EFT insights in Physics Beyond the SM

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Based on:

A. D., K. Suxho and L. Trifyllis, JHEP **1906**, 115 (2019) [arXiv:1903.12046]

A. D., M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, [arXiv:1904.03204], to appear in CPC

Outline

Motivation

SMEFT in Warsaw basis
- Gauge Sector
- Fermion Sector

The code `SmeftFR`
- The structure

Code demonstration and validation

$h \to Z\gamma$ in SMEFT

Conclusions

Motivation

- Effective Field Theories (EFTs) are mostly useful when certain terms are forbidden in $d \leq 4$ Lagrangian.
- The only **known** problem in the Standard Model (SM) of **Electroweak** interactions is that it predicts massless neutrinos.

  Weinberg's $d = 5$ operator leads to Majorana neutrino masses

  $$\mathrm{SMEFT}: \frac{C^{\nu\nu}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_L\right)^T \mathbb{C} \left(\tilde{\varphi}^\dagger \ell_L\right)$$

  One can easily construct a model by completing the portals.
- Could be there is New Physics for whatever other reason. EFT is then useful to parametrize our ignorance.
- SM is well measured with accuracy less than
  - Gauge sector $\rightarrow 1/200$
  - Fermion sector $\rightarrow 1\%$
  - Higgs sector $\rightarrow 15\%$
- LHC physics results are nowadays presented in EFT language

Motivation

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\nu\nu} Q_{\nu\nu}}{\Lambda} + \sum_{i=1}^{59} \frac{C_i Q_i}{\Lambda^2} + O(\frac{1}{\Lambda^3})$$

SMEFT contains too many parameters and complicated vertices even if we keep $d \leq 6$ operators.

Can we automatize calculations and simulations in SMEFT?

Motivation

$$\mathcal{L}_{\rm SMEFT} \ = \ \mathcal{L}_{\rm SM} \ + \ \frac{C_{\nu\nu} Q_{\nu\nu}}{\Lambda} \ + \ \sum_{i=1}^{59} \frac{C_i Q_i}{\Lambda^2} \ + \ O(\frac{1}{\Lambda^3})$$

SMEFT contains too many parameters and complicated vertices even if we keep $d \leq 6$ operators.

Can we automatize calculations and simulations in SMEFT?

YES !

Steps towards mass basis up to $1/\Lambda^2$

Step 1: Start out in a basis with a constant field redefinition of the gauge fields

Step 2: Choose redundant parameters such that gauge field kinetic terms are canonical after Spontaneous Symmetry Breaking

$$\mathcal{L}(W^I_{\mu\nu}, W^I_\mu, ...; g, ...) \to \mathcal{L}(\bar{W}^I_{\mu\nu}, \bar{W}^I_\mu, ...; \bar{g}, ...)$$

We work with the barred parameters and fields.

Step 3: Introduce gauge fixing terms[1] such that after SSB we obtain the familiar SM form

$$\mathcal{L}_{GF} \; = \; -\frac{1}{2}\,\mathbf{F}^T\hat{\xi}^{-1}\mathbf{F}, \quad \hat{\xi} = f(\xi_A, \xi_Z, \xi_W, \xi_G)$$

Step 4: Add FP-terms to restore generalized (BRST) gauge invariance.

Step 5: Diagonalize mass terms to obtain fields and parameters in mass basis

[1] A. D., W. Materkowska, M. Paraskevas, J. Rosiek and K. Suxho, JHEP **1706**, 143 (2017), arXiv:1704.03888

Fields from Warsaw to mass basis

In total the transformations from the Warsaw basis[2] to the mass basis are :

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + Z_h^{-1} h + i Z_{G^0}^{-1} G^0) \end{pmatrix} ,$$

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix} = \hat{Z}_{AZ}^{-1} \begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} ,$$

$$W_\mu^1 = \frac{1}{\sqrt{2}} (W_\mu^+ + W_\mu^-) ,$$

$$W_\mu^2 = \frac{i}{\sqrt{2}} (W_\mu^+ - W_\mu^-) ,$$

$$G_\mu^A = Z_G^{-1} g_\mu^A .$$

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

Fermion sector

The basis in the fermion sector is not fixed by the structure of gauge interactions allowing for unitary rotations in the flavour space:

$$\psi'_X = U_{\psi_X}\,\psi_X\ , \qquad \psi = \nu, e, u, d\ , \qquad X = L, R\ .$$

ψ_X correspond to real and non-negative eigenvalues of the 3×3 fermion mass matrices:

$$M'_\nu = -v^2 C'^{\nu\nu}\ , \qquad M'_e = \frac{v}{\sqrt{2}}\left(\Gamma_e - \frac{v^2}{2} C'^{e\varphi}\right),$$
$$M'_u = \frac{v}{\sqrt{2}}\left(\Gamma_u - \frac{v^2}{2} C'^{u\varphi}\right), \quad M'_d = \frac{v}{\sqrt{2}}\left(\Gamma_d - \frac{v^2}{2} C'^{d\varphi}\right).$$

The fermion flavour rotations can be adsorbed in redefinitions of Wilson coefficients, leaving CKM ($K = U^\dagger_{u_L}\,U_{d_L}$) and PMNS ($U = U^\dagger_{e_L}\,U_{\nu_L}$) matrices multiplying them.

$$C'^{\nu\nu} \to C^{\nu\nu}\ , \quad C'^{e\varphi} \to C^{e\varphi}\ , \quad \ldots$$

Introducing `SmeftFR`

- In SMEFT with all $d \leq 6$ operators and no expansion in flavour indices, there are about 120 vertices in unitary gauge or 380 vertices in R_ξ-gauges.
- `SmeftFR` is a code designed to generate the **general** set of Feynman Rules in SMEFT with $d \leq 6$ gauge invariant operators.
- It is based on `Mathematica/FeynRules` language[3]
- Output is given in various formats for further considerations

[3] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr and B. Fuks, Comput. Phys. Commun. **185**, 2250 (2014), arXiv:1310.1921

The structure

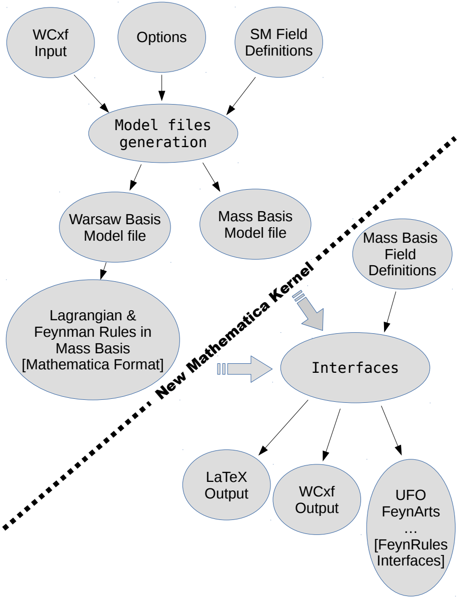
1. SM Lagrangian + extra operators in Warsaw basis encoded using `FeynRules` syntax
   - `FeynRules` "model files" generated dynamically for user-chosen subset of operators
   - general flavor structure of all Wilson coefficients assumed
   - numerical values of Wilson coefficients (including flavor- and CP-violating ones) are imported from standard files in `WCxf` ("Wilson coefficient exchange format") – could be interfaced to other SMEFT public packages, `Flavio`, `FlavorKit`, `Spheno`, `DSixTools`, `wilson`, `FormFlavor`, `SMEFTSim`, ...
   - gauge choice user-defined option (unitary or R_ξ-gauges)
   - neutrino masses incorporated in mass basis
2. Derivation of the SMEFT Lagrangian in mass-eigenstate basis, expanded consistently up-to-order $1/\Lambda^2$

The structure

3. Evaluation of Feynman rules in mass basis, available formats:
   - `Mathematica/FeynRules`
   - `Latex/Axodraw` (dedicated generator)
   - `UFO` format $\to$ "event generators"
   - `FeynArts`[4] $\to$ "symbolic calculators"
4. various options available
   - neutrino fields treated as massless Weyl or massive Majorana (in the presence of $= 5$ Weinberg operator) spinors
   - correction of `FeynRules` 4-fermion sign issues
   - corrected B-, L- violating 4-fermion vertices and 4-ν vertex
   - ...

[4] T. Hahn, Comput. Phys. Commun. **140**, 418 (2001), hep-ph/0012260

SmeftFR code structure



SmeftFR Reference

New version available since April 2019:

Code :	`SmeftFR v2.0`
URL:	http://www.fuw.edu.pl/smeft
Physics :	`ArXiv:1704.03888`, JHEP 06 (2017) 143.
Manual:	`ArXiv:1904.03204`, submitted to CPC journal
Authors:	A.D, M. Paraskevas, **J. Rosiek**, K. Suxho, L. Trifyllis

SmeftFR Demonstration

Provide a list of operators e.g., all those connected to an observable. For example

```
OpList= {"W", "phiD", "phiWB", "phil1", "vv", "ledq"}
```

SmeftFR Demonstration

Initialize Lagrangian, define gauge fixing:

```
SMEFTInitializeModel[Operators -> OpList, Gauge ->
Unitary, MajoranaNeutrino -> True, WCXFInitFile ->
WCXFInput];
```

Calculate FRs in mass basis:

```
SMEFTLoadModel[ ]
```

```
SMEFTFindMassBasis[ ]
```

```
SMEFTFeynmanRules[ ]
```

Now the SMEFT Lagrangian and interaction vertices have been created (in Mathematica form). FeynRules model files have been created.

SmeftFR Demonstration

Create the Lagrangian in Mass Basis:

`SMEFTInitializeMB[ ];`

The result is stored in `SMEFTMBLagrangian` variable.

SmeftFR Demonstration

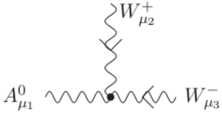
Interface to other programs:

```
SMEFTToLatex[ ];

WriteUFO[ SMEFTMBLagrangian, "Options" ];

WriteFeynArtsOutput[ SMEFTMBLagrangian, "Options"];
```

SmeftFR Demonstration

Example: $W^+W^-\gamma$ anomalous Triple Gauge Couplings (aTGC)

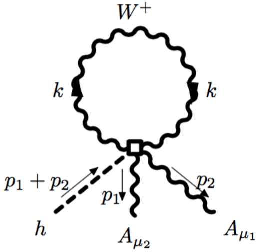
5-2 = 3 CPC parameters, 2 CPV parameters



$$
\begin{aligned}
&+\frac{i\bar{g}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}\left(\eta_{\mu_1\mu_2}(p_1-p_2)^{\mu_3}+\eta_{\mu_2\mu_3}(p_2-p_3)^{\mu_1}+\eta_{\mu_3\mu_1}(p_3-p_1)^{\mu_2}\right)\\
&-\frac{6i\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{W}\left(p_3^{\mu_1}p_1^{\mu_2}p_2^{\mu_3}-p_2^{\mu_1}p_3^{\mu_2}p_1^{\mu_3}+\eta_{\mu_1\mu_2}\left(p_1^{\mu_3}p_2\cdot p_3-p_2^{\mu_3}p_1\cdot p_3\right)\right.\\
&\left.+\eta_{\mu_2\mu_3}\left(p_2^{\mu_1}p_1\cdot p_3-p_3^{\mu_1}p_1\cdot p_2\right)+\eta_{\mu_3\mu_1}\left(p_3^{\mu_2}p_1\cdot p_2-p_1^{\mu_2}p_2\cdot p_3\right)\right)\\
&+\frac{i\bar{g}^2v^2}{\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}C^{\varphi WB}\Big(\eta_{\mu_1\mu_2}(\bar{g}^2p_1^{\mu_3}+\bar{g}'^2p_2^{\mu_3})+\eta_{\mu_2\mu_3}(\bar{g}'^2p_3^{\mu_1}-\bar{g}'^2p_2^{\mu_1})\\
&+\eta_{\mu_3\mu_1}(-\bar{g}'^2p_3^{\mu_2}-\bar{g}^2p_1^{\mu_2})\Big)\\
&-\frac{2i\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{\widetilde{W}}\Big(\epsilon_{\mu_1\mu_2\mu_3\alpha_1}\left(p_1^{\alpha_1}p_2\cdot p_3+p_2^{\alpha_1}p_1\cdot p_3+p_3^{\alpha_1}p_1\cdot p_2\right)\\
&+\epsilon_{\mu_1\mu_2\alpha_1\beta_1}(p_1-p_2)^{\mu_3}p_1^{\alpha_1}p_2^{\beta_1}+\epsilon_{\mu_2\mu_3\alpha_1\beta_1}(p_2-p_3)^{\mu_1}p_2^{\alpha_1}p_3^{\beta_1}\\
&+\epsilon_{\mu_3\mu_1\alpha_1\beta_1}(p_3-p_1)^{\mu_2}p_3^{\alpha_1}p_1^{\beta_1}\Big)\\
&+\frac{i\bar{g}^2v^2}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{\varphi\widetilde{W}B}\epsilon_{\mu_1\mu_2\mu_3\alpha_1}p_1^{\alpha_1}
\end{aligned}
$$

NLO validation

Highly non-trivial checks involve the ξ-independence of a physical process e.g., $h \to \gamma\gamma$, $h \to Z\gamma$. Seems so far there is no problem.



Only in SMEFT

1-loop calculations in SMEFT with $d \leq 6$

- Complete corrections in $h \to \gamma\gamma$

  C. Hartmann and M. Trott, Phys. Rev. Lett. **115**, no. 19, 191801 (2015) [arXiv:1507.03568 [hep-ph]].

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

  S. Dawson and P. P. Giardino, Phys. Rev. D **98**, no. 9, 095005 (2018) [arXiv:1807.11504 [hep-ph]].

- Complete corrections in $h \to Z\gamma$

  S. Dawson and P. P. Giardino, Phys. Rev. D **97**, no. 9, 093003 (2018) [arXiv:1801.01136 [hep-ph]].

  A. D., K. Suxho and L. Trifyllis, JHEP **1906**, 115 (2019) [arXiv:1903.12046 [hep-ph]].

Operators participating in $h \to \gamma\gamma$

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

CP-violating operators **do not** contribute at $1/\Lambda^2$ and at 1-loop.

Operators participating in $h \to \gamma\gamma$

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

There are **17 operators** (not including flavour and H.c.)

Operators participating in $h \to \gamma\gamma$

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

There are **6** extra operators affecting $h \to Z\gamma$ (category $\psi^2\varphi^2 D$)

Results for $\mathcal{R}_{h\to\gamma\gamma}$

- Input parameter scheme: $\{m_W, m_Z, G_F, m_h, m_t, m_q, m_\ell\}$
- Renormalization scheme: on-shell for masses + $\overline{MS}$ for Wilsons

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

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

Results for $\mathcal{R}_{h\to\gamma\gamma}$

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

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

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

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

- 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)

Calculation of $h \to Z\gamma$ in SMEFT

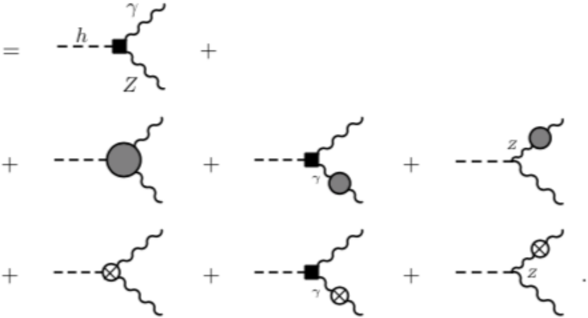
- There are **23 operators** involved out of which 17 are common with $h \to \gamma\gamma$.
- There is no overlap with operators affecting $gg \to h$, and $\Gamma_{tot}(h)$, therefore LHC sets only a bound:

$$\mathcal{R}_{h\to Z\gamma} = \frac{\Gamma(\mathrm{SMEFT}, h \to Z\gamma)}{\Gamma(\mathrm{SM}\, h \to Z\gamma)} \lesssim 6.6$$

- We calculated the decay $h \to Z\gamma$ at 1-loop in SMEFT with all $d \leq 6$ operators
- A finite, ξ-independent and renormalization scale invariant ratio $\mathcal{R}_{h\to Z\gamma}$ is found.
- The **6 new operators** do not affect $\mathcal{R}_{h\to Z\gamma}$ by more than 1%

Calculation of $h \to Z\gamma$ in SMEFT

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



Results for $\mathcal{R}_{h\to Z\gamma}$

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

Bounds from $h \to Z\gamma$ searches are weak: they are supreseded by those from $h \to \gamma\gamma$ searches.

Comparison of $\mathcal{R}_{h\to\gamma\gamma}$ with $\mathcal{R}_{h\to Z\gamma}$

- Prefactors of $C^{\varphi B}$, $C^{\varphi WB}$ are **suppressed by a factor of 3** in case of $h \to Z\gamma$ while $C^{\varphi W}$ is affected equally in both.
- No other Wilson coefficients have $\mathcal{O}(1)$ prefactors
- By considering previous bounds from $h \to \gamma\gamma$ of the order of $C \sim 10^{-2}$ make New Physics effects very small in $h \to Z\gamma$.

In summary: bounds set from $h \to \gamma\gamma$ do not allow for much New Physics room in $h \to Z\gamma$ (if assuming one coupling at a time)

Barring cancellations among coefficients, even at High Luminosity LHC with 3000 fb^{-1} where $\delta\mathcal{R}_{h\to Z\gamma} \approx 0.24$ the decay $h \to Z\gamma$ seems impossible to show deviations from the SM.

Conclusions

- The proliferation of primitive vertices in SMEFT demands computer assistance
- `SmeftFR` is a code for generating Feynman Rules in SMEFT in Warsaw basis so far limited to $d \leq 6$ operators
- `SmeftFR` calculates the FRs in Unitary or R_ξ-gauges
- Output is provided in `Latex`, `UFO` and `FeynArts` outputs
- `SmeftFR` is available at

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

- By exploiting EFT one can derive useful insights about future processes' sensitivity: a good example is $h \to \gamma\gamma$ and $h \to Z\gamma$.