302, Dawson, Giardino 1807.11504
$h \to Z\gamma$	Dedes,Suxho,Trifyllis 1903.12046,1801.01136
$h \to WW, ZZ$	Dawson, Giardino 1807.11504,1801.01136
$h \to \bar{f}f$	(Cullen,Gauld),Pecjak,Scott 1512.02508,1904.06358,2007.15238
Z decay	Hartmann,Shepherd,Trott 1611.09879, Dawson,Giardino 1808.05948
Z, W pole obs.	Dawson,Giardino 1909.02000

+ several at NLO QCD: Drell-Yan, diboson, $gg \to h$, tth, $t\bar{t}(V)$, single top, top decay. . .

Future directions

- understanding theory uncertainties
  → due to EFT truncation
  → due to missing higher loop orders / scale dependence
- streamlining morphing procedures, including acceptance corrections
- including **RG running** of SMEFT parameters in Monte Carlo (upcoming in MG, via UFO extension)
- streamlining/automating **NLO EW** calculations
- getting SMEFT effects in PDF under control
- gradually relaxing **flavor** assumptions
- new techniques from helicity amplitudes?

  Shadmi,Weiss, Henning, Melia, Ma, Shu, Xiao, Aoude, Machado, Durieux, Kitahara, Craig, Jiang, Li, Sutherland. . .
- SMEFT predictions up to $d = 8$?

Backup slides

SMEFT at $d = 6$: the Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

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

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

SMEFT at $d = 6$: the Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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

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

Flavor assumptions

Bordone,Catá,Feldmann 1910.02641
Faroughy,Isidori,Wilsch,Yamamoto 2005.05366
Brivio,(Jiang,Trott) 1709.06492, 2012.11343

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

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

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

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**:

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

$$O_{He,pr}\,\delta_{pr} \quad \text{has } \mathbf{1} \text{ independent par.}$$

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

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

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.

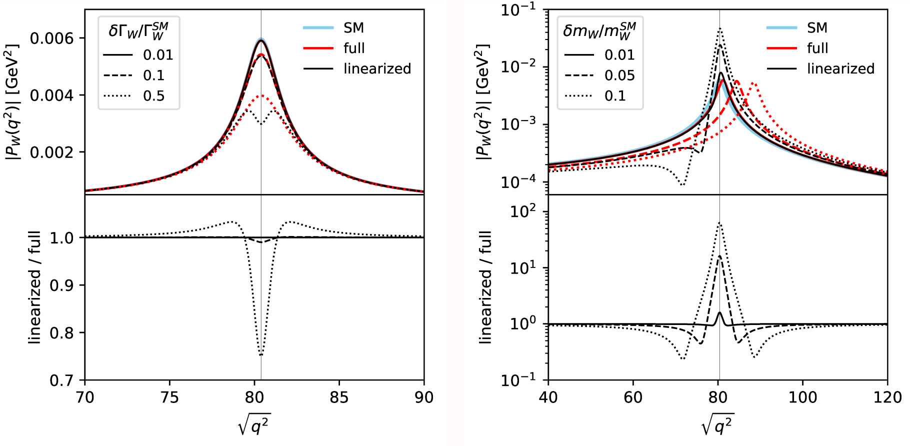
→ Wilson coefficients dependence expanded around SM solutions:

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

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

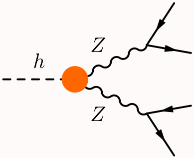
Propagator corrections

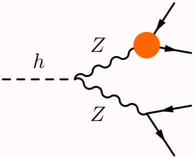
$$\frac{i(-\eta^{\mu\nu}+q^\mu q^\nu/m_W^2)}{p^2-m_W^2+i\Gamma_W m_W}\left[1+\frac{im_W\,\boxed{\Delta\Gamma_W}}{p^2-m_W^2+i\Gamma_W m_W}-\frac{(2m_W-i\Gamma_W)\,\boxed{\Delta m_W}}{p^2-m_W^2+i\Gamma_W m_W}\right]+\mathcal{O}(\Lambda^{-4})$$

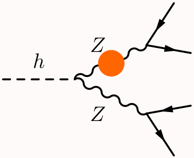


Example: H → 4f in the SMEFT

① corrections to SM diagrams







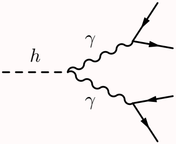
$\propto g_{\mu\nu}$ (SM-like)

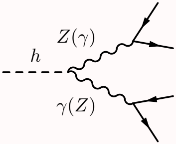
$\propto g_{\mu\nu} p\cdot q - p_\nu q_\mu$ $(Z_{\mu\nu}Z^{\mu\nu}h)$

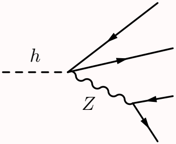
$\delta g_L, \delta g_R$

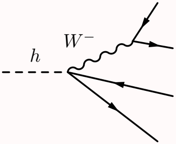
$$\frac{-im_Z\delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

② genuine SMEFT diagrams









Example: $h \to 4f$ in the SMEFT

Results with $U(3)^5$ symmetry, $\{m_W, m_Z, G_F\}$ inputs.

$$\Gamma = \Gamma_{SM}\left[1 + \sum_\alpha \bar{C}_\alpha \, N_\alpha\right], \qquad \bar{C}_\alpha = C_\alpha \frac{v^2}{\Lambda^2}$$

$\downarrow$

	$\bar{q}q \to h\bar{q}q$ VBF-like		$h \to e^+e^-\mu^+\mu^-$	
	direct	propagators	direct	propagators
$\bar{C}_{He}$		$5.32 \cdot 10^{-5}$	-1.724	0.153
$\bar{C}_{Hl}^{(1)}$		$5.32 \cdot 10^{-5}$	2.144	0.153
$\bar{C}_{Hl}^{(3)}$	-6	$1.351 \cdot 10^{-3}$	-3.856	1.147
$\bar{C}_{Hq}^{(1)}$	0.109	$-1.363 \cdot 10^{-4}$		-0.39
$\bar{C}_{Hq}^{(3)}$	-5.345	$-1.423 \cdot 10^{-3}$		-1.353
$\bar{C}_{Hu}$	-0.323	$-7.092 \cdot 10^{-5}$		-0.203
$\bar{C}_{Hd}$	0.103	$5.24 \cdot 10^{-5}$		0.150
$\bar{C}'_{ll}$	3	$-1. \cdot 10^{-3}$	3	-0.839