The decay $h \to \gamma\gamma$ in the Standard-Model Effective Field Theory

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Corfu Summer Institute: Workshop on the SM and Beyond,
6th of September, Greece

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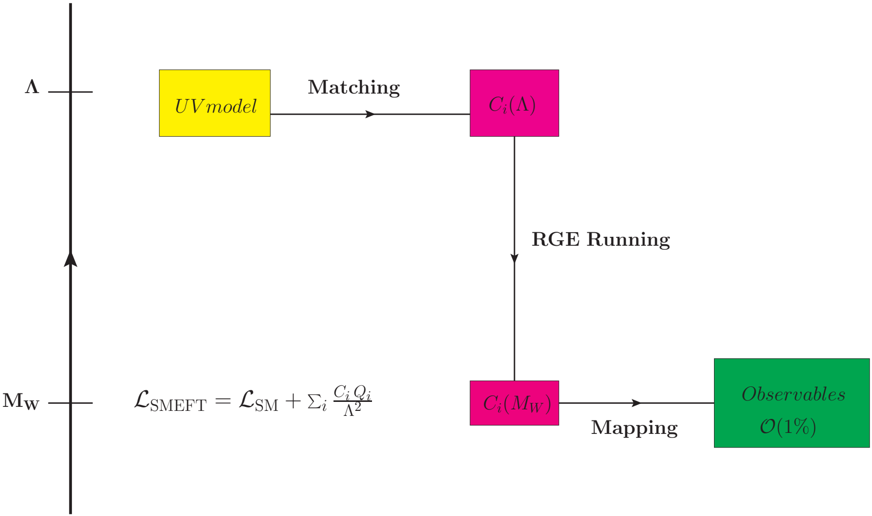
published in JHEP **1808**, 103 (2018), arXiv:1805.00302

The EFT picture



Last year at CSI....

Last year at Corfu Summer Institute:

- Quantization of SMEFT with $d = 6$ ops in standard basis
- Full set of SMEFT Feynman rules[1]
- SM-like propagators without mixings
- Coefficients for the $d = 6$ operators appear only in vertices
- Quantization in linear R_ξ-gauges
- BRST invariant SMEFT Lagrangian

We have chosen the physical observable $h \to \gamma\gamma$ to work out details at 1-loop and up-to $1/\Lambda^2$ in EFT expansion

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i Q_i}{\Lambda^2} \tag{1}$$

[1] arXiv:1704.03888

Motivation

- LHC's ratio $\mathcal{R}_{h\to\gamma\gamma}$:

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

$$\begin{aligned} \text{ATLAS:} \qquad & \mathcal{R}_{h\to\gamma\gamma} = 0.99^{+0.15}_{-0.14}\,, \\ \text{CMS:} \qquad & \mathcal{R}_{h\to\gamma\gamma} = 1.18^{+0.17}_{-0.14}\,. \end{aligned}$$

- We want to be as model independent as possible so :

BSM=SMEFT

SMEFT : complete set of $d = 6$-operators in "Warsaw" basis

A New Improved Calculation

- Prior to our work the most complete calculation had been performed in References[2]

- Our work[3] improves the current state:
  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[4]

[2] C. Hartmann and M. Trott, arXiv:1507.03568, 1505.02646
[3] A.D, M. Paraskevas, J. Rosiek, K. Suxho L. Trifyllis, arXiv:1805.00302
[4] S. Dawson and P. P. Giardino, arXiv:1807.11504 [hep-ph].

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

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

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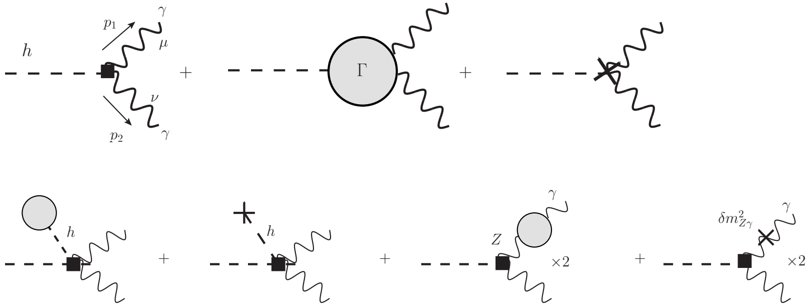
17 CP-conserving operators (not including flavour and H.c.)

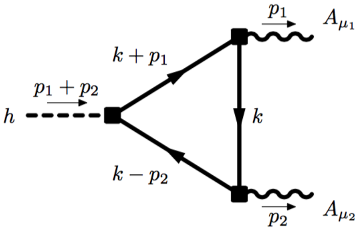
For the on-shell S-matrix amplitude we need to calculate:[5]



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

[5]We use the complete set of Feynman Rules in SMEFT and in R_ξ-gauges from A.D, W. Materkowska, M. Paraskevas, J. Rosiek, K.Suxho, JHEP **1706**, 143 (2017), arXiv:1704.03888

Examples of Diagrams



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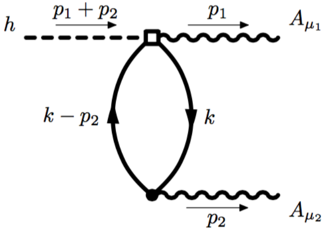

Only in SMEFT

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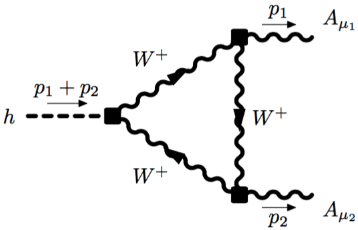

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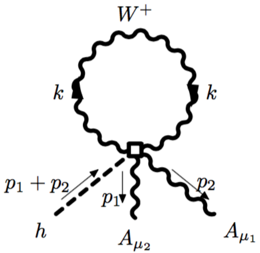

Only in SMEFT

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 DR
2. We use a hybrid renormalization scheme: on-shell in SM-quantities[6] and $\overline{\mathrm{MS}}$ in Wilson coefficients
3. We establish a ξ-independent and renormalization scale invariant $h \to \gamma\gamma$ amplitude using the β-functions of Refs[7]
4. All infinities absorbed by SMEFT parameters' counterterms
5. A closed expression for the amplitude that respects the Ward-Identities

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

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

The renormalized parameters are translated to well measured ones

$$\{\bar{g}', \bar{g}, \bar{v}, \bar{\lambda}, \bar{y}_t\} \longrightarrow \{\alpha_{\rm EM}, M_Z, M_W, G_F, M_h, m_t\}$$

and the renormalized Wilson coefficients to RG running quantities

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

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

One example of a $\mathcal{R}_{h\to\gamma\gamma}$-piece

A triangle diagram with SMEFT dipole operators affecting the $\gamma - \bar{f} - f$ vertices results in

$$\delta\mathcal{R}^{(6)}_{h\to\gamma\gamma} \simeq \frac{2M_h}{M_W \tan\theta_W} \sum_{f=e,u,d} N_{c,f}\, Q_f \times$$

$$\times \sum_{i=1}^{3} \mathrm{Re}\left[\frac{r_{f_i}^{1/2} D(r_{f_i})}{I_{\gamma\gamma}}\right] \frac{1}{G_F \Lambda^2} (C^{fB}_{ii} + 2\, T^3_f \tan\theta_W\, C^{fW}_{ii})\,.$$

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- $r_f = 4m_f^2/M_h^2$
- $C^{fB,fW}_{ii}$-coefficients in fermion mass basis
- $1/(G_F\Lambda^2)$ SMEFT expansion parameter
- large correction if $f = u$ and $i = 3$ (the top quark)

One example of a $\mathcal{R}_{h\to\gamma\gamma}$-piece

Large corrections may occur for $\Lambda = 1$ TeV and $C = 1$:

$$\begin{aligned}
\delta\mathcal{R}^{(6)}_{h\to\gamma\gamma} &= \text{prefactor} \times \frac{1}{G_F\Lambda^2} \times \frac{\text{SMEFT loop integrals}}{\text{SM loop integrals}} \\
&= O(10) \times O(10^{-1}) \times O(1) \\
&\simeq O(1)\,.
\end{aligned}$$

Not easy to be found without doing the actual calculation

Results

$$\delta\mathcal{R}_{h\to\gamma\gamma} = \sum_{i=1}^{6} \delta\mathcal{R}^{(i)}_{h\to\gamma\gamma} \simeq 0.06 \left(\frac{C^{\ell\ell}_{1221} - C^{\varphi\ell(3)}_{11} - C^{\varphi\ell(3)}_{22}}{\Lambda^2} \right) + 0.12 \left(\frac{C^{\varphi\Box} - \frac{1}{4} C^{\varphi D}}{\Lambda^2} \right)$$

$$- 0.01 \left(\frac{C^{e\varphi}_{22} + 4C^{e\varphi}_{33} + 5C^{u\varphi}_{22} + 2C^{d\varphi}_{33} - 3C^{u\varphi}_{33}}{\Lambda^2} \right)$$

$$- \left[48.04 - 1.07 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi B}}{\Lambda^2} - \left[14.29 - 0.12 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi W}}{\Lambda^2}$$

$$+ \left[26.62 - 0.52 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi WB}}{\Lambda^2}$$

$$+ \left[0.16 - 0.22 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{W}}{\Lambda^2}$$

$$+ \left[2.11 - 0.84 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{uB}_{33}}{\Lambda^2} + \left[1.13 - 0.45 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{uW}_{33}}{\Lambda^2}$$

$$- \left[0.03 + 0.01 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{uB}_{22}}{\Lambda^2} - \left[0.01 + 0.00 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{uW}_{22}}{\Lambda^2}$$

$$+ \left[0.03 + 0.01 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{dB}_{33}}{\Lambda^2} - \left[0.02 + 0.01 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{dW}_{33}}{\Lambda^2}$$

$$+ \left[0.02 + 0.00 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{eB}_{33}}{\Lambda^2} - \left[0.01 + 0.00 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{eW}_{33}}{\Lambda^2} + \ldots ,$$

Results

$$\delta\mathcal{R}_{h\to\gamma\gamma} = -\left[48.04 - 1.07\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}(\mu)}{\Lambda^2} - \left[14.29 - 0.12\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}(\mu)}{\Lambda^2} + \left[26.62 - 0.52\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}(\mu)}{\Lambda^2} + \left[2.11 - 0.84\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{33}(\mu)}{\Lambda^2} + \left[1.13 - 0.45\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{33}(\mu)}{\Lambda^2} \dots$$

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

Results

- A renormalization group independent result
- 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)

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A BSM approach worth pursuing further ...