$h \to \gamma\gamma$ and $h \to Z\gamma$ decays in SMEFT

Janusz Rosiek, University of Warsaw

janusz.rosiek@fuw.edu.pl

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

Measurement of $h \to \gamma\gamma$ and $h \to Z\gamma$ decay rates can provide a valuable constraints on New Physics models. Both processes are:

- measured experimentally with growing accuracy
- predicted in Standard Model (SM) with good accuracy and small theoretical uncertainties
- radiative decays in the SM, sensitive to virtual contributions from new particles

Experiments parametrize their result normalised to SM prediction:

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

The recent results of LHC experiments:

ATLAS: $\mathcal{R}_{h\to\gamma\gamma} = 0.96 \pm 0.14$

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

LHC: $\mu_{h\to Z\gamma} = \dfrac{\sigma(pp\to h)\times \mathrm{Br}(h\to Z\gamma)}{\sigma(pp\to h)_{\mathrm{SM}}\times \mathrm{Br}(h\to Z\gamma)_{\mathrm{SM}}} \lesssim 6.6$

We compare these results with predictions of the SM extended with higher order gauge invariant operators, based on analyses published in refs. [1, 2].

SMEFT - an universal approach to New Physics searches

Effective Field Theory extension of the Standard Model (SMEFT) became in recent years a widely accepted way of parametrizing possible deviations from the SM predictions in an universal way, independent on the details of unknown new interactions in 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:

$$L_{SMEFT} = L^{(4)}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_X C_5^X Q_X^{(5)} + \frac{1}{\Lambda^2}\sum_X C_6^X Q_X^{(6)} + \ldots$$

where Λ is the typical scale of particle masses in high energy theory, and C_X are dimensionless Wilson coefficients multiplying higher order operators O_X. The classification of all 64 independent dimension-5 and 6 operator classes in SMEFT (called "Warsaw basis") was given in ref. [3].

$h \to \gamma\gamma$ and $h \to Z\gamma$ decay calculation in SMEFT

Contributing operators

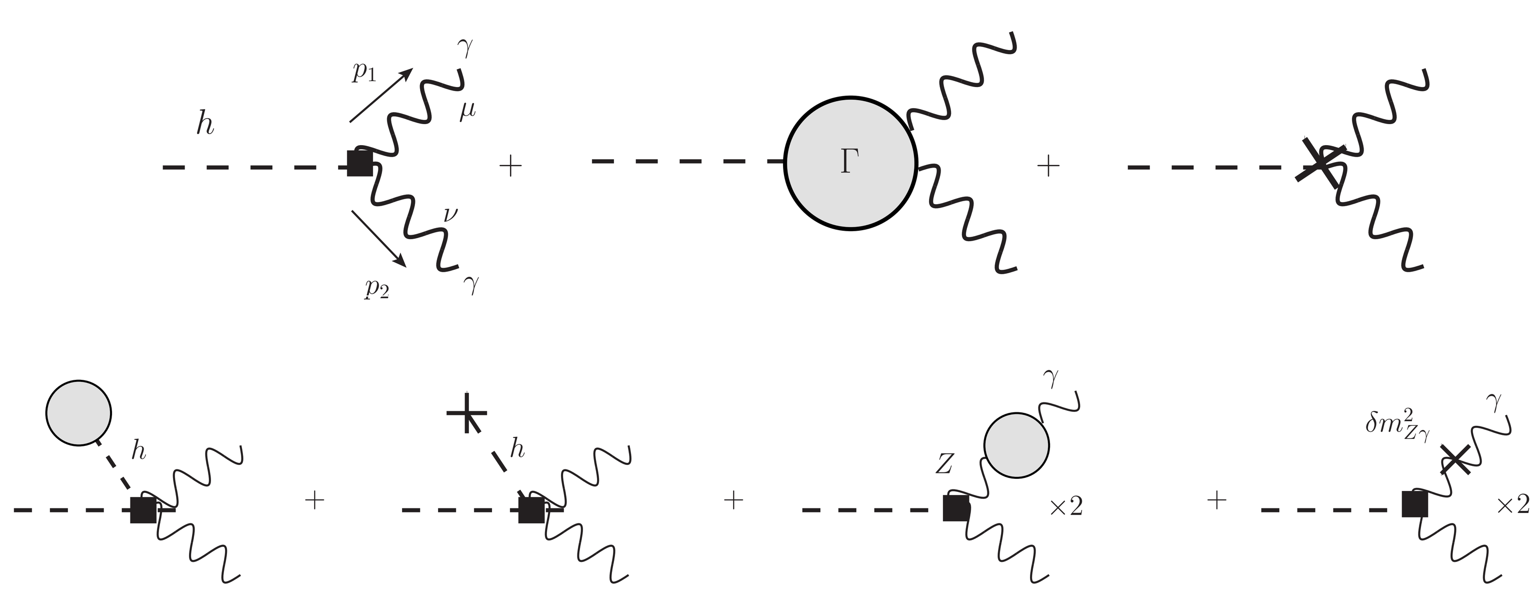
Neglecting strongly constrained CP-violating interactions, 17 $d = 6$ operators classes in Warsaw basis contribute to to $h \to \gamma\gamma$ and $h \to Z\gamma$ decay amplitudes. In the notation of ref. [3] they read (fermion chiral indices L, R are suppressed):

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}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$		
		Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$		
		Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$		
		Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$		

Amplitude calculations

Diagram classes contributing to $h \to \gamma\gamma$ and $h \to Z\gamma$ transition amplitudes illustrated in the figure below include the SMEFT "tree" contribution, the 1PI vertex corrections Γ^X from various classes of operators, the vertex counterterms to Wilson coefficients and tadpole and $Z\gamma$ self-energy contributions with their associated counterterms (crosses denote SM counterterms and the black boxes indicate pure $d = 6$ operator insertions).

Loop calculations involve interactions of complicated structure, including 3-, 4- and 5-tuple vertices, some of them momentum dependent, many including scalar and tensor Dirac structures [4]. Calculations were performed analytically in general R_ξ gauges keeping independent ξ_A, ξ_W, ξ_Z parameters, with the help of **SmeftFR** Mathematica symbolic package [5].



Removing infinities in the amplitude require non-trivial multi-parameter renormalization procedure. Hybrid renormalisation scheme has been used:

- for direct connection with measured quantities, the SM parameters were renormalized using the on-shell scheme.
- set of well measured quantities, $G_F, \alpha_{\mathrm{EM}}, M_W, M_Z, M_h, m_t$ and lighter quark masses, have been used as the numerical input for SM parameters.
- Wilson coefficients of dimension-6 operators are renormalised in the $\overline{\mathrm{MS}}$ scheme, so they can be split into running C-coefficients and counterterms as

$$\bar C(\mu) - \delta\bar C(\mu)$$

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

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 expression for the amplitude of $h \to \gamma\gamma$ decay can be expressed as:

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

with $c \equiv \cos\theta_W = \frac{M_W}{M_Z}$ and $s \equiv \sin\theta_W$. Analogous expression holds for the $A^{\mu\nu}(h \to Z\gamma)$.

The final results for both amplitudes have been explicitly checked to be

- finite.
- gauge invariant (ξ-parameters independent).
- renormalisation scale invariant, in the sense $\frac{d}{d\mu}\mathcal{A}(h\to\gamma\gamma)(\mu) = \frac{d}{d\mu}\mathcal{A}(h\to Z\gamma)(\mu) = 0$.

Semi-analytical formulae

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

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

$$\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} \simeq\ & 0.06\left(\frac{C^{\ell\ell}_{1221} - C^{\varphi\ell(3)}_{11} - C^{\varphi\ell(3)}_{22}}{\Lambda^2}\right) + 0.12\left(\frac{C^{\varphi\Box} - \frac{1}{4}C^{\varphi D}}{\Lambda^2}\right) \\
& - \left[48.0 - 1.1\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}}{\Lambda^2} - \left[14.3 - 0.1\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}}{\Lambda^2} + \left[26.6 - 0.5\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}}{\Lambda^2} \\
& + \left[0.2 - 0.2\log\frac{\mu^2}{M_W^2}\right]\frac{C^{W}}{\Lambda^2} + \left[2.1 - 0.8\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{33}}{\Lambda^2} + \left[1.1 - 0.5\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{33}}{\Lambda^2} + \ldots
\end{aligned}$$

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

Constraints on the Wilson coefficients

Experimental measurements of $\delta\mathcal{R}_{h\to\gamma\gamma}$ constrain the allowed values of several Wilson coefficients in SMEFT. Assuming one non-vanishing Wilson coefficient at a time, at the scale $\mu = M_W$ one has for operators contributing already at tree level:

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

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 $\delta\mathcal{R}_{h\to\gamma\gamma}$ are magnified by the top quark mass in loop by $\mathcal{O}(10)$ and for $\mu = M_W$ lead to constraints more than an order of magnitude stronger than derived from $\bar t t Z$ and single top production measurements at LHC:

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

Coefficients of terms in expression for $\delta\mathcal{R}_{h\to Z\gamma}$ are smaller than in $\delta\mathcal{R}_{h\to\gamma\gamma}$, thus leading to weaker constraints. Barring accidental cancellation between contributions, in SMEFT 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.

References

[1] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, JHEP **08** (2018) 103.

[2] A. Dedes, K. Suxho and L. Trifyllis, arXiv:1903.12046.

[3] B. Grządkowski, M. Iskrzyński, M. Misiak and J. Rosiek, *JHEP* **10** (2010) 085.

[4] A. Dedes, W. Materkowska, M. Paraskevas, J. Rosiek, and K. Suxho, *JHEP* **06** (2017) 143.

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