A review of EFT Tools

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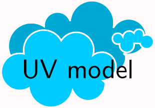
EFTs for BSM physics in a nutshell



SMEFT = EFT constructed with SM field and symmetries

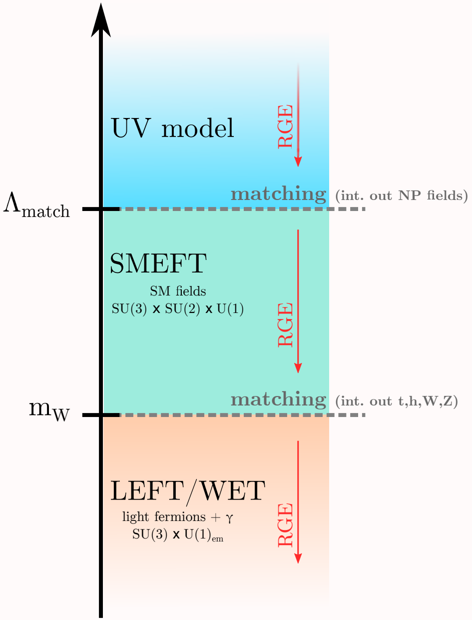
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \ldots \qquad \mathcal{L}^{(6)} = \sum_i C_i \mathcal{O}_i$$

- parameterizes non-resonant NP signals
- systematic mapping of all possible BSM effects
- a universal language for all measurements
- a proper QFT → systematically improvable

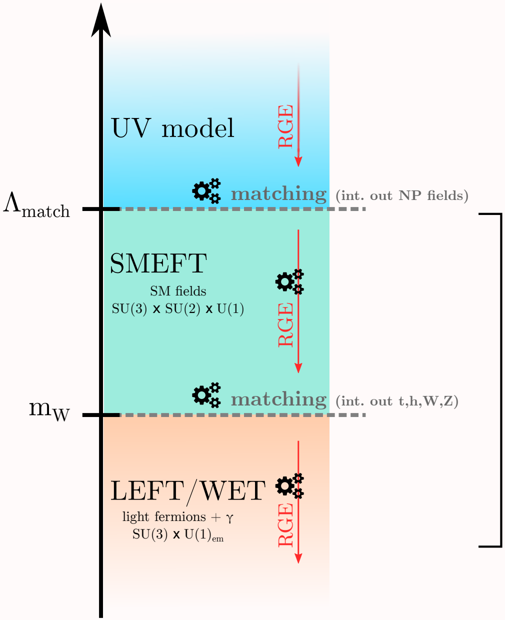
LEFT/WET = EFT with light fermions +QCD×QED

$$\mathcal{L}_{LEFT} = \mathcal{L}_{QCD+QED} + \mathcal{L}^{(3)}_{\not{L}} + \frac{1}{\Lambda^2}\mathcal{L}^{(5)} + \ldots$$

SMEFT + LEFT/WET workflow



SMEFT + LEFT/WET workflow



- basis construction & conversion
- analytic calculations
- MC simulations
- fits
- ...

About the tools in this talk

Disclaimers

there are many tools for EFT use, many developed for private use.
today I will only talk about the **most used**, **publicly available** ones

I'm an author of `SMEFTsim`, not expert in everything I'll mention.
for support/more insight please contact authors

$\rightsquigarrow$ links to papers and repositories

For more talks about EFT tools

- SMEFT-Tools 2019 + proceedings — indico.cern.ch/event/787665 — 1910.11003
- meetings of the LHC EFT WG — indico.cern.ch/category/12671/
  - Area 1: formalism, basis conversion
  - Area 2: calculations and simulations
  - Area 3,4: fits
  - Area 5: matching to UV models
  - Area 6: flavor, matching to LEFT/WET
  - + general meetings

Tools for EFT basis construction/conversion

many choices out there, different tools use different bases/conventions

BasisGen https://github.com/jccriado/basisgen Criado 1901.03501

also: DEFT Gripaios,Sutherland 1807.07546

python package

- uses Hilbert series techniques to determine the **# of operators** (class by class) in a complete basis, given fields and symmetries.

Rosetta rosetta.hepforge.org github.com/kenmimasu/Rosetta
Falkowski,Fuks,Mawatari,Mimasu,Riva,Sanz 1508.05895
Bernon,Carvalho,Falkowski,Fuks,Goertz,Mawatari,Mimasu,You 1605.02684 (ch. 18)

python package

- **numerical basis translations** in SMEFT, mainly designed for MC.
- SLHA format (`param_card.dat`). interfaces to `eHDECAY`, `Lilith`...

WCxf wcxf.github.io/
Aebischer,Kumar,Stangl,Straub et al 1712.05298

python code with YAML, JSON interface.

- **exchange format** to convert between codes conventions
- numerical conversion, via mapping to predefined bases
- I/O interfaces to many other tools for simulation, fitting and analytic manipulation

Tools for UV → SMEFT matching

1-loop matching in models streamlined with functional methods (CDE / UOLEA) Henning,Lu,Murayama, del Aguila,Kunszt,Santiago, Drozd,Ellis,Quevillon,You,Passarino,Zhang, Fuentes-Martin,Portoles,Ruiz-Femenia,Krämer,Summ,Voigt,Dittmaier...

$$S_{eff}[\phi] = S[\Phi_0] + \frac{i}{2}\,\mathrm{Tr}\log\left(-\frac{\delta^2 S}{\delta\Phi^2}\bigg|_{\Phi_0}\right)$$

MatchingTools matchingtools.readthedocs.io/en/latest Criado 1710.06445 also `MatchMaker` (not released yet)

python library.

- tree-level matching and some basis reduction. symbolic calculations

SUPER TRACER gitlab.com/supertracer/supertracer Fuentes-Martin,König,Pagès,Thomsen 2012.08506

Mathematica package.

- supertrace evaluation.
- will be embedded in a full matching code `MATCHETE` for basis reduction etc

STrEAM www.github.com/EFTMatching/STrEAM Cohen, Lu, Zhang 2012.07851

Mathematica package.

- 1-loop matching based on CDE from Cohen,Lu,Zhang 2011.02484

CoDEx Das Bakshi,Chakrabortty,Patra 1808.04403

Mathematica package.

- heavy-only 1-loop matching to Warsaw and SILH bases. supports RGE evol.

Tools for RG running and SMEFT → LEFT matching

DsixTools

dsixtools.github.io
(Celis),Fuentes-Martin,(Ruiz-Femenia),Vicente,Virto 1704.04504,2010.16341

Mathematica package

- analytical and numerical
- works in Warsaw basis for SMEFT and San Diego basis for LEFT Grzadkowski et al 1008.4884 Jenkins et al 1709.04496
- 1-loop SMEFT RGE + 1-loop LEFT RGE + multi-loop SM running
  (Alonso),Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014, Jenkins,Manohar,Stoffer 1711.05270
- 1-loop matching SMEFT-LEFT Dekens,Stoffer 1908.05295

wilson wilson-eft.github.io/
Aebischer,Kumar,Straub 1804.05033

python module, builds on `WCxf`

- basis translation, SMEFT and LEFT running, tree-level SMEFT-LEFT matching
- all operations are numerical
- interfaces to all tools using `WCxf`. much used in connection to `flavio`

Tools for Monte Carlo simulations

Most used: **MadGraph5_aMC@NLO + EFT UFO models**

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

  → 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

SMEFT 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: $\{G_F, m_Z, m_W\}$

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

both follow **validation protocol** Durieux et al 1906.12310

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

- . . .

Tools for analytic (loop) predictions

SmeftFR www.fuw.edu.pl/smeft
Dedes,Paraskevas,Rosiek,Trifyllis 1904.03204

Mathematica package, relies on FeynRules.

- generates SMEFT Feynman Rules in Warsaw basis and R_ξ **or unitary gauge**
  Dedes,Materkowska,Paraskevas,Rosiek,Suxho 1704:03888
- in principle supports export to UFO, FeynArts, FormCalc etc

SMEFT_BGFM feynrules.irmp.ucl.ac.be/wiki/SMEFT_BGFM
Corbett 2010.15852

Mathematica package, relies on FeynRules.

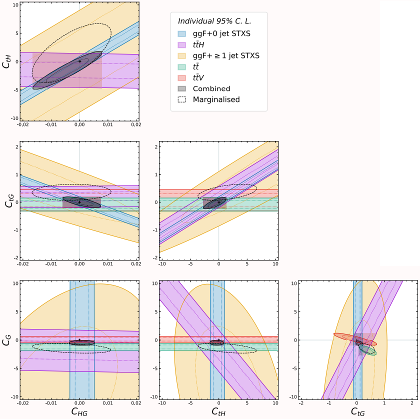
- SMEFT Feynman Rules in **Background Field Method**
- Warsaw basis + dim8 op. in geoSMEFT fomalism Helset,Martin,Trott 2001.01453
  $\rightarrow$ complete field and param. redefinitions to $\mathcal{O}(\Lambda^{-4})$
- builds on results for gauge fixing and BFM developments
  Helset,Paraskevas,Trott 1803.08001, Corbett,Trott 2010.08451
- meant to be used e.g. in FeynArts, FormCalc

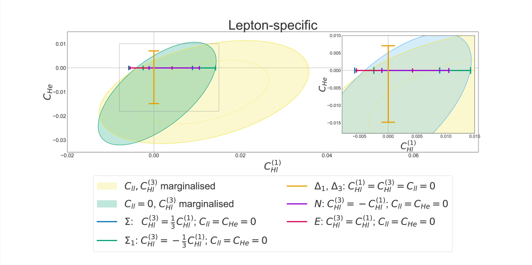
Tools for global fits

Fitmaker gitlab.com/kenmimasu/fitrepo
Ellis, Madigan, Mimasu, Sanz, You 2012.02779

python module. (not intended for public use yet, but available)

- **least squares** fitter for linear fits → analytical, very agile
- **nested sampling** for numerical fits with quadratic EFT terms.
- measurements + EFT predictions database (Higgs, diboson, top, EWPO)





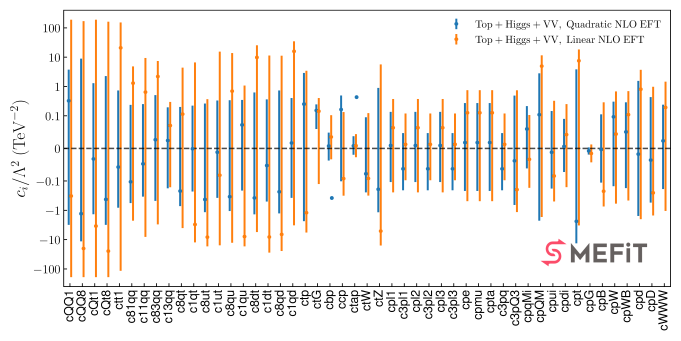
Tools for global fits

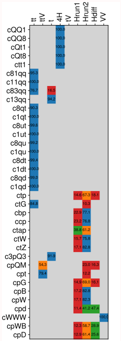
Fitmaker gitlab.com/kenmimasu/fitrepo
Ellis, Madigan, Mimasu, Sanz, You 2012.02779

SMEFiT lhcfitnikhef.github.io/SMEFT/ github.com/LHCfitNikhef/SMEFiT
Maltoni, Rojo, Vryonidou, Zhang et al 1901.05965, 1906.05296, 2101.03180, 2105.00006

python package. builds on NNPDF technology

- **MCfit** (toys/replica model) + **NestedSampling** (Bayesian, likelihood mapping)
- returns full posterior prob. can identify secondary minima (for quadratic fits)
- assumes gaussian uncertainties
- extensive stat toolbox: information geometry, Fisher matrix, PCA . . .





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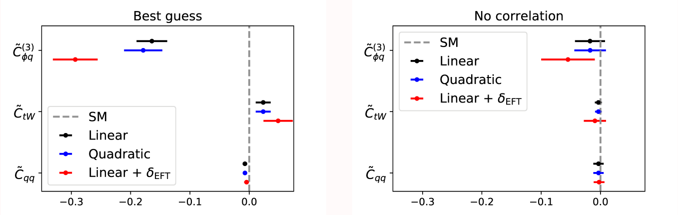
Maltoni,Rojo,Vryonidou,Zhang et al 1901.05965,1906.05296,2101.03180,2105.00006

EFTfitter tudo-physik-e4.github.io/EFTfitter.jl/dev/
Castro,Erdmann,Grunwald,Kröninger,Rosien 1605.05585

previously in C++, new version in Julia. based on BAT.jl

- bayesian. assumes gaussian measurements → focus on correct stat treatment
- pure fitter, requires implementation of models, priors, measurements, correlations. . .



Bißmann,Erdmann,Grunwald,
Hiller,Kröninger 1912.06090

Tools for global fits

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Ellis,Madigan,Mimasu,Sanz,You 2012.02779

SMEFiT lhcfitnikhef.github.io/SMEFT/ github.com/LHCfitNikhef/SMEFiT
Maltoni,Rojo,Vryonidou,Zhang et al 1901.05965,1906.05296,2101.03180,2105.00006

EFTfitter tudo-physik-e4.github.io/EFTfitter.jl/dev/
Castro,Erdmann,Grunwald,Kröninger,Rosien 1605.05585

HEPfit hepfit.roma1.infn.it https://github.com/silvest/HEPfit
deBlas et al 1910.14012

in C++. based on BAT and ROOT.

- observable predictions + bayesian fits
- huge code, used for many BSM applications, including EFT.
- implements RG running (SMEFT and LEFT), SMEFT-LEFT matching

Tools for global fits – flavor physics

flavio flav-io.github.io
Straub 1810.08132. now maintained by P. Stangl

python package.

- implements both SMEFT and LEFT
- used for observables **predictions** and **fits** (construct likelihoods).
- huge **database** of measurements for flavor physics + EWPO
- contains pre-defined **plotter** for results visualisation
- designed to be interfaced to `WCxf`, `wilson`, `smelli`

smelli (**SME**FT **li**kelihood) smelli.github.io/
Aebischer,Kumar,Stangl,Straub 1810.07698

python module. wrapper around `flavio`

- easy **global likelihood in SMEFT**
- takes care of self-consistencies with dim6 operators
- observables/values pre-selected. nuisance-free

EOS vanDyk et al. eos.github.io

C++ program

- used for **predictions and fits in quark flavor physics**
- has a large **database** of constraints, measurements etc
- can also produce **Monte Carlo events** for some flavor physics processes

Future directions

- predictions: streamlining morphing procedures
- including **RG running** of SMEFT parameters in Monte Carlo (upcoming in MG, via UFO extension)
- streamlining/automating **NLO EW** calculations
- new techniques from helicity amplitudes ?

  Shadmi,Weiss, Henning, Melia, Ma, Shu, Xiao, Aoude, Machado, Durieux, Kitahara, Craig, Jiang, Li, Sutherland. . .
- refined and more complete matching tools
- fits with up to 50 parameters ⇝ Bayesian
- Machine Learning tools

  Brehmer,Cranmer,Louppe,Pavez 1805.00013,1805.00020
  MadMiner Brehmer,Kling,Espejo,Cranmer 1907.10621

  → NN: likelihood-ratio estimator for direct inference from MC simulation

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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

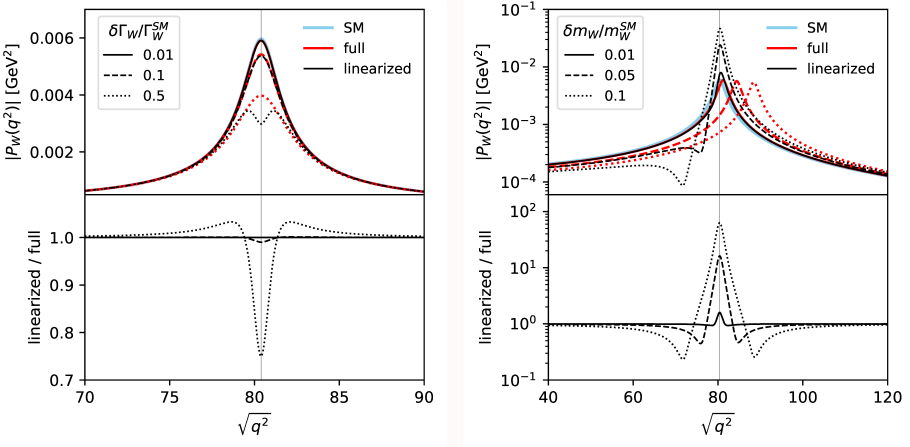
Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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

Propagator corrections

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



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

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

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

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

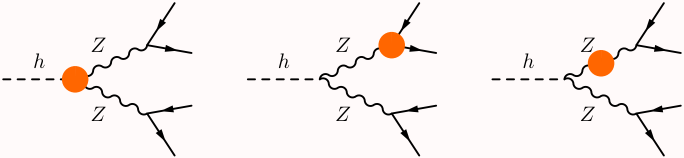
One cannot find enough obs. to solve for all C_i.

→ 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

① corrections to SM diagrams



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

$\delta g_L, \delta g_R$

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

② genuine SMEFT diagrams