Effective Field Theory approach to LHC data

Athanasios Dedes

University of Ioannina

Recent Developments in High Energy Physics and Cosmology
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In collaboration with:
J. Rosiek, K. Suxho, M. Paraskevas and L. Trifyllis

arXiv:1805.00302, arXiv:1903.12046, arXiv:1904.03204

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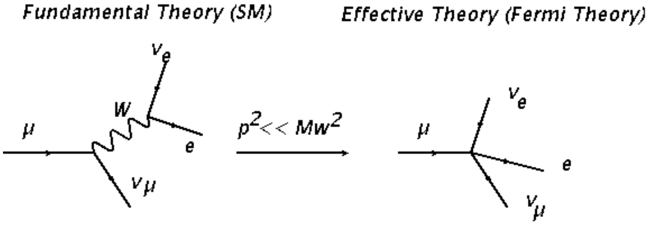


$$L_{\mathrm{SM}} \to L_{\mathrm{EFT}}^{(d=6)} = -\frac{4G_F}{\sqrt{2}}(\bar{\nu}_\mu \gamma^\mu P_L \mu)\,(\bar{e}\gamma_\mu P_L \nu_e) + O(p^4/M_W^4)$$

With only one parameter, $G_F \sim 1/\Lambda^2$, one calculates the muon decay width

$$\Gamma(\mu \to e\nu_\mu\bar{\nu}_e) = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

From $\tau_\mu = 2.197 \times 10^{-6}\ \mathrm{s}$ found $G_F \sim 1.16 \times 10^{-5}\ \mathrm{GeV}^{-2}$ which in turn means that $\Lambda \sim 300\ \mathrm{GeV}$ which is correct!!

SM EFT

Lets now suppose that there is new physics above the energy scale Λ and the SM is an effective field theory, named **the SM EFT**.

In 2010 it was discovered[1] that SM EFT contains 2499 $d \leq 6$ gauge invariant (but independent) operators.

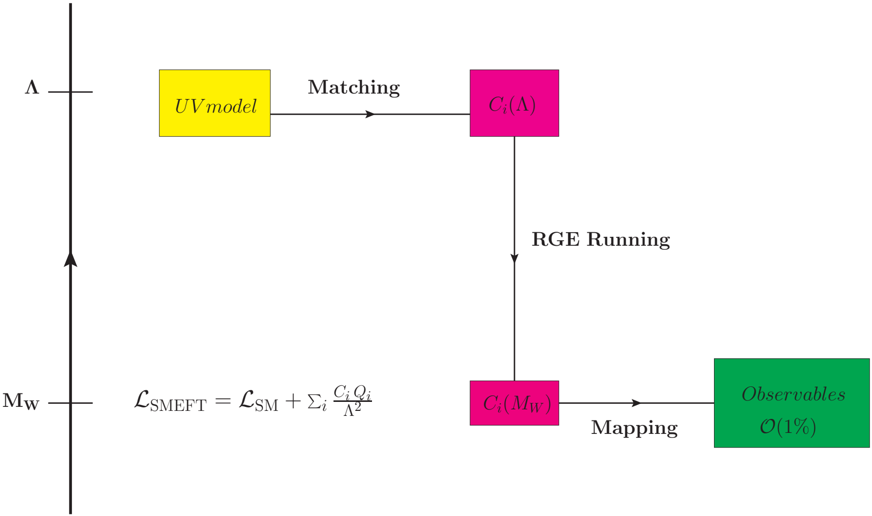
$$L_{\rm SM\ EFT} = L_{\rm SM} + \frac{C_{\nu\nu} Q_{\nu\nu}}{\Lambda} + \sum_i \frac{C_i Q_i}{\Lambda^2} + O(\frac{1}{\Lambda^3}) + \ldots$$

For example, operators Q_i look like,

$$\frac{\ell_L \ell_L \varphi\varphi}{\Lambda}, \quad \frac{\varphi^\dagger \varphi F_{\mu\nu} F^{\mu\nu}}{\Lambda^2}, \quad \frac{\bar{\ell}_L \sigma_{\mu\nu} e_R F^{\mu\nu}}{\Lambda^2}, \quad \ldots$$

[1] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, arXiv:1008.4884

The EFT picture[2]



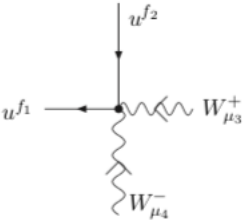
[2]B. Henning, X. Lu and H. Murayama, arXiv:1412.1837

SM EFT Feynman Rules

In order to perform amplitude calculations in SM EFT one needs the basic vertices in general quantization gauges.

There are about 400 vertices (in unitary gauge) that have been collected in one paper[3]

For example, $t + \bar{t} \to W^{+} + W^{-}$



$$-\sqrt{2}\bar{g}v \left(\sigma^{\mu_3\mu_4} P_L C^{uW*}_{f_2 f_1} + C^{uW}_{f_1 f_2} \sigma^{\mu_3\mu_4} P_R\right)$$

[3] A.D., W. Materkowska, M. Paraskevas, J. Rosiek, K. Suxho, arXiv:1704.03888

The code SmeftFR

Our group has created a code,[4] called `SmeftFR`, containing the full set of Feynman rules in $\LaTeX$ or in UFO format or in `FeynArts`.

It can feed various event generators, such as `MadGraph`, which perform amplitude (tree level) calculations for LHC.

One may then perform serious analysis for the effect of operators on different LHC observables.

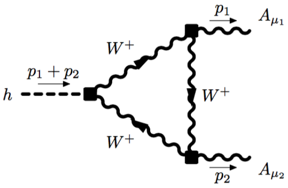
`SmeftFR` download web-page:

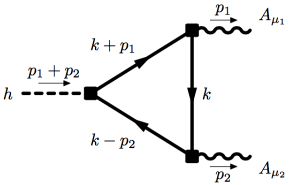
http://www.fuw.edu.pl/smeft

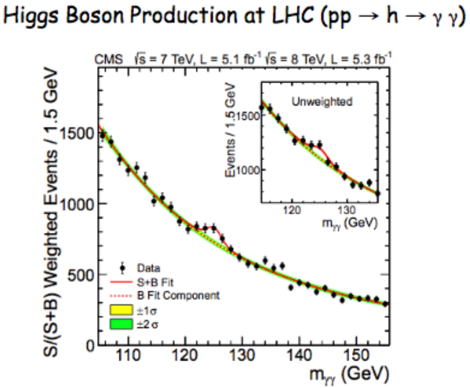
The program builts on `FeynRules` of *Mathematica*.

[4] A.D., M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, arXiv:1904.03204

The decay $h \to \gamma\gamma$ in SM







The decay $h \to \gamma\gamma$ in SM EFT

We define the ratio $\mathcal{R}_{h\to\gamma\gamma}$:

$$\mathcal{R}_{h\to\gamma\gamma} = \frac{\Gamma(\mathrm{SMEFT}, h \to \gamma\gamma)}{\Gamma(\mathrm{SM}, h \to \gamma\gamma)} = 1 + \delta\mathcal{R}_{h\to\gamma\gamma}$$

We assume that $\sigma(pp \to h)$ and $\Gamma_{tot}(h)$, are not affected by operators considered in the $h \to \gamma\gamma$ decay then

$$\text{ATLAS:} \qquad \mathcal{R}_{h\to\gamma\gamma} = 0.99^{+0.15}_{-0.14}\,,$$

$$\text{CMS:} \qquad \mathcal{R}_{h\to\gamma\gamma} = 1.18^{+0.17}_{-0.14}\,.$$

Let's remember this $\delta\mathcal{R}_{h\to\gamma\gamma}$ ~15% available from LHC data!

A New Improved Calculation

- Prior to our work the most complete calculation had been performed in References[5]

- Our work[6] improved previous calculations by:
  1. By exploiting Linear R_ξ-gauges
  2. Analytic proof of gauge invariance
  3. Simple renormalization framework
  4. Analytical and Semi-numerical expressions for $\delta\mathcal{R}_{h\to\gamma\gamma}$
  5. Bounds on Wilson coefficients

We are in good agreement with the analysis[7]

[5] C. Hartmann and M. Trott, arXiv:1507.03568, 1505.02646

[6] A.D, M. Paraskevas, J. Rosiek, K. Suxho L. Trifyllis, arXiv:1805.00302

[7] S. Dawson and P. P. Giardino, arXiv:1807.11504

Operators participating in $\mathcal{R}_{h\to\gamma\gamma}$

$Q_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{e\varphi} = (\varphi^\dagger\varphi)(\bar{l}'_p e'_r \varphi)$
$Q_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi} = (\varphi^\dagger\varphi)(\bar{q}'_p u'_r \widetilde{\varphi})$
$Q_{\varphi D} = \left(\varphi^\dagger D^\mu \varphi\right)^* \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi} = (\varphi^\dagger\varphi)(\bar{q}'_p d'_r \varphi)$
$Q_{\varphi B} = \varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	$Q_{ll} = (\bar{l}'_p \gamma_\mu l'_r)(\bar{l}'_s \gamma^\mu l'_t)$
$Q_{\varphi W} = \varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	$Q_{\varphi l}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}'_p \tau^I \gamma^\mu l'_r)$
$Q_{\varphi WB} = \varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	$Q_\varphi = (\varphi^\dagger\varphi)^3$
$Q_{eB} = (\bar{l}'_p \sigma^{\mu\nu} e'_r)\varphi B_{\mu\nu}$	$Q_{eW} = (\bar{l}'_p \sigma^{\mu\nu} e'_r)\tau^I \varphi W^I_{\mu\nu}$
$Q_{uB} = (\bar{q}'_p \sigma^{\mu\nu} u'_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{uW} = (\bar{q}'_p \sigma^{\mu\nu} u'_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$
$Q_{dB} = (\bar{q}'_p \sigma^{\mu\nu} d'_r)\varphi\, B_{\mu\nu}$	$Q_{dW} = (\bar{q}'_p \sigma^{\mu\nu} d'_r)\tau^I \varphi\, W^I_{\mu\nu}$

CP-violating operators **do not** contribute at $1/\Lambda^2$ and at 1-loop.

Operators participating in $\mathcal{R}_{h\to\gamma\gamma}$

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$Q_{\varphi W} = \varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	$Q^{(3)}_{\varphi l} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}'_p \tau^I \gamma^\mu l'_r)$
$Q_{\varphi WB} = \varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	
$Q_{eB} = (\bar{l}'_p \sigma^{\mu\nu} e'_r)\varphi B_{\mu\nu}$	$Q_{eW} = (\bar{l}'_p \sigma^{\mu\nu} e'_r)\tau^I \varphi W^I_{\mu\nu}$
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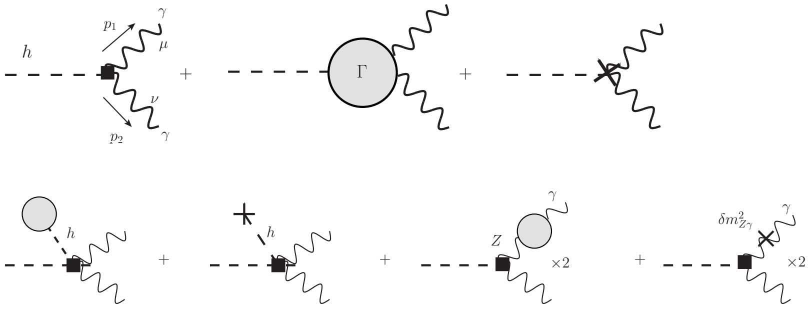
CP-violating operators **do not** contribute at $1/\Lambda^2$ and at 1-loop.

There are **17 operators** (not including flavour and H.c.)

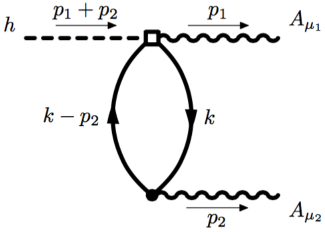
Diagrams

For the on-shell S-matrix amplitude we need to calculate:



plus external wave function renormalizations for the photon and the Higgs required by the LSZ reduction formula.

SM EFT Graphity!



Only in SMEFT

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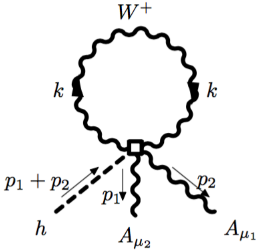

Only in SMEFT

Renormalization

We assume perturbative renormalization. We are working at 1-loop and up to $1/\Lambda^2$ in EFT expansion.

1. We regularize integrals (necessarily!) with DimReg
2. We use a simple renormalization framework[8] with $\overline{\mathrm{MS}}$ in Wilson coefficients
3. We establish a ξ-independent and renormalization scale invariant $h \to \gamma\gamma$ amplitude using the β-functions of Refs[9]
4. All infinities absorbed by SMEFT parameters' counterterms
5. A closed expression for the amplitude that respects the Ward-Identities

[8] A. Sirlin, Phys. Rev. D**22**, 1980

[9] R. Alonso, E. E. Jenkins, A. V. Manohar and M. Trott, arXiv:1308.2627, arXiv:1310.4838, arXiv:1312.2014

Renormalization

The renormalized parameters are translated to well measured ones

$$\{\bar{g}', \bar{g}, \bar{v}, \bar{\lambda}, \bar{y_t}\} \longrightarrow \{M_Z, M_W, G_F, M_h, m_t\}$$

and the renormalized Wilson coefficients to RG running quantities

$$C \longrightarrow C(\mu)$$

Nothing special w.r.t textbook renormalization technics !!

Results for $\mathcal{R}_{h\to\gamma\gamma}$

$$\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} = & -\left[48.04 - 1.07\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}(\mu)}{\Lambda^2} \\
& -\left[14.29 - 0.12\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}(\mu)}{\Lambda^2} \\
& +\left[26.17 - 0.52\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}(\mu)}{\Lambda^2} \\
& +\left[2.11 - 0.84\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{33}(\mu)}{\Lambda^2} \\
& +\left[1.13 - 0.45\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{33}(\mu)}{\Lambda^2} \\
& \ldots
\end{aligned}$$

Λ is in TeV units and μ is the renormalization scale parameter

This is a renormalization scale invariant result

Results for $\mathcal{R}_{h\to\gamma\gamma}$

- Bounds on C's from $\delta\mathcal{R}_{h\to\gamma\gamma} \lesssim 15\%$ for $\mu = M_W$

$$\frac{|C^{\varphi B}|}{\Lambda^2} \lesssim \frac{0.003}{(1\ \mathrm{TeV})^2}\,, \qquad \frac{|C^{\varphi W}|}{\Lambda^2} \lesssim \frac{0.011}{(1\ \mathrm{TeV})^2}\,,$$

$$\frac{|C^{\varphi WB}|}{\Lambda^2} \lesssim \frac{0.006}{(1\ \mathrm{TeV})^2}\,,$$

$$\frac{|C^{uB}_{33}|}{\Lambda^2} \lesssim \frac{0.071}{(1\ \mathrm{TeV})^2}\,, \qquad \frac{|C^{uW}_{33}|}{\Lambda^2} \lesssim \frac{0.133}{(1\ \mathrm{TeV})^2}\,.$$

- Bounds for $C^{\varphi WB}$ comparable to the EW ones
- Bounds onto all other Wilsons from $h \to \gamma\gamma$ are an order of magnitude stronger than other observables (e.g., top-quark)

$h \to Z\gamma$ in SM EFT

- Now, there are **23 operators** involved out of which 17 are common with $h \to \gamma\gamma$.
- There is no overlap with operators affecting $gg \to h$, and $\Gamma_{tot}(h)$, therefore LHC sets only a bound:

$$\mathcal{R}_{h\to Z\gamma} = \frac{\Gamma(\mathrm{SMEFT}, h \to Z\gamma)}{\Gamma(\mathrm{SM}\, h \to Z\gamma)} \lesssim 6.6$$

- We have just finished[8] the decay $h \to Z\gamma$ at 1-loop in SMEFT with all $d \leq 6$ operators (see talk by Kristaq Suxho)
- A finite, ξ-independent and renormalization scale invariant ratio $\mathcal{R}_{h\to Z\gamma}$ is found.
- The **6 new operators** do not affect $\mathcal{R}_{h\to Z\gamma}$ by more than 1%
- Our result is in agreement with the revised version of Ref[9]

[8] A. D., K. Suxho and L. Trifyllis, arXiv: 1903.12046

[9] S. Dawson and P. P. Giardino, arXiv:1801.01136

Results for $\mathcal{R}_{h\to Z\gamma}$

$$
\begin{aligned}
\delta\mathcal{R}_{h\to Z\gamma} = &+\left[14.99 - 0.35\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}(\mu)}{\Lambda^2}\\
&-\left[14.88 - 0.15\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}(\mu)}{\Lambda^2}\\
&+\left[9.44 - 0.26\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}(\mu)}{\Lambda^2}\\
&\ldots
\end{aligned}
$$

Bounds from $h \to Z\gamma$ searches are weak: they are supreseded by those from $h \to \gamma\gamma$ searches.

Comparison of $\mathcal{R}_{h\to\gamma\gamma}$ with $\mathcal{R}_{h\to Z\gamma}$

- Prefactors of $C^{\varphi B}$, $C^{\varphi WB}$ are **suppressed by a factor of 3** in case of $h \to Z\gamma$ while $C^{\varphi W}$ is affected equally in both.
- No other Wilson coefficients have $\mathcal{O}(1)$ prefactors
- By considering previous bounds from $h \to \gamma\gamma$ of the order of $C \sim 10^{-2}$ make New Physics effects very small in $h \to Z\gamma$.

Conclusion : Bounds set from $h \to \gamma\gamma$ do not allow for much New Physics room in $h \to Z\gamma$ (if assuming one coupling at a time)

Barring cancellations among coefficients, even at High Luminosity LHC with 3000 fb^{-1} where $\delta\mathcal{R}_{h\to Z\gamma} \approx 0.24$ the decay $h \to Z\gamma$ seems impossible to show deviations from the SM.

Summary

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6. Only quite a few operators affect mostly the amplitudes.
   Bounds on Wilsons set from current LHC data only by $\mathcal{R}_{h\to\gamma\gamma}$

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7. $\mathcal{R}_{h\to\gamma\gamma}$ and $\mathcal{R}_{h\to Z\gamma}$ go hand in hand. Barring cancellations in mind, the latter shows low NP sensitivity even at future stages of LHC data.

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7. $\mathcal{R}_{h\to\gamma\gamma}$ and $\mathcal{R}_{h\to Z\gamma}$ go hand in hand. Barring cancellations in mind, the latter shows low NP sensitivity even at future stages of LHC data.
8. A FCC or FLC will be ideal in disentangling observables with this EFT approach

SM EFT is a BSM approach worth pursuing further

Back-up slide: EOM

Certain operators e.g., $[(D_\mu G^{\mu\nu})^A - ig\bar{q}T^A\gamma^\nu q]$ vanish when using classical Equations of Motion (EOM)

There are two serious modifications :

- quantum effects
- renormalization

Politzer[10] proved that, although Green functions are affected by these operators, S-matrix elements vanish

QFT: S-matrix elements can be obtained from the vacuum expectation value of a time order product of any operator that has non-vanishing matrix elements between the vacuum and the one-particle states of the particles participating in the reaction.

[10] H. D. Politzer, Nucl. Phys. B **172**, 349 (1980).

Back-up: possible UV-field content

A translation from dominant operators in $h \to \gamma\gamma$ and $h \to Z\gamma$ to fields[11]

UV tree operators affecting $h \to \gamma\gamma$ and $h \to Z\gamma$						
Spin	Field	$C^{\varphi B}$	$C^{\varphi W}$	$C^{\varphi WB}$	C^{uB}	C^{uW}
Spin-0	$\mathcal{S}(1,1)_0$	✓	✓			
	$\Xi(1,3)_0$			✓		
Spin-$\frac{1}{2}$	$U(3,1)_{\frac{2}{3}}$				✓	
	$Q_1(3,2)_{\frac{1}{6}}$				✓	✓
	$T_2(3,3)_{\frac{2}{3}}$					✓
Spin-1	$\mathcal{L}_1(1,2)_{\frac{1}{2}}$	✓	✓	✓	✓	✓

[11] J. de Blas, J. C. Criado, M. Perez-Victoria and J. Santiago, JHEP **1803**, 109 (2018) [arXiv:1711.10391 [hep-ph]].