$h \to \gamma\gamma$ decay in the Standard Model Effective Field Theory at NLO.

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Outline

Introduction

Systematic approach to loop SMEFT calculations

- SMEFT construction and physical field basis
- SMEFT quantization in R_ξ gauges
- SMEFT Feynman Rules Mathematica package

$h \to \gamma\gamma$ decay in SMEFT

Conclusions

Based on:
Dedes, Materkowska, Paraskevas, JR, Suxho, JHEP 1706 (2017) 143
Dedes, Paraskevas, JR, Suxho, Trifyllis, JHEP 1808 (2018) 103

EFT approach based on Appelquist-Carazzone decoupling theorem:

Assumption: renormalizable gauge QFT is embedded into a larger renormalizable theory, with new particle mass scale M

Conclusion: effects of larger theory at scale $E \ll M$ suppressed by powers of E/M.

Well-known and successful since Fermi theory:

- theoretical: instead of studying a plethora of New Physics models, describe new effects in terms of the EFT.
- experimental: detect quantum effects of virtual new particles at current scales but precision at least E_{SM}^2/M^2

Disadvantage(s):

- no direct connection to underlying symmetry principles
- technically complicated (many parameters, non-renormalizable).

Buchmuller, Wyler 1986; Grządkowski, Iskrzyński, Misiak, JR 2010: derivation of irreducible basis of gauge invariant operators of dimension 5 and 6 constructed from the SM fields ("Warsaw basis")

$$L_{SMEFT} = L_{SM}^{(4)} + \frac{1}{\Lambda} C_{\nu\nu}^{(5)} O_{\nu\nu}^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \dots$$

- 1 dimension-5 operator (L-violating, Weinberg 1979):
- 59 (63 if lepton and/or baryon number not conserved) independent dimension-6 operators.

Fermionic operators and their Wilson coefficients carry flavor indices $\rightarrow$ many couplings are 3×3 or $3 \times 3 \times 3 \times 3$ matrices in flavor space.

Including symmetry properties under flavor permutations - 2499 free parameters in dim-6 SMEFT.

Hundreds of SMEFT analyses published – often difficult to combine due to difference in basis/conventions/input parameter choices.

Systematic calculational setup, particularly at loop level

First: operator basis choice. I choose "Warsaw basis" as complete and most universally used (beside Higgs and gauge also in flavor physics).

It is an "electroweak basis" – set of **gauge invariant operators** before the **Spontaneous Symmetry Breaking**, given in terms of unphysical fields.

Second: field basis choice: – **physical field basis** (mass eigenstates after the SSB) best for direct comparison with experiments.

Up to technical complications, extension of the normal SM treatment:

- perform the SSB and Higgs mechanism
- find physical fields and effective couplings
- quantize the theory - gauge fixing choice
- derive the Feynman rules
- calculate amplitudes

Transition to physical basis modify interaction vertices. Example – after SSB new contributions to bilinear terms in gauge and Higgs sector:

$$\begin{aligned}\mathcal{L}_{\mathrm{EW}} \quad &\supset \quad C^{\varphi}(\varphi^\dagger\varphi)^3 \;+\; C^{\varphi\Box}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) \;+\; C^{\varphi D}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)\\ &+ \quad C^{\varphi W}(\varphi^\dagger\varphi)W^I_{\mu\nu}W^{I\mu\nu} + C^{\varphi B}(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu} + C^{\varphi WB}(\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu}\\ &+ \quad C^{\varphi G}(\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\mu\nu}\end{aligned}$$

Restoring canonical form of bilinear terms $\to$ corrections to vev, field normalisation, field masses and SM couplings:

$$\begin{aligned}\bar{v} &= \sqrt{\frac{2m^2}{\lambda} + \frac{3m^3}{\sqrt{2}\lambda^{5/2}}C^{\varphi}}\\ \bar{g} &= (1 + C^{\varphi W}v^2)g\\ \bar{g}' &= (1 + C^{\varphi B}v^2)g'\\ \bar{M}_Z &= \frac{1}{2}\sqrt{\bar{g}^2 + \bar{g}'^2}\,v\left(1 + \frac{\bar{g}\bar{g}'v^2C^{\varphi WB}}{\bar{g}^2 + \bar{g}'^2} + \frac{1}{4}C^{\varphi D}v^2\right)\\ &\dots\end{aligned}$$

Also: changes in field normalisation and mixing.

"Bar" quantities must be identified (in the lowest order) with physical masses and couplings.

After rescaling bilinear structure and propagators are SM-like, but shifts in couplings and field normalisation generate new interactions:

$$\begin{aligned} L_{SM}^{(4)}(g, g', M_Z, \ldots, W, B, \Phi, \ldots) &\rightarrow L_{SM}^{(4)}(\bar{g}, \bar{g}', \bar{M}_Z, \ldots, Z, F, h, \ldots) \\ &+ \quad \mathrm{dim} - 6 \text{ terms} \end{aligned}$$

Shifts in the SM Lagrangian redefinitions must be added to "direct" interaction vertices from the new operators – interaction in physical field basis may look different than in Warsaw basis.

Next non-trivial step – feasible gauge fixing choice.

SMEFT quantization

Loop calculations - consistent and convenient gauge fixing required. Gauge fixing conditions should:

- Cancel the unwanted Goldstone-gauge boson bilinear mixing.
- Lead to SM-like propagators in terms of the effective mass basis parameters and fields.
- Preserve the BRST invariance of the full Lagrangian.

Important observation: SMEFT gauge-Goldstone mixing ("unwanted terms") in terms of physical/canonical fields and physical masses:

$$\mathcal{L}_{G-EW} = i\bar{M}_W (W_\mu^+ \partial^\mu G^- - W_\mu^- \partial^\mu G^+) - \bar{M}_Z\, Z_\mu\, \partial^\mu G^0$$

Identical as in the SM. Allows to use R_ξ-gauge fixing also for SMEFT!

Non-trivial - until 2017 SMEFT loop calculations done in technically complicated gauges (BFM etc.)

EW gauge fixing terms choice:

$$\mathcal{L}_{GF} = -\frac{1}{2}\boldsymbol{F}^\top \hat{\boldsymbol{\xi}}^{-1} \boldsymbol{F}$$

with

$$\boldsymbol{F} = \begin{pmatrix} F^1 \\ F^2 \\ F^3 \\ F^0 \end{pmatrix} = \begin{pmatrix} \left(1 - C^{\phi W}\right) \partial_\mu W^{1\mu} \\ \left(1 - C^{\phi W}\right) \partial_\mu W^{2\mu} \\ \left(1 - C^{\phi W}\right) \partial_\mu W^{3\mu} \\ \left(1 - C^{\phi B}\right) \partial_\mu B^{\mu} \end{pmatrix} - \frac{v\hat{\boldsymbol{\xi}}}{2} \begin{pmatrix} -i\bar{g}\,\frac{G^+ - G^-}{\sqrt{2}} \\ \bar{g}\,\frac{G^+ + G^-}{\sqrt{2}} \\ -\bar{g}\left(1 + \frac{1}{4}C^{\varphi D} v^2\right) G^0 \\ \bar{g}'\left(1 + \frac{1}{4}C^{\varphi D} v^2\right) G^0 \end{pmatrix}$$

4×4 symmetric matrix $\hat{\xi}$ is

$$\hat{\boldsymbol{\xi}} = \begin{pmatrix} \xi_W & & & 0 \\ & \xi_W & & \\ 0 & & \multicolumn{2}{c}{\mathbb{X}\begin{pmatrix} \xi_Z & \\ & \xi_A \end{pmatrix}\mathbb{X}^\top} \end{pmatrix}$$

where $\mathbb{X}$ is the 2×2 mixing matrix of the neutral electroweak gauge bosons (Weinberg angle rotation plus NP corrections).

Gauge fixing expressed in physical basis:

$$\begin{aligned}\mathcal{L}_{GF} = & - \frac{1}{\xi_W}(\partial^\mu W^+_\mu + i\xi_W M_W G^+)(\partial^\nu W^-_\nu - i\xi_W M_W G^-) \\ & - \frac{1}{2\xi_Z}(\partial^\mu Z_\mu + \xi_Z M_Z G^0)^2 - \frac{1}{2\xi_A}(\partial^\mu A_\mu)^2\end{aligned}$$

Identical to the SM with the standard linear R_ξ gauges fixing!

Ghost terms necessary to restore BRST invariance:

$$\mathcal{L}_{FP} = \bar{\boldsymbol{N}}^\top \begin{pmatrix} \mathbb{1}_{2\times 2} & 0_{2\times 2} \\ 0_{2\times 2} & (\mathbb{X}^\top)^{-1}\mathbb{X}^{-1} \end{pmatrix} (\hat{\boldsymbol{M}}_F N)$$

where ghosts $N^i = (N^1, N^2, N^3, N^0)$ and antighosts $\bar{N}^i = (\bar{N}^1, \bar{N}^2, \bar{N}^3, \bar{N}^0)$

Matrix $\hat{M}_F$ - obtained by applying the BRST-operator, $\boldsymbol{s}$ on gauge-fixing functionals F^i:

$$\hat{M}_F^{ij} N^j = \boldsymbol{s} F^i$$

with BRST operator action:

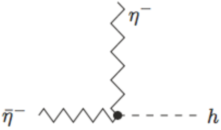
$$\begin{array}{rcl} \boldsymbol{s}\varphi & = & -i\bar{g}' Y \varphi \; N^0 - i\bar{g} T^I \varphi \; N^I \;, \\ \boldsymbol{s}\varphi^\dagger & = & +i\bar{g}' \varphi^\dagger \; Y N^0 + i\bar{g} \varphi^\dagger T^I \; N^I \;, \\ \boldsymbol{s}\bar{B}_\mu & = & \partial_\mu N^0 \;, \\ \boldsymbol{s}\bar{W}^I_\mu & = & \partial_\mu N^I - \bar{g} \epsilon^{IJK} \bar{W}^J_\mu N^K \;. \end{array}$$

Result: canonical bilinear ghost terms with squared masses

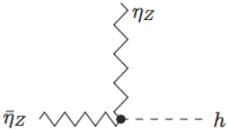
$$M^2_{\eta^A} = 0, \quad M^2_{\eta^W} = \xi_W M^2_W, \quad M^2_{\eta^Z} = \xi_Z M^2_Z.$$

Ghost propagators identical as in SM $\rightarrow$ all corrections from dimension-6 operators appear in ghost vertices.

Examples:



$$+\frac{1}{4}i\bar{g}^2 v\xi_W + \frac{1}{4}i\bar{g}^2 v^3 \xi_W C^{\varphi\Box} - \frac{1}{16}i\bar{g}^2 v^3 \xi_W C^{\varphi D}$$



$$+\frac{1}{4}iv\xi_Z\left(\bar{g}^2+\bar{g}'^2\right)+\frac{1}{4}iv^3\xi_Z\left(\bar{g}^2+\bar{g}'^2\right)C^{\varphi\Box} + \frac{1}{16}iv^3\xi_Z\left(\bar{g}^2+\bar{g}'^2\right)C^{\varphi D}+\frac{1}{2}i\bar{g}\bar{g}'v^3\xi_Z C^{\varphi WB}$$

Everything ready for amplitude calculations? Not so simple:

Tree level: $\sim$ 100 complicated vertices in unitary gauge.

Loop: $\sim$ 400 vertices in R_ξ gauges, up to 6-tuple field interactions appear.

Full ready-to-use list of Feynman rules in mass basis listed in 2017 JHEP paper.

Calculations needs to be automatised, starting from Feynman rules generation in physical basis.

SMEFT Feynman Rules package

Mathematica/FeynRules v2.3 SMEFT package (not just “model file”):

- starting point: SM Lagrangian + extra operators in Warsaw basis encoded using FeynRules syntax
  - FeynRules “model files” generated dynamically for user-chosen subset of SMEFT operators (suitable for given process, saves calculation time and avoids overly complicated expressions.)
  - numerical values of Wilson coefficients (including flavor and CP-violating ones) imported from WCxf standard (“Wilson coefficient exchange format”) files (could be easily interfaced to other SMEFT public packages, currently *Flavio, FlavorKit, Spheno, DSixTools, wilson, FormFlavor, SMEFTSim*)
- analytical evaluation of bilinears and canonically normalised physical fields
- derivation of SMEFT Lagrangian in mass-eigenstates basis, expanded consistently to order $1/\Lambda^2$

- evaluation of Feynman rules in mass basis, available formats:
  - *Mathematica/FeynRules*
  - *Latex* (dedicated Latex generator, not the *FeynRules* internal routine)
  - *UFO* (Universal File) format, can be imported by Monte Carlo generators, *FeynArts*, ...
- extra options
  - gauge choice (unitary or R_ξ)
  - neutrinos treated as massless Weyl or massive Majorana spinors
  - correction of FeynRules 4-fermion sign problems
  - ... (still in development)

Downloadable at `www.fuw.edu.pl/smeft`

Application: $h \to \gamma\gamma$ decay in SMEFT at 1-loop

SM prediction: finite and precise, small theoretical uncertainties. Radiative process - sensitive to contributions from new operators.

Experiments report results relative to SM prediction:

$$\mathcal{R}_{h\to\gamma\gamma} \equiv 1 + \delta\mathcal{R}_{h\to\gamma\gamma} = \frac{\Gamma(\mathrm{EXP}, h \to \gamma\gamma)}{\Gamma(\mathrm{SM}, h \to \gamma\gamma)} \,.$$

Spring 2018 constraints:

$$\begin{aligned} \text{ATLAS:} \qquad \mathcal{R}_{h\to\gamma\gamma} &= 0.99^{+0.15}_{-0.14}\,, \\ \text{CMS:} \qquad \mathcal{R}_{h\to\gamma\gamma} &= 1.18^{+0.17}_{-0.14}\,, \end{aligned}$$

Prior to our work several calculations, the most complete one: Hartmann and Trott, arXiv:1507.03568, 1505.02646

Improvements in our analysis:

- exploiting linear R_ξ-gauges (previously technically complicated BFM gauge fixing).
- analytic proof of gauge invariance
- simple renormalization framework
- complete analytical and semi-numerical expressions for $\delta R_{h\to\gamma\gamma}$
- bounds on Wilson coefficients

1-loop calculation with complications:

- 17 CP conserving dim-6 operators contribute, not counting flavor and H.c. (neglected: 10 CP violating ones, strongly suppressed by CP observables like EDM etc.)
- complicated structure of interaction vertices, 3-, 4- and 5-tuple, some momentum dependent, many include scalar and tensor Dirac structures.
- non-trivial multi-parameter renormalization procedure.
- calculation performed in general R_ξ gauges with independent ξ_A, ξ_W, ξ_Z parameters - ξ cancellation provides strict cross checks.

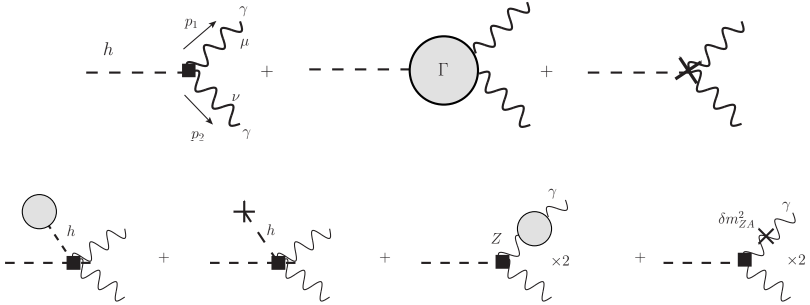
Contributing CP-conserving operators:

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

Q_φ - present in vertices but cancels out completely in the amplitude.

Q_{ll} and $Q^{(3)}_{\varphi l}$ enter indirectly through corrections to Fermi constant.

On-shell S-matrix amplitude



plus external wave function renormalization for the photon and the Higgs required by the LSZ reduction formula.

Renormalization

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

- hybrid renormalization scheme: on-shell in SM-quantities (a la Sirlin 1980) and $\overline{MS}$ in Wilson coefficients
- all infinities absorbed by SM and EFT counterterms as normal
- a closed expression for the amplitude that respects the Ward identities

The renormalized parameters are translated to well measured ones

$$\{g', g, v, \lambda, y_t\} \longrightarrow \{M_Z, M_W, G_F, M_h, m_t\}$$

Fermi constant G_F - derived from the muon lifetime (tree level):

$$\frac{G_F}{\sqrt{2}} = \frac{\bar{g}^2}{8\sqrt{2}M_W^2}\left[1 + v^2(C_{11}^{\varphi l(3)} + C_{22}^{\varphi l(3)}) - v^2 C_{1221}^{ll}\right]$$

Wilson coefficients renormalized in MS-bar scheme $\rightarrow$ renormalization scale dependent.

$$C - \delta C = \bar{C}(\mu) - \delta\bar{C}$$

Full renormalization scheme - complicated (as the model itself) but fairly standard procedure, in spite of working with non-renormalizable theory.

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

Renormalized amplitude:

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

where

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

Γ^X denote vertex diagrams, Π_X - self energy diagrams.

Analytical result for Γ^X and Π_X given in the paper. We checked explicitly that $\mathcal{A}_{h\to\gamma\gamma}$ is:

- finite
- gauge invariant (ξ independent)
- renormalisation scale invariant, in the sense $\frac{d}{d\mu}\mathcal{A}_{h\to\gamma\gamma}(\mu) = 0$ (proven using RGE for $C's$ by Alonso, Jenkins, Manohar, Trott).

Comparison with existing calculation (Hartmann & Trott 2015) - we found some errors, missing 1/4 in normalisation and Yukawa coupling factors.

New 2018 papers (Dawson, Giardino and Dawson, Ismail) agree with our result.

Semi-analytic formulae:

$$
\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} \;\simeq\;& 0.06\left(\frac{C^{\ell\ell}_{1221} - C^{\varphi\ell(3)}_{11} - C^{\varphi\ell(3)}_{22}}{\Lambda^2}\right) + 0.12\left(\frac{C^{\varphi\Box} - \frac{1}{4}C^{\varphi D}}{\Lambda^2}\right) \\
&- 0.01\left(\frac{C^{e\varphi}_{22} + 4C^{e\varphi}_{33} + 5C^{u\varphi}_{22} + 2C^{d\varphi}_{33} - 3C^{u\varphi}_{33}}{\Lambda^2}\right) \\
&- \left[48.04 - 1.07\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}}{\Lambda^2} - \left[14.29 - 0.12\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}}{\Lambda^2} \\
&+ \left[26.62 - 0.52\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}}{\Lambda^2} + \left[0.16 - 0.22\log\frac{\mu^2}{M_W^2}\right]\frac{C^{W}}{\Lambda^2} \\
&+ \left[2.11 - 0.84\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{33}}{\Lambda^2} + \left[1.13 - 0.45\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{33}}{\Lambda^2} \\
&- \left[0.03 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{22}}{\Lambda^2} - \left[0.01 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{22}}{\Lambda^2} \\
&+ \left[0.03 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C^{dB}_{33}}{\Lambda^2} - \left[0.02 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C^{dW}_{33}}{\Lambda^2} \\
&+ \left[0.02 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C^{eB}_{33}}{\Lambda^2} - \left[0.01 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C^{eW}_{33}}{\Lambda^2} + \ldots,
\end{aligned}
$$

Only 5 operators contribute significantly and can be bounded by the current LHC experimental measurement. Taking $\mu = M_W$, one has for operators contributing already at tree level:

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

Competing constraints on $C^{\varphi B}, C^{\varphi W}, C^{\varphi WB}$ from EW precision measurements - similar order of magnitude.

At loop level, contributions from C^{uB}_{ii} and C^{uW}_{ii} proportional to fermion mass in the loop - magnified for top quark by $\mathcal{O}(10)$. Constraints for $\mu = M_W$:

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

Constraints on C^{uB}_{33} and C^{uW}_{33} from the $\bar{t}tZ$ and single top production measurements at LHC: more than an order of magnitude weaker.

Conclusions

1. “Warsaw basis” derivation revived interest in SMEFT analyses. Very complicated model, requires systematic step by step development.
2. Starting point for systematic and consistent analyses of physical processes: expressing the SMEFT Lagrangian in terms of physical fields and technically workable gauge fixing.
3. *Mathematica* code calculating Feynman rules in physical basis both in symbolic and printable formats available (download at `www.fuw.edu.pl/smeft`).
4. Example of a non-trivial loop calculation: $h \to \gamma\gamma$ decay.
   - Testing field for Feynman rules, gauge invariance and renormalization procedures.
   - Compact final expression - useful input for SMEFT parameter bounds and fitting.