The decay $h \to Z\gamma$ in Standard Model Effective Field Theory (SM-EFT)

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[1] "The decay $h \to Z\gamma$ in the Standard-Model Effective Field Theory", arXiv:1903.12046 [hep-ph].

Outline

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1. Introduction and Motivation
2. Feynman Rules in SM-EFT
3. The SM-EFT code
4. $h \to Z\gamma$ amplitude in SM-EFT

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4. $h \to Z\gamma$ amplitude in SM-EFT
5. $h \to Z\gamma$ results

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Motivation

Theorem (Weinberg's "Folk Theorem":[a])

[a] S. Weinberg, "Effective Field Theory, Past and Future," [arXiv:0908.1964]

"If one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order of perturbation theory, the result will simply be the most general possible S-matrix consistent with perturbative unitarity, analyticity, cluster decomposition, and the assumed symmetry properties."[a]

[a] S. Weinberg, "Phenomenological Lagrangians" Physica A **96**, 327 (1979).

Instead of studying a plethora of BSM physics models, the "Folk Theorem" + experiments may guide us towards a new level of understanding.

This path may be proven to be useful at LHC and future colliders.

Introduction

Every serious attempt in applying the "Folk-Theorem" at loop level should consist of the proper power counting rules for renormalizability of the theory:

propagators go like p^{-2} as $p \to \infty$

In early 70's, (t' Hooft, B. Lee, Fujikawa, Lee, Sanda, Yao) has been shown that this can be realized in linear gauges called R_ξ-gauges. Then

Every physical observable should be ξ-independent.

Our work quantized SM-EFT in R_ξ-gauges [2]. Previous works[3] include only a partial list of FRs in unitary or non-linear gauges.

[2] JHEP **1706**, 143 (2017), JHEP **1902** (2019) 051.

[3] For a review see G. Passarino and M. Trott, arXiv:1610.08356 [hep-ph].

Electroweak sector

NP effects can be parameterized by coefficients of higher dimensional operators.

Example: some $d = 6$ operators in "Warsaw" basis:[4]

$$\frac{C^{\varphi B}}{\Lambda^2}\,\varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu} \;+\; \frac{C^{\varphi W}}{\Lambda^2}\,\varphi^\dagger\varphi W^I_{\mu\nu}W^{I\,\mu\nu} \;+\; \frac{C^{\varphi WB}}{\Lambda^2}\,\varphi^\dagger\tau^I\varphi W^I_{\mu\nu}B^{\mu\nu}$$

are linearly independent i.e., they are not connected by EOM or integration by parts.

[4] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, JHEP **1010**, 085 (2010) [arXiv:1008.4884 [hep-ph]]

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After SSB we obtain:

- new vertices i.e., $h\gamma\gamma$, $hh\gamma\gamma, hZ\gamma, \ldots$ already at "tree level"
- corrections to gauge boson propagators
- new admixtures of propagators

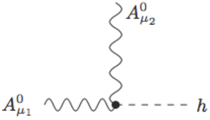
[4] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, JHEP **1010**, 085 (2010) [arXiv:1008.4884 [hep-ph]]

The procedure

The procedure we followed[5] in deriving the SM-EFT Feynman Rules (FRs) consists of the following steps:

- Within the "Warsaw" (gauge) basis we perform the SSB mechanism $\longrightarrow$ canonical kinetic terms.
- Move to mass basis and define physical fields.
- Introduce suitable R_ξ-gauge fixing and ghost terms.
- Check BRST invariance.
- Canonical forms of propagators for all fields.
- Evaluate FRs for all sectors in R_ξ-gauges.

[5] A. Dedes, W. Materkowska, M. Paraskevas, J. Rosiek and K. Suxho, JHEP **1706**, 143 (2017) [arXiv:1704.03888 [hep-ph]].



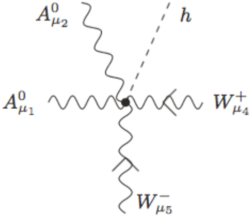
$$
\begin{aligned}
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi W}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right) \\
&\quad + \frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi B}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right) \\
&\quad - \frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi WB}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right) \\
&\quad + \frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}} p_1^{\alpha_1} p_2^{\beta_1} \epsilon_{\mu_1\mu_2\alpha_1\beta_1} + \frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\tilde{B}} p_1^{\alpha_1} p_2^{\beta_1} \epsilon_{\mu_1\mu_2\alpha_1\beta_1} \\
&\quad - \frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}B} p_1^{\alpha_1} p_2^{\beta_1} \epsilon_{\mu_1\mu_2\alpha_1\beta_1}
\end{aligned}
$$

where from now on $C \equiv \frac{C}{\Lambda^2}$ and

$$
\bar{g} \equiv (1 - C^{\varphi W} v^2)^{-1} g\,, \qquad \bar{g}' \equiv (1 - C^{\varphi B} v^2)^{-1} g'.
$$

Here v is the "true" i.e., corrected v.e.v.

One more interesting FR from the Gauge-Higgs sector is:



$$-\frac{4i\bar{g}^2\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2}\left(\eta_{\mu_1\mu_5}\eta_{\mu_2\mu_4}+\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_5}-2\eta_{\mu_1\mu_2}\eta_{\mu_4\mu_5}\right)C^{\varphi W}$$

Contributes to $h \to \gamma\gamma$ at one-loop if we connect the W-line: pure SM-EFT contribution.

SM-EFT code

- Most of the vertices are reasonably compact even for manual calculations.
- On the other hand, there are many vertices (~ 380 in R_ξ - gauges).
- A Mathematica code, the `SmeftFR` code, based on `FeynRules` package has been developed[6].
- `SmeftFR` starts from the original Lagrangian and performs all calculations till `Latex` printing the FRs in unitary or R_ξ-gauges for any subset of up-to $d = 6$ operators we decide.

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

[6] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, L. Trifyllis, "SmeftFR – Feynman rules generator for the Standard Model Effective Field Theory", (arXiv:1904.03204 [hep-ph])

ξ-independence at tree level and one-loop in SM-EFT

A first, non-trivial check of our SM-EFT FRs is to prove that amplitudes like:

$$\ell_{f_1} + \ell_{f_2} \longrightarrow \ell_{f_3} + \ell_{f_4}$$

mediated by Z and Goldstone bosons (G^0) are ξ-independent after using explicit dependencies on masses from the non-renormalizable operators[7]. Other checks involve, the Goldstone boson equivalence theorem, tree level unitarity bounds, but we also have proved the ξ-independence in one-loop processes e.g., $h \to \gamma\gamma$ [8] and $h \to Z\gamma$ [9].

[7] L. Trifyllis, MSc thesis, Ioannina, January, 2018.

[8] "The decay $h \to \gamma\gamma$ in the Standard-Model Effective Field Theory", (JHEP 1808 (2018) 103), A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, L. Trifyllis.

[9] "The decay $h \to Z\gamma$ in the Standard-Model Effective Field Theory", (arXiv:1903.12046), A. Dedes, K. Suxho, L. Trifyllis.

$h \to Z\gamma$ in SM-EFT

Measuring New Physics with the decay $h \to Z\gamma$.

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

If we assume that operators that affect the $h \to Z\gamma$ decay, do not affect the $gg \to h$, then LHC sets the bound [10]:

$$\mathcal{R}_{h\to Z\gamma} \;= \lesssim 6.6$$

Our aim is to calculate $\delta\mathcal{R}_{h\to Z\gamma}$ with BSM = SM-EFT at one-loop.

[10] ATLAS, **JHEP 10** (2017) 112, arXiv:1708.00212.

Effective operators affecting $h \to Z\gamma$

$Q_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{e\varphi} = (\varphi^\dagger\varphi)(\bar{l}'_p e'_r \varphi)$
$Q_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi} = (\varphi^\dagger\varphi)(\bar{q}'_p u'_r \widetilde{\varphi})$
$Q_{\varphi D} = \left(\varphi^\dagger D^\mu \varphi\right)^* \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi} = (\varphi^\dagger\varphi)(\bar{q}'_p d'_r \varphi)$
$Q_{\varphi B} = \varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	$Q_{eW} = (\bar{l}'_p \sigma^{\mu\nu} e'_r)\tau^I \varphi W^I_{\mu\nu}$
$Q_{eB} = (\bar{l}'_p \sigma^{\mu\nu} e'_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}'_p \tau^I \gamma^\mu l'_r)$
$Q^{(1)}_{\varphi l} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}'_p \gamma^\mu l'_r)$	$Q^{(1)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}'_p \gamma^\mu q'_r)$
$Q_{\varphi W} = \varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	$Q_{uW} = (\bar{q}'_p \sigma^{\mu\nu} u'_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$
$Q_{\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}'_p \gamma^\mu e'_r)$	$Q_{uB} = (\bar{q}'_p \sigma^{\mu\nu} u'_r)\widetilde{\varphi}\, B_{\mu\nu}$
$Q_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}'_p \gamma^\mu u'_r)$	$Q_{\varphi WB} = \varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{dW} = (\bar{q}'_p \sigma^{\mu\nu} d'_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}'_p \gamma^\mu d'_r)$
$Q_{dB} = (\bar{q}'_p \sigma^{\mu\nu} d'_r)\varphi\, B_{\mu\nu}$	$Q_{ll} = (\bar{l}'_p \gamma_\mu l'_r)(\bar{l}'_s \gamma^\mu l'_t)$
$Q^{(3)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}'_p \tau^I \gamma^\mu q'_r)$	

23 operators, not including different flavours and CP-violation.

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 Dimensional Regularization.
2. We use a hybrid renormalization scheme: on-shell in SM-quantities and $\overline{MS}$ in Wilson coefficients.
3. We establish a ξ-independent and renormalization scale invariant $h \to Z\gamma$ amplitude using the β-functions by Manohar et.al[11].
4. All infinities absorbed by SM and EFT counterterms as normal.
5. A closed expression for the amplitude that respects the Ward-Identities.

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

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

The $h \to Z\gamma$ Amplitude in SM-EFT

$$i\,\mathcal{A}^{\mu\nu}(h \to Z\gamma) = \langle \gamma(\,\epsilon^{\mu}, p_1),\; Z(\epsilon^{\nu}, p_2)\,|\,S\,|\,h(q)\,\rangle = 4i\left[\,p_1^{\nu}\,p_2^{\mu} - (p_1\cdot p_2)\,g^{\mu\nu}\,\right]\mathcal{A}_{h\to Z\gamma}\;,$$

$$\begin{aligned}
\mathcal{A}_{h\to Z\gamma} \quad = \quad & \Bigg\{ -s\,c\,v\,C^{\varphi B}(\mu)\left[1 + \mathcal{X}^{\varphi B} - \frac{1}{t}\left(\frac{A_{Z\gamma}(M_Z^2) + \delta m^2_{Z\gamma}}{M_Z^2}\right) + t\left(\frac{A_{Z\gamma}(0) + \delta m^2_{ZA}}{M_Z^2}\right)\right] \\
+ \quad & s\,c\,v\,C^{\varphi W}(\mu)\left[1 + \mathcal{X}^{\varphi W} + t\left(\frac{A_{Z\gamma}(M_Z^2) + \delta m^2_{Z\gamma}}{M_Z^2}\right) - \frac{1}{t}\left(\frac{A_{Z\gamma}(0) + \delta m^2_{ZA}}{M_Z^2}\right)\right] \\
+ \quad & \frac{s^2 - c^2}{2}\,v\,C^{\varphi WB}(\mu)\left[1 + \mathcal{X}^{\varphi WB} - \frac{2\,s\,c}{s^2 - c^2}\left(\frac{A_{Z\gamma}(M_Z^2) + A_{Z\gamma}(0) + 2\delta m^2_{Z\gamma}}{M_Z^2}\right)\right] \\
+ \quad & \frac{1}{M_W}\,\overline{\Gamma}^{\mathrm{SM}} \;+ \sum_{X\neq\varphi B,\varphi W,\varphi WB} v\,C^{X}(\mu)\,\Gamma^{X}\Bigg\}_{\mathrm{finite}}\,.
\end{aligned}$$

$$\mathcal{X}^{i} = \Gamma^{i} - \frac{\delta C^{i}}{C^{i}} - \frac{\delta v}{v} + \frac{1}{2}\Pi'_{hh}(M_h^2) + \frac{1}{2}A'_{ZZ}(M_Z^2) + \frac{1}{2}A'_{\gamma\gamma}(0), \qquad i = \varphi B,\ \varphi W,\ \varphi WB$$

SM counterterms[12] and EFT counterterms are enough to absorb infinities.

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

Results [13]

Consider the "tree level SM-EFT" operators $Q^{\varphi B}$, $Q^{\varphi W}$, $Q^{\varphi WB}$.
Input parameters scheme: $\{G_F,\, M_W,\, M_Z,\, M_h\}$,

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

where Λ is in TeV units.

Non-log parts are the most important in $\delta\mathcal{R}_{h\to Z\gamma}$!

[13] A. Dedes, K. Suxho, L. Trifyllis, arXiv: 1903.12046 [hep-ph].

Results

From LHC analysis, $\mathcal{R}_{h\to Z\gamma} \approx 6.6$, and therefore

$$\frac{|C^{\varphi B}|}{\Lambda^2} \lesssim \frac{0.4}{(1\,TeV)^2}, \quad \frac{|C^{\varphi W}|}{\Lambda^2} \lesssim \frac{0.4}{(1\,TeV)^2}, \quad \frac{|C^{\varphi WB}|}{\Lambda^2} \lesssim \frac{0.7}{(1\,TeV)^2}.$$

- For $\Lambda = 1\ \mathrm{TeV}$ it must be $C^{\varphi V} \sim 0.5$.
- The exp/th combined analysis confirms a perturbative approach to EFT (at least for these operators).
- These Wilson coefficients receive bounds from other observables $(h \to \gamma\gamma)$[14].

We derive the contributions to $\delta\mathcal{R}_{h\to Z\gamma}$ from all other operators.
The **new operators** do not affect the $\mathcal{R}_{h\to Z\gamma}$ by more than 1 %.

[14] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, L. Trifyllis, JHEP 1808 (2018) 103, arXiv: 1805.00302 [hep-ph]

Results

Comparison with $h \to \gamma\gamma$ results [15].
Input parameters scheme: $\{G_F,\, M_W,\, M_Z,\, M_h\}$, LHC bound:
$\delta\mathcal{R}_{h\to\gamma\gamma} \lesssim 15\%$,

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

For $\Lambda \sim 1\,TeV$, from $\delta\mathcal{R}_{h\to\gamma\gamma} \simeq 15\% \Rightarrow 0.003 < \frac{|C^{\varphi V}|}{\Lambda^2} < 0.01$.

[15] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, L. Trifyllis, JHEP 1808 (2018) 103, arXiv: 1805.00302 [hep-ph]

Results

Comparison with $h \to \gamma\gamma$ results [16].

- The prefactors of $C^{\varphi B}$ and $C^{\varphi WB}$ are suppressed by a factor ~ 3 in $h \to Z\gamma$ w.r.t $h \to \gamma\gamma$. The prefactor of $C^{\varphi W}$ is almost the same.
- Assuming one coupling at a time, we find that bounds on Wilson coefficients from $h \to Z\gamma$ are weaker than those from $h \to \gamma\gamma$ (almost one or two orders of magnitude).

$$\frac{|C^{\varphi B}_{h\to\gamma\gamma}|}{\Lambda^2} \lesssim \frac{0.003}{(1\,TeV)^2}, \quad \frac{|C^{\varphi W}_{h\to\gamma\gamma}|}{\Lambda^2} \lesssim \frac{0.010}{(1\,TeV)^2}, \quad \frac{|C^{\varphi WB}_{h\to\gamma\gamma}|}{\Lambda^2} \lesssim \frac{0.006}{(1\,TeV)^2}.$$

$$\frac{|C^{\varphi B}_{h\to Z\gamma}|}{\Lambda^2} \lesssim \frac{0.4}{(1\,TeV)^2}, \quad \frac{|C^{\varphi W}_{h\to Z\gamma}|}{\Lambda^2} \lesssim \frac{0.4}{(1\,TeV)^2}, \quad \frac{|C^{\varphi WB}_{h\to Z\gamma}|}{\Lambda^2} \lesssim \frac{0.7}{(1\,TeV)^2}.$$

[16] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, L. Trifyllis, JHEP 1808 (2018) 103, arXiv: 1805.00302 [hep-ph]

Conclusions

- We consider the SM augmented with $d = 6$ effective operators in "Warsaw" basis (SM-EFT).
- We calculate the amplitude $h \to Z\gamma$ at one-loop and at $1/\Lambda^2$ in SM-EFT with all operators apart from CP-violating ones.
- We used an adaptive renormalization scheme for SM-EFT: a hybrid between on-shell and $\overline{MS}$ schemes.
- Amplitude which is gauge and renormalization group invariant, finite and ξ-independent.
- Comparison with LHC's ratio $\mathcal{R}_{h\to Z\gamma}$ results in bounds on Wilson coefficients C/Λ^2.
- We find that bounds on Wilson coefficients from $h \to Z\gamma$ are weaker than those from $h \to \gamma\gamma$.
- Both $h \to Z\gamma$ and $h \to \gamma\gamma$ are useful examples for future NLO calculations in SM-EFT.

I would like to thank the State Shcolarships Foundation (I.K.Y.) for full financial support of my research.

Thank you!

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[17] 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.

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