$h \to \gamma\gamma$ in Standard Model Effective Field Theory (SMEFT)

Christos Soutzios

University of Ioannina, Greece

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In collaboration with A. Dedes, J. Rosiek, M. Paraskevas, L. Trifyllis [1], [2]

[1] "Feynman rules for the Standard Model Effective Field Theory in R_ξ-gauges", JHEP **1706**, 143 (2017) [arXiv:1704.03888 [hep-ph]].

[2] work in progress

Outline

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1. Introduction and Motivation
2. Feynman Rules in SMEFT
3. The SMEFT code
4. $h \to \gamma\gamma$ Amplitude in SMEFT

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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 and B. Lee, and then Fujikawa, Lee, Sanda and independently Yao, showed that this can be realized in linear gauges called R_ξ-gauges (due to the arbitrary ξ-parameters involved). Then

Every physical observable should be ξ-independent.

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

[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., $h\gamma\gamma$, $hh\gamma\gamma, \ldots.$ 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]]

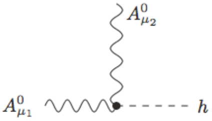
The procedure

The procedure we followed[5] in deriving the SMEFT 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]].

Example : $h\gamma\gamma$-vertex in SMEFT



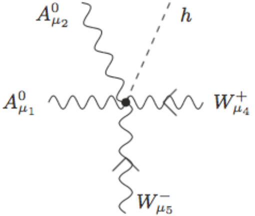
$$
\begin{aligned}
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi W}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right) \\
&+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi B}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right) \\
&-\frac{4i\bar{g}\bar{g}'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

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

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

also 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 SMEFT contribution.

SMEFT code

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

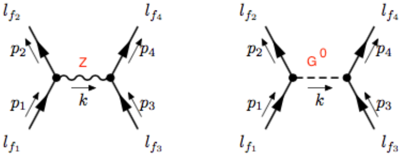
http://www.fuw.edu.pl/smeft

ξ-independence at tree level

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

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

mediated by Z-gauge and Goldstone bosons (G^0)



are ξ-independent after using explicit dependencies on masses from the non-renormalizable operators.[6]

Other checks involve, the Goldstone boson equivalence theorem, tree level unitarity bounds, ST identities, but the ultimate check should be the ξ-independence of a physical process e.g., $h \rightarrow \gamma\gamma$.

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

$h \to \gamma\gamma$

Measuring New Physics with the decay $h \to \gamma\gamma$:

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

Latest measurement comes from LHC[7]

$$\mathcal{R}_{h\to\gamma\gamma} = 0.99^{+0.15}_{-0.14}$$

Our aim is to calculate the ratio $\mathcal{R}$ with BSM = SMEFT at one-loop

[7] ATLAS Collaboration, arXiv 1802.04146

Effective operators affecting $h \to \gamma\gamma$ [8]

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

20 operators, not including different flavors and CP-violation

[8] C. Hartmann and M. Trott, "Higgs Decay to Two Photons at One Loop in the Standard Model Effective Field Theory", Phys. Rev. Lett. 115 (2015),[arXiv:1507.03568]

Renormalization

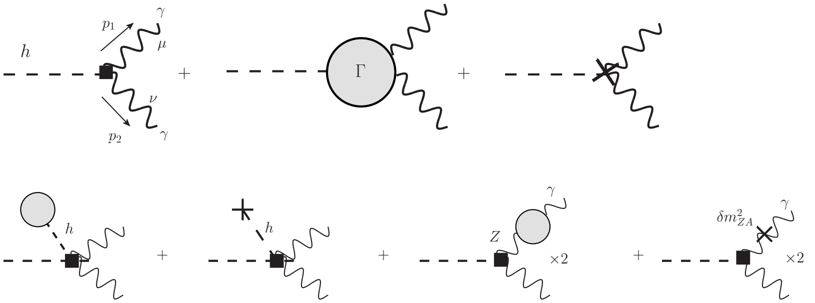
We assume perturbative renormalization. We are working at 1-loop and up to $1/\Lambda^2$ in EFT expansion.

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 $h \to \gamma\gamma$ amplitude using the β-functions by Manohar et.al[9]
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 !!

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

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.

The $h \to \gamma\gamma$ Amplitude in SMEFT

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

where

$$\begin{aligned}
\mathcal{A}_{h\to\gamma\gamma} \quad = \quad & \Bigg\{ c^2\, v\, \bar{C}^{\varphi B}(\mu)\left[1 + \Gamma^{\varphi B} - \frac{\delta v}{v} + \frac{1}{2}\Pi'_{HH}(M_h^2) - \Pi_{\gamma\gamma}(0) + 2\tan\theta_W \left(\frac{A_{Z\gamma}(0) + \delta m_{ZA}^2}{M_Z^2}\right)\right] \\
+ \quad & s^2\, v\, \bar{C}^{\varphi W}(\mu)\left[1 + \Gamma^{\varphi W} - \frac{\delta v}{v} + \frac{1}{2}\Pi'_{HH}(M_h^2) - \Pi_{\gamma\gamma}(0) - \frac{2}{\tan\theta_W} \left(\frac{A_{Z\gamma}(0) + \delta m_{ZA}^2}{M_Z^2}\right)\right] \\
- \quad & sc\, v\, \bar{C}^{\varphi WB}(\mu)\left[1 + \Gamma^{\varphi WB} - \frac{\delta v}{v} + \frac{1}{2}\Pi'_{HH}(M_h^2) - \Pi_{\gamma\gamma}(0) - \frac{2}{\tan 2\theta_W} \left(\frac{A_{Z\gamma}(0) + \delta m_{ZA}^2}{M_Z^2}\right)\right] \\
+ \quad & \frac{1}{M_W}\,\bar{\Gamma}^{\rm SM} \;+ \sum_{X \neq \varphi B, \varphi W, \varphi WB} v\, C^{X}(\mu)\, \Gamma^{X} \Bigg\}_{\rm finite} .
\end{aligned}$$

SM counterterms[10] and EFT counterterms are enough to absorb infinities.

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

Results (preliminary)[11]

Consider the "tree level SM EFT" operators $Q^{\varphi B}, Q^{\varphi W}, Q^{\varphi WB}$.

$$\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} &= \left[-31.9 + 1.1\,\log\left(\frac{\mu^2}{M_W^2}\right)\right]\frac{C^{\varphi B}(\mu)}{\Lambda^2} \\
&+ \left[-26.7 + 0.1\,\log\left(\frac{\mu^2}{M_W^2}\right)\right]\frac{C^{\varphi W}(\mu)}{\Lambda^2} \\
&+ \left[\ 33.9 - 0.6\,\log\left(\frac{\mu^2}{M_W^2}\right)\right]\frac{C^{\varphi WB}(\mu)}{\Lambda^2}
\end{aligned}$$

where Λ is in TeV units.

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

[11] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, L. Trifyllis, work in progress

Results (preliminary)

From LHC analysis, $\delta R_{h \to \gamma\gamma} \approx 0.15$, and therefore

$$\frac{C^{\varphi V}}{\Lambda^2} \lesssim 0.005 \, .$$

- For $C^{\varphi V} = 1$ we must have $\Lambda \gtrsim 10 \ \mathrm{TeV}$
- For $\Lambda = 1 \ \mathrm{TeV}$ it must be $C^{\varphi V} \lesssim 0.005$ i.e., $C^{\varphi V}$ are loop induced operators in UV justifying an old work by Arzt, Einhorn and Wudka
- the exp/th combined analysis confirms a perturbative approach to EFT (at least for these operators)
- These Wilson coefficients receive bounds from other EW observables.[12]

We derive the contributions to $\mathcal{R}_{h \to \gamma\gamma}$ from all other operators.

[12] J. Ellis, C. W. Murphy, V. Sanz, and T. You, "Updated Global SMEFT Fit to Higgs, Diboson and Electroweak Data", arXiv:1803.03252

UV-models relevant to $h \to \gamma\gamma$

Every charged particle belonging to a chiral multiplet that receives part of its mass from the SM Higgs field contributes to the above operators.

Consider for example a Dark Matter model[13] with two $SU(2)_L$ fermion Doublets, $D_{1,2}$, that couple to the Higgs field H and a fermion triplet T,

$$D_1 H T \; + \; D_2 H^\dagger T \; + \; M D_1 D_2 \; + \; \mathrm{H.c}$$

Upon "integration out" of D, T-fields the above operators, $H^\dagger H F_{\mu\nu} F^{\mu\nu}$, are induced at one loop.

[13] A. Dedes, D. Karamitros, Phys. Rev. D**89**, 2014 [arXiv:1403.7744]

Conclusions

- We consider the SM augmented with $d = 6$ non-renormalizable operators in "Warsaw" basis (SM EFT)
- We calculate the amplitude $h \to \gamma\gamma$ 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
- Large finite parts w.r.t to log-parts – justification of our calculation
- Compare with LHC's ratio $\mathcal{R}_{h \to \gamma\gamma}$ results in bounds on Wilson coefficients C/Λ^2

$h \to \gamma\gamma$: a useful warming-up for future NLO calculations in SMEFT

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[14] 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.

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