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$h \to \gamma\gamma$ and $h \to Z\gamma$ decays in Standard Model Effective Field Theory

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We present the calculation of the $h \to \gamma\gamma$ and $h \to Z\gamma$ decay rates at the one-loop in the Standard Model Effective Field Theory (SMEFT), based on analyses published in refs. [1, 2]. The calculation has been performed including all relevant SMEFT operators up to mass-dimension 6, without resorting to any flavour or CP-conservation assumptions. The expressions for the on-shell amplitudes have been checked to be gauge invariant, renormalisation scale invariant and gauge fixing parameter independent. Final results are presented as compact semi-numerical formulae, easy to use in the interpretation of experimental data or in multi-parameter fits constraining the SMEFT parameters.

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1. $h \to \gamma\gamma$ and $h \to Z\gamma$ decays in New Physics searches

The Higgs boson decay processes $h \to \gamma\gamma$ and $h \to Z\gamma$ are extremely important probes for physics beyond the Standard Model (SM). Both processes are:

- measured experimentally with growing accuracy (especially $h \to \gamma\gamma$),
- predicted in SM with good accuracy and small theoretical uncertainties,
- generated in the SM at loop level only, thus sensitive to virtual contributions from new particles.

Therefore, measurements of their decay rates can provide valuable constraints on New Physics models.

Respective experimental searches are actively performed by the CMS and ATLAS collaborations at LHC [3, 4, 5, 6]. The $h \to \gamma\gamma$ decay has been observed. Both collaborations parametrize the result for its decay rate normalised to the SM prediction, using the quantity:

$$\mathscr{R}_{h\to\gamma\gamma} \equiv 1 + \delta\mathscr{R}_{h\to\gamma\gamma} = \frac{\Gamma(\mathrm{EXP}, h \to \gamma\gamma)}{\Gamma(\mathrm{SM}, h \to \gamma\gamma)} \tag{1.1}$$

The reported results are within 15% w.r.t. the SM prediction:

$$\begin{aligned} &\text{ATLAS [4]:} && \mathscr{R}_{h\to\gamma\gamma} = 0.96 \pm 0.14 \\ &\text{CMS [3, 5]:} && \mathscr{R}_{h\to\gamma\gamma} = 1.18^{+0.17}_{-0.14} \end{aligned} \tag{1.2}$$

For the $h \to Z\gamma$ decay only the upper bound is currently known. Using the data from center-of-mass energy $\sqrt{s} = 13$ TeV proton-proton collisions with integrated luminosity 36.1 fb^{-1} and assuming Higgs boson mass $M_h = 125.09$ GeV ATLAS [6] has found at 95% confidence level

$$\text{ATLAS [6]:} \qquad \mu_{h\to Z\gamma} = \frac{\sigma(pp \to h) \times \mathrm{Br}(h \to Z\gamma)}{\sigma(pp \to h)_{\mathrm{SM}} \times \mathrm{Br}(h \to Z\gamma)_{\mathrm{SM}}} \lesssim 6.6. \tag{1.3}$$

The results listed above can be used to constrain parameters of theories going beyond the SM. In recent years, Effective Field Theory extension of the Standard Model (SMEFT) became a widely accepted way of parametrizing possible deviations from the SM predictions in an universal way, independent on the details of unknown new interactions of higher energy models. SMEFT is constructed by adding to the SM Lagrangian all independent gauge invariant operators constructed out of the SM fields, up to some maximal mass dimension. For most applications it is sufficient to consider operators up to dimension 6:

$$L_{SMEFT} = L^{(4)}_{SM} + \frac{1}{\Lambda}\sum_X C^X_5 Q^{(5)}_X + \frac{1}{\Lambda^2}\sum_X C^X_6 Q^{(6)}_X + \dots \tag{1.4}$$

where Λ is the typical scale of particle masses in high energy theory, and C^X are dimensionless Wilson coefficients multiplying higher order operators Q_X. The classification of all 64 independent dimension-5 and 6 operator classes in SMEFT (called “Warsaw basis”) was given in ref. [7].

In this contribution, we compare the experimental results (1.2, 1.3) with predictions of SMEFT including operators up to mass-dimension 6, based on analyses published in refs. [1, 2].

X^3		$\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^* \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
		$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \widetilde{\varphi})$
				$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$ and ψ^4	
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{\varphi} W_{\mu\nu}^I$		
		Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{\varphi} B_{\mu\nu}$		
		Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$		
		Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$		

Table 1: Dimension-6 operators classes contributing to $h \to \gamma\gamma$ decay amplitude. For brevity fermion chiral indices L, R are suppressed.

2. $h \to \gamma\gamma$ and $h \to Z\gamma$ decay rate calculation in SMEFT

2.1 Contributing operators

In the general case 17 classes of dimension-6 operators in Warsaw basis contribute to $h \to \gamma\gamma$ and 23 such classes contribute $h \to Z\gamma$ decay amplitudes (16 operator classes are common for both decays). Operators contributing to $h \to \gamma\gamma$ decay are listed, in the notation of ref. [7], in Table 1 (see ref. [2] for the analogous table for $h \to Z\gamma$ decay).

There are no contributions from CP-violating operators up to dimension-6 terms in SMEFT expansion. This is based upon the fact that the SM amplitude is CP-invariant (symmetric in particle momenta interchange) and all interference terms with CP-violating coefficients (anti-symmetric in particle momenta interchange) vanish identically at the order $\mathscr{O}(\frac{1}{\Lambda^2})$.

2.2 Amplitude calculations

Diagram classes contributing to $h \to \gamma\gamma$ transition amplitude are illustrated in Fig. 1 . They include the SMEFT tree-level contribution, the 1PI vertex corrections from various classes of operators, the vertex counterterms to Wilson coefficients and tadpole and $Z\gamma$ self-energy contributions with their associated counterterms. Diagrams contributing to the $h \to Z\gamma$ process are similar and differ only by the additional self-energy corrections on the external Z-boson line.

Loop calculations involve interactions of complicated structure, including 3-, 4- and 5-tuple primary vertices, some of them momentum dependent, many including scalar and tensor Dirac structures [8]. To avoid calculational mistakes, all computations were performed analytically (with

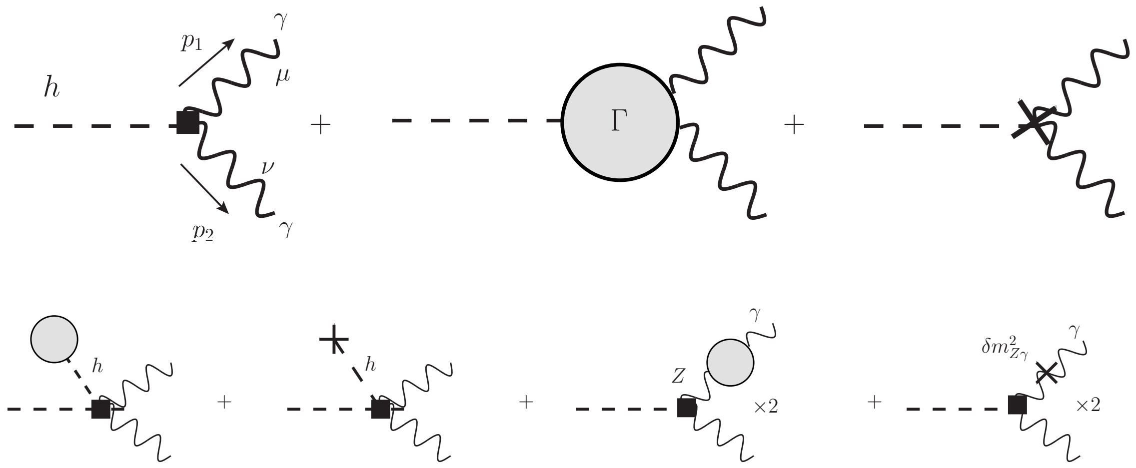

Figure 1: Diagram classes contributing to $h \to \gamma\gamma$ decay. Crosses denote SM counterterms and the black boxes indicate pure $d = 6$ operator insertions.

the help of `SmeftFR` Mathematica symbolic package [9][1]) in general R_ξ gauges, keeping independent ξ_A, ξ_W, ξ_Z parameters in propagators of photon, W boson and Z boson, respectively. Exact cancellation of all the gauge parameters in the final expressions for the decay amplitudes provided a strict cross-check of the correctness of our analysis.

Contrary to the SM results, both decay amplitudes in SMEFT are infinite at the 1-loop level. Removing infinities require non-trivial multi-parameter renormalization procedure. To that end, hybrid renormalisation scheme has been used:

- for direct connection with measured quantities, the SM parameters were renormalized using the on-shell scheme (based on the scheme developed in ref. [10]).
- set of well measured quantities, G_F, M_W, M_Z, M_h, m_t and lighter quark masses, have been used as the numerical input for SM parameters. In the numerical analysis we assume:

$$
\begin{aligned}
G_F &= 1.1663787(6) \times 10^5 \text{ GeV}^2, \\
M_W &= 80.385(15) \text{ GeV}, \\
M_Z &= 91.1876(21) \text{ GeV}, \\
M_h &= 125.09 \pm 0.24 \text{ GeV}, \\
m_t &= 173.1 \pm 0.6 \text{ GeV}.
\end{aligned}
$$

- Wilson coefficients of dimension-6 operators are renormalised in the $\overline{\text{MS}}$ scheme, so they can be split into running C-coefficients and counterterms as

$$\bar{C}(\mu) - \delta\bar{C}(\mu) \tag{2.1}$$

  where μ is the renormalisation scale and $\delta\bar{C}$ is a counterterm subtracting the infinite part only.

[1] `SmeftFR` code is publicly available at `www.fuw.edu.pl/smeft`

Denoting the scalar and transverse vector boson self-energy functions by Π_{HH} and Π_{VV}, respectively, and using symbol Γ^X for the 1PI vertex correction, the finite renormalized amplitude of $h \to \gamma\gamma$ decay can be expressed as:

$$
\begin{aligned}
& i\mathscr{A}^{\mu\nu}(h \to \gamma\gamma) == 4i \left[p_1^\nu p_2^\mu - (p_1 \cdot p_2)\, g^{\mu\nu} \right] \times \\
& \Bigg\{ c^2 v C^{\varphi B} \left[1 + \Gamma^{\varphi B} - \frac{\delta C^{\varphi B}}{C^{\varphi B}} - \frac{\delta v}{v} + \frac{1}{2} \frac{\partial \Pi'_{HH}(M_h^2)}{\partial p^2} + \frac{\partial \Pi_{\gamma\gamma}(0)}{\partial p^2} + 2 \tan\theta_W \frac{\Pi_{Z\gamma}(0) + \delta m_{Z\gamma}^2}{M_Z^2} \right] \\
& + s^2 v C^{\varphi W} \left[1 + \Gamma^{\varphi W} - \frac{\delta C^{\varphi W}}{C^{\varphi W}} - \frac{\delta v}{v} + \frac{1}{2} \frac{\partial \Pi'_{HH}(M_h^2)}{\partial p^2} + \frac{\partial \Pi_{\gamma\gamma}(0)}{\partial p^2} - \frac{2}{\tan\theta_W} \frac{\Pi_{Z\gamma}(0) + \delta m_{Z\gamma}^2}{M_Z^2} \right] \\
& - sc\, v C^{\varphi WB} \left[1 + \Gamma^{\varphi WB} - \frac{\delta C^{\varphi WB}}{C^{\varphi WB}} - \frac{\delta v}{v} + \frac{1}{2} \frac{\partial \Pi'_{HH}(M_h^2)}{\partial p^2} + \frac{\partial \Pi_{\gamma\gamma}(0)}{\partial p^2} - \frac{2}{\tan 2\theta_W} \frac{\Pi_{Z\gamma}(0) + \delta m_{Z\gamma}^2}{M_Z^2} \right] \\
& + \frac{1}{M_W} \overline{\Gamma}^{\mathrm{SM}} + \sum_{X \neq \varphi B, \varphi W, \varphi WB} v C^X \Gamma^X \Bigg\}_{finite}
\end{aligned} \tag{2.2}
$$

with $c \equiv \cos\theta_W = \frac{M_W}{M_Z}$ and $s \equiv \sin\theta_W$. Explicit analytical expressions for 2- and 3-point Green's functions in eq. (2.2) and for the δv, $\delta m_{Z\gamma}^2$ counterterms can be found in ref. [1], while the analogous expressions for the $\mathscr{A}^{\mu\nu}(h \to Z\gamma)$ are given in ref. [2].

As a cross-check of calculations, the final results for both amplitudes have been explicitly checked to be

- finite
- gauge invariant (ξ-parameters independent)
- renormalisation scale invariant, in the sense $\frac{d}{d\mu}\mathscr{A}(h \to \gamma\gamma)(\mu) = \frac{d}{d\mu}\mathscr{A}(h \to Z\gamma)(\mu) = 0$ (for the proof using also the results of refs. [11, 12, 13]).

3. Semi-analytical formulae and constraints on the Wilson coefficients

After substituting known SM parameter values, the results for $\delta\mathscr{R}_{h\to\gamma\gamma}$ and $\delta\mathscr{R}_{h\to Z\gamma}$ can be presented in terms of compact semi-analytic formulae, providing valuable and easy to use input for the experimental analyses and for multi-dimensional fits constraining SMEFT parameters.

Neglecting the terms with numerical coefficients smaller than 0.05, one has:

$$
\begin{aligned}
\delta\mathscr{R}_{h\to\gamma\gamma} \simeq\ & 0.18 \left(\frac{C^{\ell\ell}_{1221} - C^{\varphi\ell(3)}_{11} - C^{\varphi\ell(3)}_{22}}{\Lambda^2} \right) + 0.12 \left(\frac{C^{\varphi\Box} - 2C^{\varphi D}}{\Lambda^2} \right) \\
& - \left[48.0 - 1.1 \log\frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi B}}{\Lambda^2} - \left[14.3 - 0.1 \log\frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi W}}{\Lambda^2} + \left[26.2 - 0.5 \log\frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi WB}}{\Lambda^2} \\
& + \left[0.2 - 0.2 \log\frac{\mu^2}{M_W^2} \right] \frac{C^{W}}{\Lambda^2} + \left[2.1 - 0.8 \log\frac{\mu^2}{M_W^2} \right] \frac{C^{uB}_{33}}{\Lambda^2} + \left[1.1 - 0.5 \log\frac{\mu^2}{M_W^2} \right] \frac{C^{uW}_{33}}{\Lambda^2} + \ldots
\end{aligned} \tag{3.1}
$$

$$\begin{aligned}
\delta\mathscr{R}_{h\to Z\gamma} \simeq\ & 0.18\frac{C^{ll}_{1221} - C^{\varphi l(3)}_{11} - C^{\varphi l(3)}_{22}}{\Lambda^2} + 0.12\frac{C^{\varphi\Box} - C^{\varphi D}}{\Lambda^2} \\
&+ \left[15.0 - 0.4\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}}{\Lambda^2} - \left[14.9 - 0.2\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}}{\Lambda^2} + \left[9.4 - 0.3\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}}{\Lambda^2} \\
&+ \left[0.1 - 0.2\log\frac{\mu^2}{M_W^2}\right]\frac{C^{W}}{\Lambda^2} - \left[0.1 - 0.04\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{33}}{\Lambda^2} + \left[0.7 - 0.3\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{33}}{\Lambda^2} + \ldots
\end{aligned} \tag{3.2}$$

Full semi-analytical expressions, including the small terms neglected in formulae given above, can be found in refs. [1, 2].

Eq. (3.2) combined with experimental measurements of $\delta\mathscr{R}_{h\to\gamma\gamma}$ can be used to derive the order-of-magnitude bounds on the allowed values of several Wilson coefficients in SMEFT, valid on assumption of no significant fine-tuning between terms in eq. (3.2). Assuming one non-vanishing Wilson coefficient at a time, at the scale $\mu = M_W$ one has for operators contributing already at tree level:

$$\frac{|C^{\varphi B}|}{\Lambda^2} \lesssim \frac{0.003}{(1\ \text{TeV})^2} \qquad \frac{|C^{\varphi W}|}{\Lambda^2} \lesssim \frac{0.011}{(1\ \text{TeV})^2} \qquad \frac{|C^{\varphi WB}|}{\Lambda^2} \lesssim \frac{0.006}{(1\ \text{TeV})^2} \tag{3.3}$$

Competing constraints on $C^{\varphi B}, C^{\varphi W}, C^{\varphi WB}$ from electroweak precision measurements have similar order of magnitude.

Interestingly, loop level contributions from C^{uB}_{33} and C^{uW}_{33} to $\delta\mathscr{R}_{h\to\gamma\gamma}$ are magnified by the top quark mass in loop by $\mathscr{O}(10)$ and for $\mu = M_W$ lead to constraints more than an order of magnitude stronger than those derived from direct (tree-level) $\bar{t}tZ$ and single top production measurements at LHC:

$$\frac{|C^{uB}_{33}|}{\Lambda^2} \lesssim \frac{0.071}{(1\ \text{TeV})^2} \qquad \frac{|C^{uW}_{33}|}{\Lambda^2} \lesssim \frac{0.133}{(1\ \text{TeV})^2} \tag{3.4}$$

Expression for $\delta\mathscr{R}_{h\to Z\gamma}$ depends on the extended set of Wilson coefficients, including all apart one of those which contribute to the $\delta\mathscr{R}_{h\to\gamma\gamma}$. However, numerical prefactors in all terms in eq. (3.3) are numerically smaller than in eq. (3.2). As also current experimental measurements of $\delta\mathscr{R}_{h\to Z\gamma}$ are less constraining, eq. (3.3) leads to weaker order-of-magnitude bounds than given in eqs. (3.3, 3.4). Nevertheless, using both expressions simultaneously can strengthen the more sophisticated limits obtained from the multi-dimensional SMEFT parameter fits.

4. Summary

We have discussed the $h \to \gamma\gamma$ and $h \to Z\gamma$ decay rates at one-loop in SMEFT [1, 2], presenting the final results in the form of simple and easy to use in other analyses semi-analytic formulae depending linearly on the set of Wilson coefficients of dimension-6 operators. We have shown that with the current experimental accuracy $\delta\mathscr{R}_{h\to\gamma\gamma}$ can be used to put constraints on $C^{\varphi B}, C^{\varphi W}, C^{\varphi WB}, C^{uB}_{33}$ and C^{uW}_{33} coefficients which are comparable or stronger than derived from other measurements. Comparing numerical factors in expressions for both decay rates, one can also draw the general conclusion that in all scenarios barring accidental cancellation between contributions, it is unlikely to observed deviations from the SM prediction in the $h \to Z\gamma$ decay without observing them first in $h \to \gamma\gamma$ decay.

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