One-Loop Phenomenology in the SM EFT

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Outline

1. Introduction & Motivation
2. Renormalisation scheme in SMEFT
3. Phenomenology in SMEFT
4. Summary

Publications

Collaborators: A. Dedes, J. Rosiek, M. Paraskevas, K. Suxho

- *The decay $h \to \gamma\gamma$ in SMEFT*, AD, MP, JR, KS, LT
  JHEP **08** (2018) 103 [arXiv:1805.00302[hep-ph]]
- *The decay $h \to Z\gamma$ in SMEFT*, AD, KS, LT
  JHEP **06** (2019) 115 [arXiv:1903.12046[hep-ph]]
- *smeftFR – Feynman rules generator for the SMEFT*, AD, MP, JR, KS, LT
  Comput.Phys.Commun. **247** (2020) 106931 [arXiv:1904.03204[hep-ph]]

Why use Effective (Field) Theories?

- Separation of scales
- Each theory is an effective theory
- Calculate measurable quantities without UV input
- Systematically reduce theoretical error

For a review: Manohar, arXiv:1804.05863[hep-ph]

- Categorising operators

Dimensionality	Renormalisation	Relevance
$D < d$	super-renormalisable	relevant
$D = d$	renormalisable	marginal
$D > d$	non-renormalisable	irrelevant

d: dimensionality of spacetime D: dimensionality of operator

- An EFT is a QFT with a power counting formula
  E.g. $\delta = p/\Lambda$, where Λ is a UV scale
- Approaching the cut-off makes the EFT lose its predictive power
- Renormalisation works perfectly fine inside the EFT validity region in a truncated EFT
- Effective operators are suppressed, not wrong

SM is a phenomenologically successful theory for the EW (and strong) interactions

- Renormalisable, quantum gauge field theory
- Clearly *not* the Theory of Everything but an effective theory
- The most general SM EFT Lagrangian can be written as

$$\mathcal{L}_{\mathsf{SMEFT}} = \mathcal{L}_{\mathsf{SM}} + \sum_{p=1}^{\infty} \sum_{i} \frac{c_{p,i}}{\Lambda^p} Q_i^{(4+p)}$$

where Λ is the energy scale of the UV theory, and $c_{p,i}$s are the Wilson coefficients of the effective operators

- The SM is a limiting case of the SMEFT ($\Lambda \to \infty$)

A non-redundant set of dim-6 SMEFT is the "Warsaw basis".[1]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

The full set of Feynman Rules for dim-6 SMEFT in linear R_ξ-gauges has been produced using version 1.0 of `SmeftFR`.[2]

[1] B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek [arXiv:1008.4884]

[2] A. Dedes, W. Materkowska, M. Paraskevas, J. Rosiek, K. Suxho [arXiv:1704.03888]

- Prior to our work:
  $h \to \gamma\gamma$: C. Hartmann and M. Trott [arXiv:1507.03568; 1505.02646]
  $h \to Z\gamma$: S. Dawson and P.P. Giardino [arXiv:1801.01136]

- Features of our work
  - Use of linear R_ξ-gauges
  - Analytic proof of gauge invariance
  - Simple renormalisation framework
  - Analytical and semi-numerical expressions for $\delta\mathcal{R}_{h\to\gamma\gamma,\,Z\gamma}$
  - Bounds on Wilson coefficients

Calculating the decays $h \to \gamma\gamma$ and $h \to Z\gamma$

- We choose a hybrid renormalisation scheme
  - On-shell renormalisation for the SM-like couplings[3]
  - $\overline{\text{MS}}$ renormalisation for the Wilson coeffients[4]
- The decays $h \to \gamma\gamma$, $Z\gamma$, are loop-generated in the SM
- SM renormalisation conditions for the SM-like couplings

[3] Following A. Sirlin (1980)

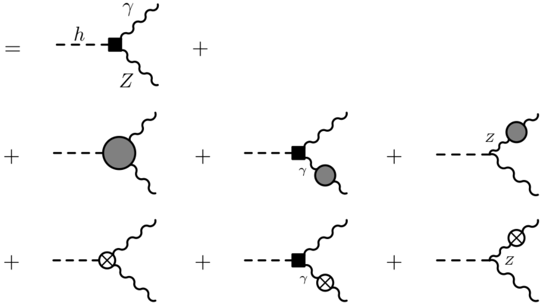
[4] R. Alonso, E.E. Jenkins, A.V. Manohar, M. Trott, arXiv:1308.2627; 1310.4838; 1312.2014

On-shell S-matrix element for $h \to Z\gamma$ reads

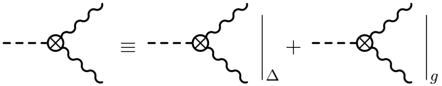
$$\langle \gamma(\,\epsilon^{\mu}, p_1), Z(\epsilon^{\nu}, p_2)|S|h(q)\rangle = \sqrt{Z_h}\sqrt{Z_\gamma}\sqrt{Z_Z}\,\left[i\mathcal{A}^{\mu\nu}(h \to Z\gamma)\right]\epsilon^*_\mu(p_1)\,\epsilon^*_\nu(p_2)$$

where the amplitude is

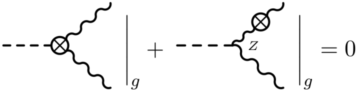
$$i\mathcal{A}^{\mu\nu}(h \to Z\gamma)\epsilon^*_\mu(p_1)\,\epsilon^*_\nu(p_2) \;=$$



- We renormalise couplings, not fields
- Renormalisation conditions
  - Cancelation of tadpoles, $\delta m_V^2 = \mathrm{Re}\, A_{VV}(M_V^2)$, etc
- Splitting the counterterms



where $\Delta^{\mu\nu}(p_1, p_2) = p_1^\nu p_2^\mu - (p_1 \cdot p_2) g^{\mu\nu}$, we find



- Interesting cancelations (even in the SM)

Deviations from the SM

$$\mathcal{R}_\chi = \frac{\Gamma(\text{BSM}, \chi)}{\Gamma(\text{SM}, \chi)} = 1 + \delta\mathcal{R}_\chi$$

$\chi = h \to \gamma\gamma,\ h \to Z\gamma$

Assuming that operators affecting $h \to \gamma\gamma$, $Z\gamma$ decays do *not* affect $\sigma(pp \to h)$ and $\Gamma_{tot}(h)$, then

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

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

LHC: $\mathcal{R}_{h\to Z\gamma} \lesssim 6.6$

$$
\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} = &-\left[48.04 - 1.07\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}(\mu)}{\Lambda^2} \\
&-\left[14.29 - 0.12\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}(\mu)}{\Lambda^2} \\
&+\left[26.17 - 0.52\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}(\mu)}{\Lambda^2} \\
&+\left[2.11 - 0.84\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{uB}(\mu)}{\Lambda^2} \\
&+\left[1.13 - 0.45\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{uW}(\mu)}{\Lambda^2} \\
&+\ldots
\end{aligned}
$$

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

- Bounds on C's from $\delta\mathcal{R}_{h\to\gamma\gamma} \lesssim 15\%$ for $\mu = M_W$

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

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

$$\frac{|C^{\varphi WB}|}{\Lambda^2} \lesssim \frac{0.006}{(1\ \mathrm{TeV})^2}\,,$$

- 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)

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

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

- Weaker bounds than $h \to \gamma\gamma$
- 23 operators (17 common with $h \to \gamma\gamma$)
- New operators affect ratio $< 1\%$, but are Potentially Tree-Generated: Disentangle new physics models

Using our result for $h \to \gamma\gamma$ and $h \to Z\gamma$ at one-loop and the tree-level result for the ΔS parameter we perform a principal component analysis[5]

Theoretical inputs: $\mu = m_W$, $\Lambda = 1$TeV

$$\begin{aligned} \delta R_{h\to\gamma\gamma} &= -48.04 C^{\varphi B} - 14.29 C^{\varphi W} + 26.17 C^{\varphi WB}, \\ \delta R_{h\to Z\gamma} &= +14.99 C^{\varphi B} - 14.88 C^{\varphi W} + 9.44 C^{\varphi WB}, \\ \Delta S &= 13.35 C^{\varphi WB} \end{aligned}$$

Experiment: $O_{exp} = (1.10, 2.05, 0.02) \pm (0.10, 0.95, 0.10)$

Best fit Wilsons:

$$\begin{aligned} C^{\varphi B} &= 0.015 \pm 0.030 \\ C^{\varphi W} &= -0.055 \pm 0.100 \\ C^{\varphi WB} &= 0.001 \pm 0.015 \end{aligned}$$

[5] K.Mantzaropoulos, LT

We present

- The EFT approach to physics Beyond the SM
- Higgs decays in the SMEFT
- Renormalisation procedure for SMEFT calculations
- Analytic calculation of observables in SMEFT

Future Plans

- EW precision data
- Extend renormalisation scheme
- ...

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Thank you!