A log story short: running contributions to radiative Higgs decays in the SMEFT

Based on 2405.20371

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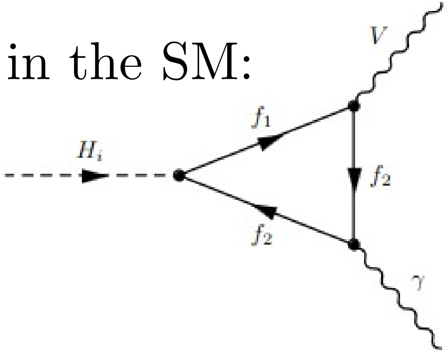
Higgs decays in the SMEFT

Loop in the SM:



$$\mathcal{L}_{\text{SMEFT}} \supset C_{h\gamma\gamma}\frac{v}{\Lambda^2} h F_{\mu\nu}F^{\mu\nu}$$

- Warsaw basis:

$$C_{h\gamma\gamma} = e^2\left(\frac{C_{\phi W}}{g_2^2} + \frac{C_{\phi B}}{g_1^2} - \frac{C_{\phi WB}}{g_1 g_2}\right)$$

- Every dim-6 operator with field-strength tensor is **necessarily generated at loop-level.**
- An operator must have at least 4 Higgses or fermions for it to be potentially tree-level generated

Higgs decays in the SMEFT

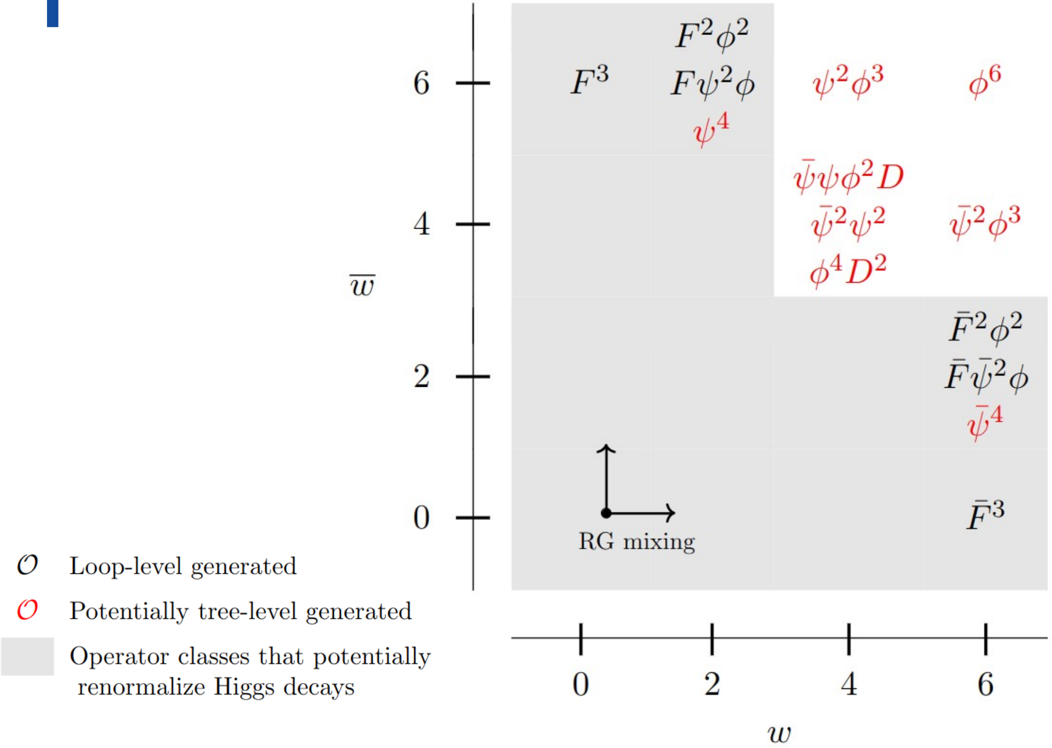
$$\mathcal{L}_{\text{SMEFT}} \supset C_{h\gamma\gamma} \frac{v}{\Lambda^2} h F_{\mu\nu} F^{\mu\nu}$$

$$C_{h\gamma\gamma}(m) = C_{h\gamma\gamma}(\Lambda) + \frac{\gamma_i C_i}{16\pi^2} \log\left(\frac{m}{\Lambda}\right)$$

- If **tree-level operator mixes into loop**, RGE is of the same order (with a log-enhancement)
- Does not happen in Higgs decays at dimension-six SMEFT

Grojean, Jenkins, Manohar and Trott, 1711.10391
Elias-Miro, Espinosa, Masso and Pomarol 1302.5661
Alonso, Jenkins, Manohar and Trott 1308.2627, 1310.4838, 1312.2014

RG mixing structure of EFTs

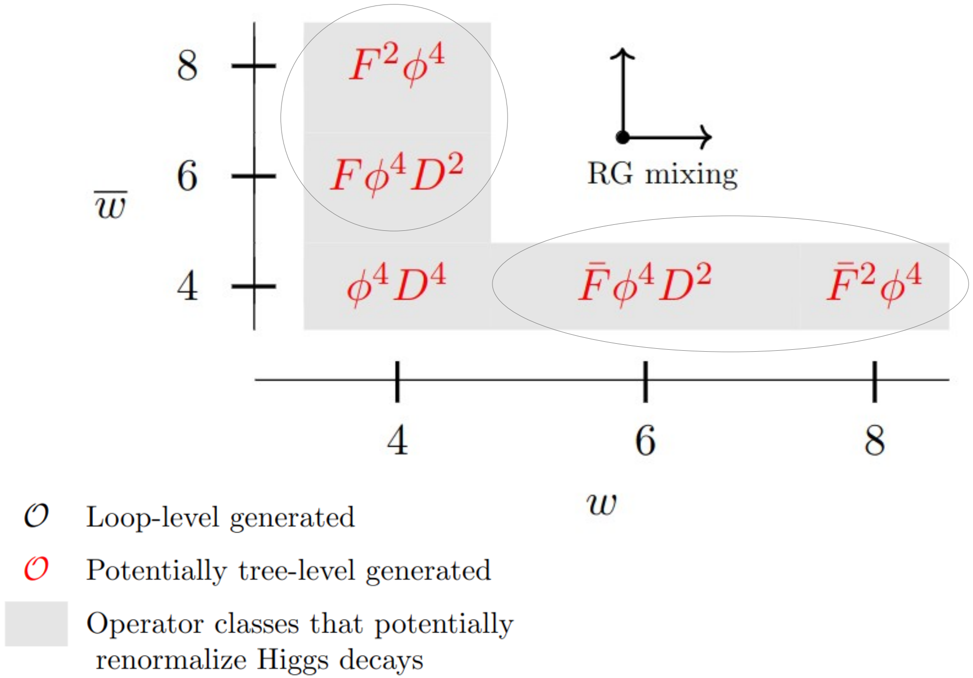


- RGE structure almost aligns with perturbative generation
- Explained by non-renormalization theorem:

$$\gamma_{ij} = 0 \quad \text{if} \quad \omega(\mathcal{O}_i) < \omega(\mathcal{O}_j)$$
$$\text{or} \quad \overline{\omega}(\mathcal{O}_i) < \overline{\omega}(\mathcal{O}_j)$$

Cheung and Shen 1505.01844

RG mixing structure of EFTs – dim eight



- Richer structure at dimension-eight
  - Theorem allows for more **trees mixing into loops**

    Craig, Jiang, Li and Sutherland, 2001.00017
    Murphy, 2005.00059

- More operators can trigger the Higgs decays but we work in vanishing Yukawas limit

Matching at tree-level

Consider all (scalar) extensions coupling to two Higgs:

		$S \sim (1,1,0)$	$\Xi \sim (1,3,0)$	$\Xi_1 \sim (1,3,1)$
$\phi^4 D^4$	$\mathcal{O}_{\phi^4}^{(1)}$		4	
	$\mathcal{O}_{\phi^4}^{(2)}$			8
	$\mathcal{O}_{\phi^4}^{(3)}$	2	-2	
$X\phi^4 D^2$	$g\mathcal{O}_{W\phi^4 D^2}^{(1)}$			
	$g'\mathcal{O}_{B\phi^4 D^2}^{(1)}$			
$X^2\phi^4$	$g^2\mathcal{O}_{\phi^4 W^2}^{(1)}$		0	
	$g^2\mathcal{O}_{\phi^4 W^2}^{(3)}$			
	$g'g\mathcal{O}_{\phi^4 WB}^{(1)}$			
	$g'^2\mathcal{O}_{\phi^4 B^2}^{(1)}$			

$$\mathscr{L}_\Xi = \frac{1}{2}D_\mu \Xi^a D^\mu \Xi^a - \frac{1}{2}M^2 \Xi^a \Xi^a - \kappa_\Xi \Xi^a \phi^\dagger \sigma^a \phi$$

- Results presented in dim 8 Green's basis

Chala, Carmona and G. G., 2112.12724

- **Scalar extensions do not generate** the operator classes responsible for the Higgs decays

Corbett, Helset, Martin and Trott 2102.02819
Chala and Santiago 2110.01624
Banerjee, Chakrabortty, Englert, Rahaman and Spannowsky 2210.14761
Ellis, Mimasu and Zampedri, 2304.06663

Matching at tree-level

Criado and Perez-Victoria, 1811.09413
Hays, Helset, Martin and Trott 2007.00565
Chala, Carmona and G. G., 2112.12724
Dawson, Forslund, Schnubel, 2404.01375

Consider all (vector) extensions coupling to two Higgs:

		$\mathcal{B}^\mu \sim (1,1,0)$	$\mathcal{B}_1^\mu \sim (1,1,1)$	$\mathcal{W}^\mu \sim (1,3,0)$	$\mathcal{W}_1^\mu \sim (1,3,1)$
$\phi^4 D^4$	$\mathcal{O}_{\phi^4}^{(1)}$	-2	2	$\frac{1}{2}$	
	$\mathcal{O}_{\phi^4}^{(2)}$	2		$\frac{1}{2}$	
	$\mathcal{O}_{\phi^4}^{(3)}$		-2	-1	
$X\phi^4 D^2$	$g\mathcal{O}_{W\phi^4 D^2}^{(1)}$	2	2	$-\frac{1}{2}(1+2k_{\mathcal{W}})$	
	$g'\mathcal{O}_{B\phi^4 D^2}^{(1)}$	-2	$-2k_{\mathcal{B}_1}$	$\frac{3}{2}$	
$X^2\phi^4$	$g^2\mathcal{O}_{\phi^4 W^2}^{(1)}$	$\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{16}(1+2k_{\mathcal{W}})$	$\frac{1}{32}(k_{\mathcal{W}_1,2}-1)$
	$g^2\mathcal{O}_{\phi^4 W^2}^{(3)}$				$\frac{1}{32}(k_{\mathcal{W}_1,2}-1)$
	$g'g\mathcal{O}_{\phi^4 WB}^{(1)}$		$\frac{1}{4}(1-k_{\mathcal{B}_1})$	$\frac{1}{8}(1-k_{\mathcal{W}})$	$\frac{1}{16}(k_{\mathcal{W}_1,1}+k_{\mathcal{W}_1,2}-2)$
	$g'^2\mathcal{O}_{\phi^4 B^2}^{(1)}$	$-\frac{1}{4}$	$-\frac{1}{4}k_{\mathcal{B}_1}$	$\frac{3}{16}$	$\frac{1}{16}(k_{\mathcal{W}_1,1}-1)$

Matching at tree-level

Consider all (vector) extensions coupling to two Higgs:

$$\mathscr{L}_{\mathcal{B}_1} \supset -i\, g'\, k_{\mathcal{B}_1}\, \mathcal{B}_1^{\dagger\mu} \mathcal{B}_1^{\nu} B_{\mu\nu}\,,$$

$$\mathscr{L}_{\mathcal{W}} \supset -\frac{1}{2}\, g\, k_{\mathcal{W}}\, \epsilon^{abc} \mathcal{W}^{\mu a} \mathcal{W}^{\nu a} W^{c}_{\mu\nu}\,,$$

$$\mathscr{L}_{\mathcal{W}_1} \supset -i\, g'\, k_{\mathcal{W}_{1},1}\, \mathcal{W}^{\dagger a}_{1\mu} \mathcal{W}^{a}_{1\nu} B^{\mu\nu} - g\, k_{\mathcal{W}_{1},2}\, \epsilon^{abc} \mathcal{W}^{\dagger a}_{1\mu} \mathcal{W}^{b}_{1\nu} W^{\mu\nu c}$$

- **Tree-level perturbative unitarity** in the UV entails $k_{\mathcal{X}} = 1$

Ferrara, Porrati and Telegdi (1992)
Henning, Lu and Murayama, 1412.1837
Feuillat, Lucio and Pestieau hep-ph/0010145
Djukanovic, Schindler, Gegelia and Scherer hep-ph/0505180
Barbieri, Isidori, Pattori and Senia 1512.01560
Biggio, Bordone, Di Luzio and Ridolfi 1607.07621

When this is imposed, generation of Higgs decays vanishes at tree-level

Renormalization group equations

Using dimension-eight RGEs

Chala, G. G., Ramos and Santiago, 2106.05291
Huber and De Angelis, 2108.03669
Das Bakshi, Chala, Carmona and G. G., 2205.03301

$$
\begin{aligned}
16\pi^2\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\left(\frac{\mathcal{A}\left[h\gamma\gamma\right]}{v^3/\Lambda^4}\right) = &-3e^2 g'^2\left(\frac{C^{(1)}_{\phi^4 W^2}}{g^2}+\frac{C^{(3)}_{\phi^4 W^2}}{g^2}-\frac{C^{(1)}_{\phi^4 WB}}{g' g}+\frac{C^{(1)}_{\phi^4 B^2}}{g'^2}\right)\\
&+e^2 g^2\left(-9\frac{C^{(1)}_{\phi^4 W^2}}{g^2}+3\frac{C^{(3)}_{\phi^4 W^2}}{g^2}+3\frac{C^{(1)}_{\phi^4 WB}}{g' g}\right.\\
&\qquad\left.-9\frac{C^{(1)}_{\phi^4 B^2}}{g'^2}+\frac{3}{2}\frac{C^{(1)}_{W\phi^4 D^2}}{g}+\frac{3}{2}\frac{C^{(1)}_{B\phi^4 D^2}}{g'}\right)\\
&+e^2\lambda\left(36\frac{C^{(1)}_{\phi^4 W^2}}{g^2}+28\frac{C^{(3)}_{\phi^4 W^2}}{g^2}-32\frac{C^{(1)}_{\phi^4 WB}}{g' g}\right.\\
&\qquad\left.+36\frac{C^{(1)}_{\phi^4 B^2}}{g'^2}-\frac{C^{(1)}_{W\phi^4 D^2}}{g}-\frac{C^{(1)}_{B\phi^4 D^2}}{g'}\right),
\end{aligned}
$$

- Triggered by operators in potentially tree-level generated classes
  - But are these **linear combinations actually generated**?

Renormalization group equations

$$16\pi^2\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\left(\frac{\mathcal{A}\left[h\gamma\gamma\right]}{v^3/\Lambda^4}\right) = e^2\begin{cases} g_{\mathcal{B}_1}^2(\lambda - \frac{3}{2}g^2)(k_{\mathcal{B}_1} - 1), & \mathcal{B}_1 \sim (1,1,1) \\ \frac{1}{2}g_{\mathcal{W}}^2(\lambda - \frac{3}{2}g^2)(k_{\mathcal{W}} - 1), & \mathcal{W} \sim (1,3,0) \\ \frac{1}{4}g_{\mathcal{W}_1}^2(\lambda - \frac{3}{2}g^2)(k_{\mathcal{W}_{1,1}} - 1), & \mathcal{W}_1 \sim (1,3,1) \end{cases}$$

No trees mixing into loops for

$h \to \gamma\gamma$ **for** $k_{\mathcal{X}} = 1$

Renormalization group equations

$$16\pi^2\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\left(\frac{\mathcal{A}\left[h\gamma Z\right]}{v^3/\Lambda^4}\right) = g'g^3\begin{cases} \frac{3}{2}\frac{\kappa_\Xi^2}{M^2}, & \Xi\sim(1,3,0),\\ -3\frac{|\kappa_{\Xi_1}|^2}{M^2}, & \Xi_1\sim(1,3,1),\\ \frac{9}{4}g_{\mathcal{B}_1}^2, & \mathcal{B}_1\sim(1,1,1),\ k_{\mathcal{B}_1}=1,\\ -\frac{9}{8}g_{\mathcal{W}}^2, & \mathcal{W}\sim(1,3,0),\ k_{\mathcal{W}}=1 \end{cases}$$

Trees mix into operators responsible for $h\to\gamma Z$ at dimension-eight

A new basis

	Scalar extensions			Vector extensions			
	S $(1,1,0)$	Ξ $(1,3,0)$	Ξ_1 $(1,3,1)$	$\mathcal{B}^\mu$ $(1,1,0)$	$\mathcal{B}_1^\mu$ $(1,1,1)$	$\mathcal{W}^\mu$ $(1,3,0)$	$\mathcal{W}_1^\mu$ $(1,3,1)$
$\mathcal{O}_{\phi^4}^{(1)}$		4		-2	2	$1/2$	
$\mathcal{O}_{\phi^4}^{(2)}$			8	2		$1/2$	
$\mathcal{O}_{\phi^4}^{(3)}$	2	-2			-2	-1	
$C_{h\gamma\gamma}$	0						
$C_{h\gamma Z}$							
C_3							
C_4							
C_5							
C_{TLO}				$\frac{1}{4}$	$\frac{1}{4}$	$-3/16$	

$$\frac{\mathcal{A}\,[h\gamma\gamma]^{(8)}}{v^3/\Lambda^4} = 2e^2 C_{h\gamma\gamma}\,,$$

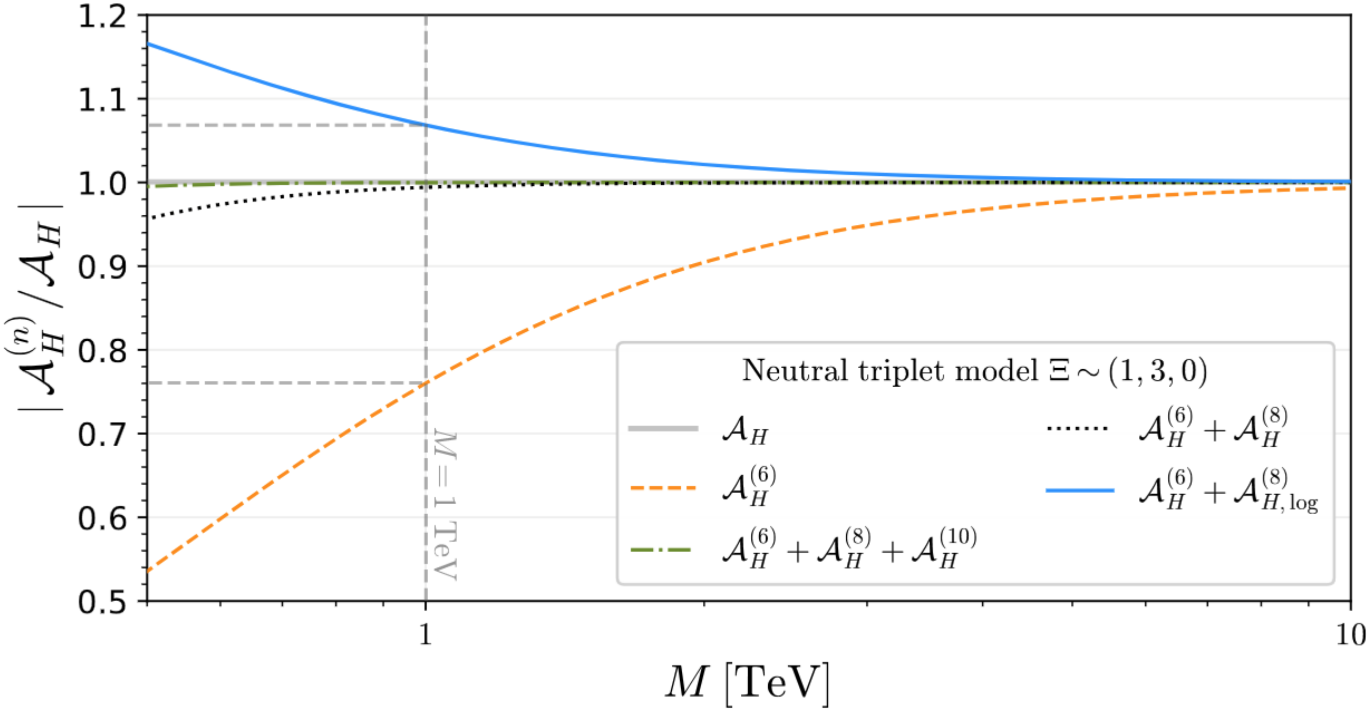
$$\frac{\mathcal{A}\,[h\gamma Z]^{(8)}}{v^3/\Lambda^4} = 2e^2\,\frac{g^2-g'^2}{g'g}\,C_{h\gamma\gamma} + 2g'g\,C_{h\gamma Z}$$

Only one direction is tree-level generated

A full model

$$\mathscr{L}_\Xi = \frac{1}{2} D_\mu \Xi^a D^\mu \Xi^a - \frac{1}{2} M^2 \Xi^a \Xi^a - \kappa_\Xi \Xi^a \phi^\dagger \sigma^a \phi$$

- Compared with full results in **Hue, Arbuzov, Hong, Nguyen, Si and Long, 1712.05234** **Degrande, Hartling and Logan, 1708.08753**



Decay width

- Pheno estimate:
  - Use numerical results from

    Dawson and Giardino, 1801.01136
    Dedes, Suxho and Trifyllis, 1903.12046
    Hays, Helset, Martin and Trott, 2007.00565

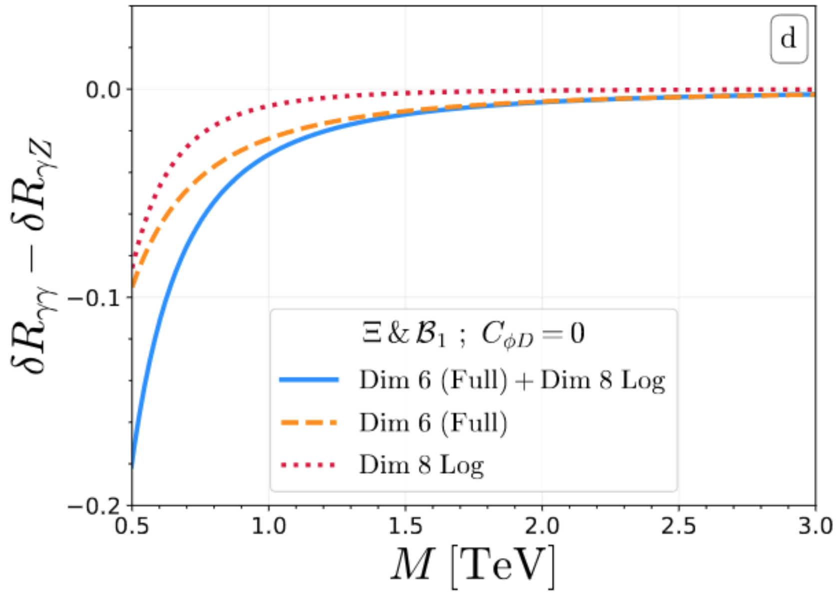
  - Include: dimension-six one-loop effects + dimension-eight RGE effects
  - Not including: one-loop dimension-eight (non-RGE) terms
- Can the logarithm of dimension-eight important?
- The decay $h \to \gamma Z$ is dominated by indirect effects at dimension-six

Influence for the decay width – custodial symmetry?

$$\frac{1+\delta\mathcal{R}_{\gamma\gamma}}{1+\delta\mathcal{R}_{\gamma Z}} = 1+\delta\mathcal{R}_{\gamma\gamma} - \delta\mathcal{R}_{\gamma Z} + O(\delta\mathcal{R}^2)$$
$$= 1 - \left(\frac{1\text{ TeV}}{\Lambda}\right)^2 \left(0.12 C_{\phi D} - 0.02 C_{u\phi,33} + 0.049\bar{C}_{\phi B} - 0.002\bar{C}_{\phi W} - 0.024\bar{C}_{\phi WB}\right)$$
$$+ 0.0007\left(\frac{1\text{ TeV}}{\Lambda}\right)^4 \left(6C_{\text{TLO}} + \frac{3}{8}C^{(1)}_{\phi^4} - \frac{3}{8}C^{(2)}_{\phi^4}\right)\log\left(\frac{m_h}{\Lambda}\right) + O(\delta\mathcal{R}^2)\,, \tag{5.7}$$

- Most indirect contributions cancelled. However the leading numerical term comes from custodial-symmetry breaking
  - In scalar scenarios **logarithm and custodial-symmetry are correlated**! Need vectors to break correlation

Influence at the observable level – custodial symmetry?



- Adding a heavy vector allows for the cancellation of tree-level $C_{\phi D}$, while mantaining a non-zero dimension-eight RGE.

- Matching with results from dictionaries

  de Blas, Criado, Perez-Victoria and Santiago, 1711.10391
  G. G., Olgoso and Santiago, 2303.16965

- Dimension-eight RGE corresponds to **25% of the full result**

Conclusions

- RGE mixing structure is richer at dimension-eight
- No trees mixing into loops for $h \to \gamma\gamma$ or $h \to gg$
- Trees renormalizing $h \to \gamma Z$ arises at dimension-eight whereas it was absent at dimension-six – new qualitative behaviour at higher-order
- Relevance to observations dependent on the model
- We find custodial preserving scenarios in which dimension-eight effect might be important

Thanks

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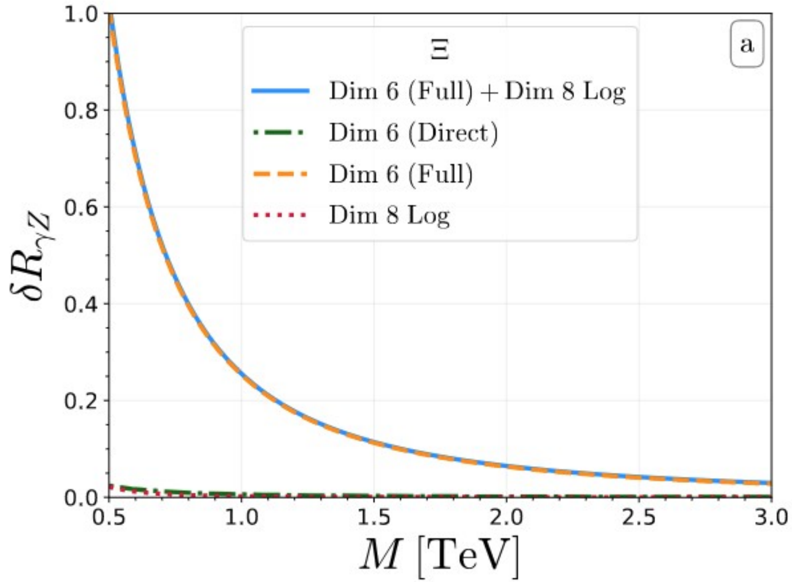
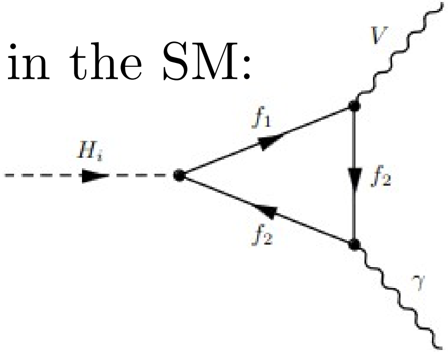
Influence for the decay width



- Indirect contributions at dimension-six completely dominate
- One could imagine more complicated models or ...

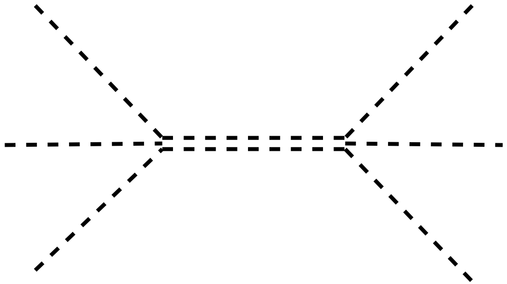
Higgs decays in the SMEFT

Loop in the SM:



$$\mathcal{L}_{\text{SMEFT}} \supset C_{h\gamma\gamma}\frac{v}{\Lambda^2}hF_{\mu\nu}F^{\mu\nu}$$

- For basis of operators with non-vanishing leading terms (non-zero amplitudes for the lowest field content):



+ Considering that UV respects SM gauge symmetries – gauge bosons couple diagonally:

- An operator must have at least 4 Higgses or fermions for it to be potentially tree-level generated