# The impact of dimension-8 operators on the 2HDM

Duarte Fontes Brookhaven National Laboratory

based on arXiv: 2205.01561,

in collaboration with Sally Dawson, Samuel Homiller and Matthew Sullivan

June 15, 2022

- Although the Standard Model (SM) is extremely powerful, there is physics beyond it (BSM)
- The SM Effective Field Theory – **SMEFT** – is a very convenient description of heavy BSM physics:
  - It configures a consistent and general description of deviations from the SM

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Sigma_{n,i} \frac{C_i^n O_i^n}{\Lambda^{n-4}}$$

  - Conversion between experimental data and theory has to be done only once
- Ultimate goal of the SMEFT framework:
  - Find a pattern of non-zero deviations in the SMEFT coefficients $C_i^n$
  - Associate that pattern with a particular BSM model
- How *good* is such association?
  - This can be investigated by looking at particular BSM models
  - Usually, one truncates the SMEFT expansion with dimension-6 operators
  - But is that *good enough*?

[Perez, Toscano, Wudka, 9506457]
[Englert et al, 1403.7191]
[Brehmer et al, 1510.03443]
[Gorbahn, No, Sanz, 1502.07352]
[Bélusca-Maïto et al, 1611.01112]
[Dawson, Murphy, 1704.07851]
[Dawson, Homiller, Lane, 2007.01296]

- There are some scenarios in which dimension-6 operators are expected to be insufficient

  [Contino et al, 1604.06444]

- Considering dimension-6 squared (without **dimension-8**) effects is formally inconsistent
  - For an amplitude $\mathcal{A} \propto a_0\, g_{\rm SM} + a_1 \frac{C^{(6)}}{\Lambda^2} + a_2 \frac{C^{(8)}}{\Lambda^4} + \ldots$ , we have:

$$|\mathcal{A}|^2 \propto |a_0\, g_{\rm SM}|^2 + \frac{2}{\Lambda^2} {\rm Re}[a_0\, a_1\, g_{\rm SM}\, C^{(6)}] + \frac{1}{\Lambda^4} \Big\{ |a_1\, C^{(6)}|^2 + 2\, {\rm Re}[a_0\, a_2\, g_{\rm SM}\, C^{(8)}] \Big\} + \ldots$$

- Effects of **dimension-8** operators have been considered in very few cases...

  [Hays et al, 1808.00442] [Corbett, 2102.02819] [Dawson, Homiller, Sullivan, 2110.06929]

  ... and the results turn out to be very model dependent

- **Those effects** are expected to be interesting in the 2 Higgs Doublet Model (2HDM):
  - Dimension-6 operators cannot capture the Higgs-gauge interactions of the 2HDM

    [Bélusca-Maïto et al, 1611.01112]
  - It provides a sufficiently rich description, without being too cumbersome
  - I shall investigate LHC Higgs signals at leading order (LO)

- 2HDM in a nutshell:
  - take the SM, with its scalar doublet $(\Phi_1)$, and add an extra one $(\Phi_2)$
  - impose a $Z_2$ symmetry, according to which $\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$
  - both $\Phi_1$ and $\Phi_2$ have vevs: $\frac{v_1}{\sqrt{2}}$ and $\frac{v_2}{\sqrt{2}}$ ; then, define $\beta$ such that $\tan\beta = v_2/v_1$
  - rotate to the Higgs basis:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

  - in that basis, where only $H_1$ has vev,

$$\mathcal{L}_{\text{2HDM}} \ni \mathcal{L}_{\text{kin}} + \mathcal{L}_Y - V,$$

$$\mathcal{L}_{\text{kin}} = (D_\mu H_1)^\dagger (D^\mu H_1) + (D_\mu H_2)^\dagger (D^\mu H_2)$$

$$\begin{aligned} V = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left(Y_3 H_1^\dagger H_2 + \text{h.c.}\right) + \frac{Z_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{Z_2}{2}\left(H_2^\dagger H_2\right)^2 \\ & + Z_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + Z_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left\{ \frac{Z_5}{2}\left(H_1^\dagger H_2\right)^2 + Z_6 \left(H_1^\dagger H_1\right)\left(H_1^\dagger H_2\right) \right. \\ & \left. + Z_7 \left(H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \text{h.c.} \right\}, \end{aligned}$$

$$\mathcal{L}_Y = -\lambda_u^{(1)*} H_1^\dagger \widehat{q}_L u_R - \lambda_u^{(2)*} H_2^\dagger \widehat{q}_L u_R - \lambda_d^{(1)} \bar{d}_R H_1^\dagger q_L - \lambda_d^{(2)} \bar{d}_R H_2^\dagger q_L - \lambda_l^{(1)} \bar{e}_R H_1^\dagger l_L - \lambda_l^{(2)} \bar{e}_R H_2^\dagger l_L + \text{h.c.}$$

$\widehat{q}_L \equiv -i\sigma_2 (\bar{q}_L)^{\mathrm{T}}$ , such that $H_j^\dagger \widehat{q}_L = \bar{q}_L \tilde{H}_j$

- extend $Z_2$ to the fermions ➡ 4 types of 2HDM: Type-I, Type-II, Type-L, Type-F

- the Yukawa parameters read: $\lambda_f^{(1)} = \frac{\sqrt{2}}{v} m_f, \quad \lambda_f^{(2)} = \frac{\eta_f}{\tan\beta} \lambda_f^{(1)}$

| | Type-I | Type-II | Type-L | Type-F |
|---|---|---|---|---|
| $\eta_u$ | 1 | 1 | 1 | 1 |
| $\eta_d$ | 1 | $-\tan^2\beta$ | 1 | $-\tan^2\beta$ |
| $\eta_l$ | 1 | $-\tan^2\beta$ | $-\tan^2\beta$ | 1 |

*N.B.*: this is *not* a model, but simply one solution of the generally CP violating model

- consider the particular scenario where $Y_3, Z_5, Z_6, Z_7$ all take real values.

Then:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1^{\rm H} + iG_0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2^{\rm H} + iA) \end{pmatrix}$$

where all states are mass eigenstates but $h_1^{\rm H}, h_2^{\rm H}$. By introducing $\alpha$ , we find:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + s_{\beta-\alpha}\, h_{125} + c_{\beta-\alpha}\, H_0 + iG_0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(c_{\beta-\alpha}\, h_{125} - s_{\beta-\alpha}\, H_0 + iA) \end{pmatrix}$$

where $h_{125}$ is the scalar found at the LHC, and $H_0, A, H^+$ are new scalars

- write the Z's of the potential in terms of more convenient parameters:

$$Z_1 = \frac{\left[m_{h_{125}}^2 + m_{H_0}^2 \cot(\beta-\alpha)^2\right] \sin(\beta-\alpha)^2}{v^2},$$

$$Z_3 = \frac{2\,(m_{H^\pm}^2 - Y_2)}{v^2},$$

$$Z_4 = \frac{2\,m_A^2 + m_{h_{125}}^2 + m_{H_0}^2 - 4\,m_{H^\pm}^2 + (m_{h_{125}}^2 - m_{H_0}^2)\cos\left[2\,(\beta-\alpha)\right]}{2\,v^2},$$

$$Z_5 = \frac{-2\,m_A^2 + m_{h_{125}}^2 + m_{H_0}^2 + (m_{h_{125}}^2 - m_{H_0}^2)\cos\left[2\,(\beta-\alpha)\right]}{2\,v^2},$$

$$Z_6 = \frac{(m_{h_{125}}^2 - m_{H_0}^2)\sin\left[2\,(\beta-\alpha)\right]}{2\,v^2}$$

- take some of the parameters as independent:

$$\beta-\alpha,\ m_{h_{125}},\ Y_2,\ m_{H_0},\ m_A,\ m_{H^\pm},\ \beta,\ m_f$$

$Y_2 \equiv \Lambda^2 \gg v^2$

- Assuming $H_2$ to be heavy, we want to *integrate* it *out*
  - write the equation of motion (EoM) for $H_2$
  - assume a solution of the form $H_{2c} = H_{2c}^{(0)} + \dfrac{H_{2c}^{(1)}}{Y_2} + \dfrac{H_{2c}^{(2)}}{{Y_2}^2}$
  - (the different $H_{2c}^{(i)}$ can be determined by solving the EoM order by order)
  - replace $H_2$ by $H_{2c}$ in the Lagrangian
- The effective Lagrangian reads:

$$\mathcal{L}_{\rm eff} = F_4 + \frac{F_6}{Y_2} + \frac{F_8}{Y_2^2} + \mathcal{O}\left(\frac{1}{Y_2^3}\right)$$

and we label both the absolute (or canonical) dimension and the effective dimension

[Egana-Ugrinovic, Thomas, 1512.00144]

example: $$\frac{F_{8,4}}{Y_2^2} \ni \frac{Y_3^2}{Y_2^2}\left(D_\mu H_1\right)^\dagger \left(D^\mu H_1\right)$$

eff dim. 8 — abs. dim. 4

then, we have:

$$\begin{aligned} F_4 &= F_{4,2} + F_{4,4}, \\ F_6 &= F_{6,2} + F_{6,4} + F_{6,6}\,, \\ F_8 &= F_{8,4} + F_{8,6} + F_{8,8}, \end{aligned}$$

I omit leptons

$$F_{4,2} = -Y_1 H_1^\dagger H_1,$$

$$F_{4,4} = (D_\mu H_1)^\dagger (D^\mu H_1) - \frac{Z_1}{2}\left(H_1^\dagger H_1\right)^2 - \left(\lambda_u^{(1)} \bar{u}_R \widehat{q}_L^\dagger H_1 + \lambda_d^{(1)} \bar{d}_R H_1^\dagger q_L + \text{h.c.}\right)$$

operators with 4 fermions will not be relevant

$$F_{6,2} = |Y_3|^2 (H_1^\dagger H_1),$$

$$F_{6,4} = Y_3 \lambda_u^{(2)*} H_1^\dagger \widehat{q}_L u_R + Y_3 \lambda_d^{(2)} \bar{d}_R H_1^\dagger q_L + Y_3 Z_6^* (H_1^\dagger H_1)^2 + \text{h.c.},$$

$$F_{6,6} = (H_1^\dagger H_1)\left[|Z_6|^2 (H_1^\dagger H_1)^2 + \left\{Z_6 \lambda_u^{(2)*} H_1^\dagger \widehat{q}_L u_R + Z_6 \lambda_d^{(2)} \bar{d}_R H_1^\dagger q_L + \text{h.c.}\right\}\right] + 4\text{F}$$

$$F_{8,4} = |Y_3|^2 (D_\mu H_1)^\dagger (D^\mu H_1) - (H_1^\dagger H_1)^2 \left[|Y_3|^2 Z_{34} + \frac{1}{2}(Y_3)^2 Z_5^* + \frac{1}{2}(Y_3^*)^2 Z_5\right],$$

$$\begin{aligned} F_{8,6} = {} & \{Y_3 Z_6^* + Y_3^* Z_6\} (H_1^\dagger H_1)(D_\mu H_1)^\dagger (D^\mu H_1) + \left\{Y_3 Z_6^* (D_\mu H_1)^\dagger H_1 + \text{h.c.}\right\} \partial^\mu (H_1^\dagger H_1) \\ & + \left\{Y_3^* \lambda_u^{(2)} \left(D_\mu (\widehat{q}_L u_R)\right)^\dagger (D^\mu H_1) + Y_3^* \lambda_d^{(2)*} \left(D_\mu (\bar{d}_R q_L)\right)^\dagger (D^\mu H_1) + \text{h.c.}\right\} \\ & - (H_1^\dagger H_1)^3 \left[Y_3 Z_{34} Z_6^* + Y_3 Z_5^* Z_6 + \text{h.c.}\right] \\ & - (H_1^\dagger H_1)\left[H_1^\dagger \widehat{q}_L u_R \left(Y_3 Z_{34} \lambda_u^{(2)*} + Y_3^* Z_5 \lambda_u^{(2)*}\right) + \bar{d}_R H_1^\dagger q_L \left(Y_3 Z_{34} \lambda_d^{(2)} + Y_3^* Z_5 \lambda_d^{(2)}\right) + \text{h.c.}\right], \end{aligned}$$

$$\begin{aligned} F_{8,8} = {} & |Z_6|^2 (H_1^\dagger H_1)^2 (D_\mu H_1)^\dagger (D^\mu H_1) + 2|Z_6|^2 (H_1^\dagger H_1) \partial_\mu (H_1^\dagger H_1) \partial^\mu (H_1^\dagger H_1) \\ & - (H_1^\dagger H_1)^4 \left[Z_{34} |Z_6|^2 + \frac{1}{2} Z_5^* Z_6^2 + \frac{1}{2} Z_5 (Z_6^*)^2\right] \\ & - (H_1^\dagger H_1)^2 \left[H_1^\dagger \widehat{q}_L u_R \left(Z_{34} Z_6 \lambda_u^{(2)*} + Z_5 Z_6^* \lambda_u^{(2)*}\right) + \bar{d}_R H_1^\dagger q_L \left(Z_{34} Z_6 \lambda_d^{(2)} + Z_5 Z_6^* \lambda_d^{(2)}\right) + \text{h.c.}\right] \\ & + \left\{\left[Z_6^* \lambda_u^{(2)} \left(D_\mu (\widehat{q}_L u_R)\right)^\dagger + Z_6^* \lambda_d^{(2)*} \left(D_\mu (\bar{d}_R q_L)\right)^\dagger\right]\left[\partial^\mu (H_1^\dagger H_1) H_1 + (H_1^\dagger H_1)(D^\mu H_1)\right] + \text{h.c.}\right\} + 4\text{F} \end{aligned}$$

- This is the effective Lagrangian, and has an implicit *matching:*

$$F_{6,4} \ni Y_3 Z_6^* (H_1^\dagger H_1)^2$$

coefficient with 2HDM params. only — operator with light fields only

- Yet, this effective Lagrangian is not convenient to study deviations from the SM
  - It is not written as SM + higher order terms
- Besides, for some operators, a basis-change is useful
- We want to write it in the SMEFT format, and render the matching explicit

SMEFT → SM + dim-6 opers. + dim-8 opers.

dim-6 opers.: [Grzadkowski et al, 1008.4884]; dim-8 opers.: [Murphy, 2005.00059]

- We need to use:
  - Integration by parts
  - EoM
  - SU(2) identities
- Finally, the 2HDM doublet $H_1$ and the SM doublet $\mathcal{H}$ are related via:

$$H_1 = \mathcal{H}\left(1 - \frac{|Y_3|^2}{2Y_2^2}\right)$$

- The SMEFT Lagrangian is then:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{S_{\text{all},6}}{\Lambda^2} + \frac{S_{\text{all},8}}{\Lambda^4} + \mathcal{O}\left(\frac{1}{\Lambda^6}\right),$$

$$\begin{aligned}
S_{\text{all},6} &= C_{\mathcal{H}}(\mathcal{H}^\dagger\mathcal{H})^3 + \Big\{ C_{u\mathcal{H}}\,(\mathcal{H}^\dagger\mathcal{H})\,\bar{q}_L u_R \tilde{\mathcal{H}} + C_{d\mathcal{H}}\,(\mathcal{H}^\dagger\mathcal{H})\,\bar{q}_L d_R \mathcal{H} + \text{h.c.} \Big\} + 4\text{F} \\
S_{\text{all},8} &= C_{\mathcal{H}^8}(\mathcal{H}^\dagger\mathcal{H})^4 + C^{(1)}_{\mathcal{H}^6}(\mathcal{H}^\dagger\mathcal{H})^2\,(D_\mu\mathcal{H})^\dagger\,(D^\mu\mathcal{H}) + \Big\{ C_{qu\mathcal{H}^5}(\mathcal{H}^\dagger\mathcal{H})^2 \bar{q}_L u_R \tilde{\mathcal{H}} \\
&\quad + C^{(1)}_{qu\mathcal{H}^3D^2}(D_\mu\mathcal{H})^\dagger(D^\mu\mathcal{H})\bar{q}_L u_R \tilde{\mathcal{H}} + C^{(2)}_{qu\mathcal{H}^3D^2}\Big[(D_\mu\mathcal{H})^\dagger\tau^I(D^\mu\mathcal{H})\Big]\Big[\bar{q}_L u_R \tau^I \tilde{\mathcal{H}}\Big] \\
&\quad + C^{(5)}_{qu\mathcal{H}^3D^2}\Big[(D_\mu\mathcal{H})^\dagger\mathcal{H}\Big]\Big[\bar{q}_L u_R \widetilde{D^\mu\mathcal{H}}\Big] + C_{qd\mathcal{H}^5}(\mathcal{H}^\dagger\mathcal{H})^2\bar{q}_L d_R \mathcal{H} \\
&\quad + C^{(1)}_{qd\mathcal{H}^3D^2}(D_\mu\mathcal{H})^\dagger(D^\mu\mathcal{H})\bar{q}_L d_R \mathcal{H} + C^{(2)}_{qd\mathcal{H}^3D^2}\Big[(D_\mu\mathcal{H})^\dagger\tau^I(D^\mu\mathcal{H})\Big]\Big[\bar{q}_L d_R \tau^I \mathcal{H}\Big] \\
&\quad + C^{(5)}_{qd\mathcal{H}^3D^2}(\mathcal{H}^\dagger D_\mu\mathcal{H})(\bar{q}_L d_R D^\mu\mathcal{H}) + \text{h.c.} \Big\} + 4\text{F},
\end{aligned}$$

- The explicit matching is:

$$C_{\mathcal{H}} = C^{[6]}_{\mathcal{H}} + \frac{C^{[8]}_{\mathcal{H}}}{\Lambda^2} = |Z_6|^2 + \frac{1}{\Lambda^2}\Big(Y_3 Z_1 Z_6^* + Y_3^* Z_1 Z_6 - Y_3 Z_{34} Z_6^* - Y_3^* Z_{34} Z_6 - Y_3 Z_5^* Z_6 - Y_3^* Z_5 Z_6^* + 2Y_1 |Z_6|^2\Big)$$

$$C_{u\mathcal{H}} = C^{[6]}_{u\mathcal{H}} + \frac{C^{[8]}_{u\mathcal{H}}}{\Lambda^2} = Z_6 \lambda_u^{(2)*} + \frac{1}{\Lambda^2}\Big(Y_3^* Z_6 \lambda_u^{(1)} + Y_3 Z_1 \lambda_u^{(2)*} - Y_3 Z_{34} \lambda_u^{(2)*} - Y_3^* Z_5 \lambda_u^{(2)*} + 3Y_1 Z_6 \lambda_u^{(2)*}\Big)$$

$$C_{d\mathcal{H}} = C^{[6]}_{d\mathcal{H}} + \frac{C^{[8]}_{d\mathcal{H}}}{\Lambda^2} = Z_6^* \lambda_d^{(2)*} + \frac{1}{\Lambda^2}\Big(Y_3 Z_6^* \lambda_d^{(1)} + Y_3^* Z_1 \lambda_d^{(2)*} - Y_3^* Z_{34} \lambda_d^{(2)*} - Y_3 Z_5^* \lambda_d^{(2)*} + 3Y_1 Z_6^* \lambda_d^{(2)*}\Big)$$

and

$$
\begin{aligned}
C_{\mathcal{H}^8} &= -Z_{34}|Z_6|^2 - \frac{1}{2}Z_5^* Z_6^2 - \frac{1}{2}Z_5 (Z_6^*)^2 + 2Z_1|Z_6|^2, \\
C_{\mathcal{H}^6}^{(1)} &= -|Z_6|^2, \\
C_{qu\mathcal{H}^5} &= -Z_{34}Z_6\lambda_u^{(2)*} - Z_5 Z_6^* \lambda_u^{(2)*} + |Z_6|^2\lambda_u^{(1)} + 3Z_1 Z_6 \lambda_u^{(2)*}, \\
C_{qu\mathcal{H}^3D^2}^{(1)} &= -3Z_6\lambda_u^{(2)*}, \\
C_{qu\mathcal{H}^3D^2}^{(2)} &= Z_6\lambda_u^{(2)*}, \\
C_{qu\mathcal{H}^3D^2}^{(5)} &= -2Z_6\lambda_u^{(2)*}, \\
C_{qd\mathcal{H}^5} &= -Z_{34}Z_6^*\lambda_d^{(2)*} - Z_5^* Z_6 \lambda_d^{(2)*} + |Z_6|^2\lambda_d^{(1)} + 3Z_1 Z_6^* \lambda_d^{(2)*}, \\
C_{qd\mathcal{H}^3D^2}^{(1)} &= -3Z_6^*\lambda_d^{(2)*}, \\
C_{qd\mathcal{H}^3D^2}^{(2)} &= -Z_6^*\lambda_d^{(2)*}, \\
C_{qd\mathcal{H}^3D^2}^{(5)} &= -2Z_6^*\lambda_d^{(2)*}.
\end{aligned}
$$

- The validity of the EFT approach requires decoupling:
  - $m_A^2 \sim m_{H_0}^2 \sim m_{H^\pm}^2 \sim Y_2 \equiv \Lambda^2 \gg v^2, \qquad m_{h_{125}}^2 \simeq v^2,$
  - $|\cos(\beta-\alpha)| \propto \dfrac{v^2}{\Lambda^2}$ → decoupling thus implies alignment, $\cos(\beta-\alpha) \to 0$
- Hence, we expand the results to quadratic order in $\cos(\beta-\alpha)$. Examples:
  - $\dfrac{C_{u\mathcal{H}}}{\Lambda^2} = -\dfrac{2}{\sqrt{2}}(\sqrt{2}G_F)^{3/2}\dfrac{\cos(\beta-\alpha)}{\tan\beta}\eta_u m_u - \dfrac{\cos(\beta-\alpha)\, m_u\,(\sqrt{2}G_F)^{3/2}}{\sqrt{2}\,\Lambda^2}\left[\cos(\beta-\alpha)\,\Lambda^2 - \dfrac{6\, m_h^2\, \eta_u}{\tan\beta}\right]$
  - $\dfrac{C_{\mathcal{H}^8}}{\Lambda^4} = 2\,\cos(\beta-\alpha)^2\, m_h^2\,(\sqrt{2}G_F)^3$
- To calculate in SMEFT, we define as independent parameters the set:

$$G_F, M_W, M_Z, m_h, m_f \quad \text{(and WCs)}$$

and we rewrite the dependent parameters in terms of them:

$$\bar{g}_2 = (\sqrt{2}G_F)^{1/2}\, 2\, M_W,$$

$$Y_f = \sqrt{2}(\sqrt{2}G_F)^{1/2}\, m_f + \frac{C_{f\mathcal{H}}}{2\sqrt{2}\,G_F\Lambda^2} + \frac{C_{qf\mathcal{H}^5}}{8\,G_F^2\Lambda^4} + \frac{C_{\mathcal{H}^6}^{(1)} m_f}{4\sqrt{2}\,(\sqrt{2}G_F)^{3/2}\Lambda^4}$$

$$\lambda = \frac{G_F m_h^2}{\sqrt{2}} + \frac{3C_{\mathcal{H}}}{2\sqrt{2}G_F\Lambda^2} + \frac{3C_{\mathcal{H}^8}}{4G_F^2\Lambda^4} + \frac{C_{\mathcal{H}^6}^{(1)} m_h^2}{4\sqrt{2}G_F\Lambda^4}$$

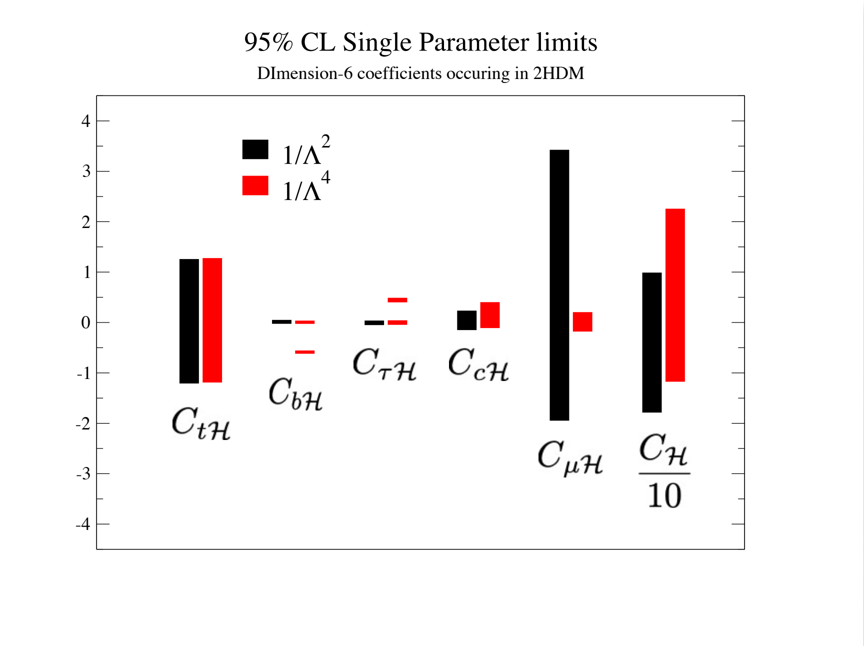
- Higgs signal strengths:

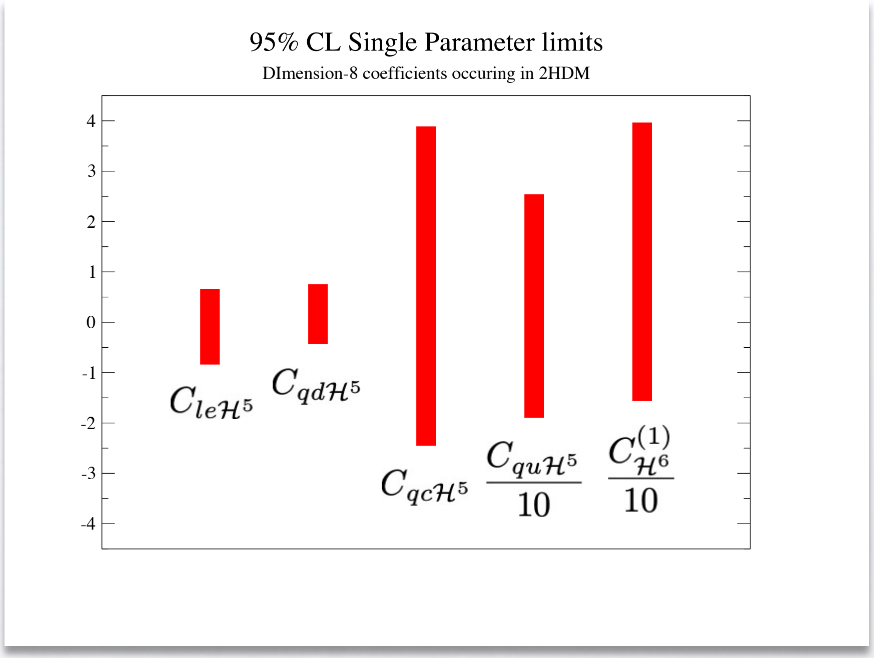
$$\mu^{P}_{pp\to h\to f} = \frac{\sigma^{P}(pp\to h)}{\sigma^{P}(pp\to h)_{\rm SM}} \times \frac{{\rm BR}(h\to f)}{{\rm BR}(h\to f)_{\rm SM}}$$

prod. modes: $ggh$, VBF, $Wh$, $Zh$, $t\bar{t}h$

final states: $\gamma\gamma$, $b\bar{b}$, $\tau^+\tau^-$, $W^+W^-$, $ZZ$

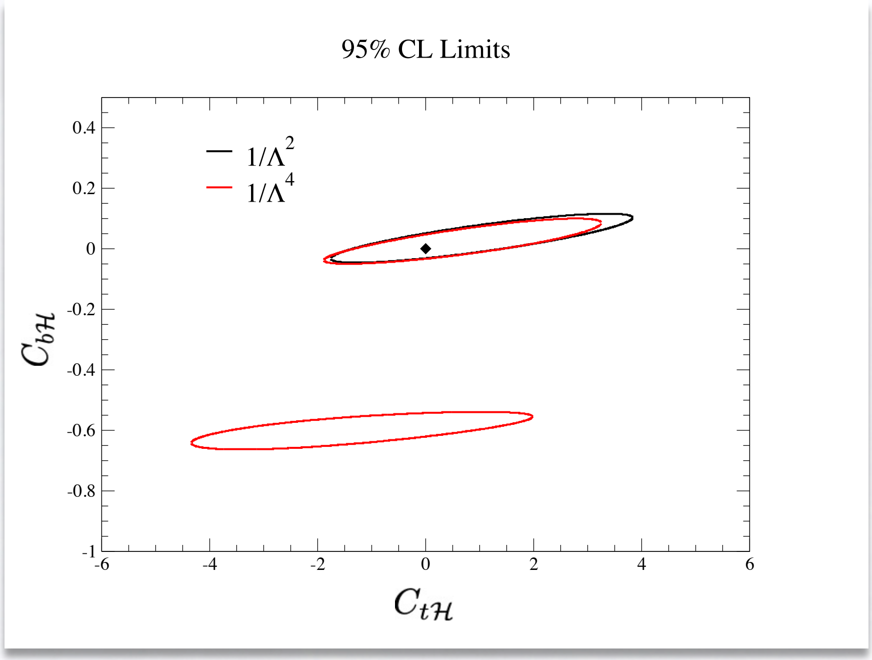
- Pure SMEFT results:
  - Single parameter limits on WCs:



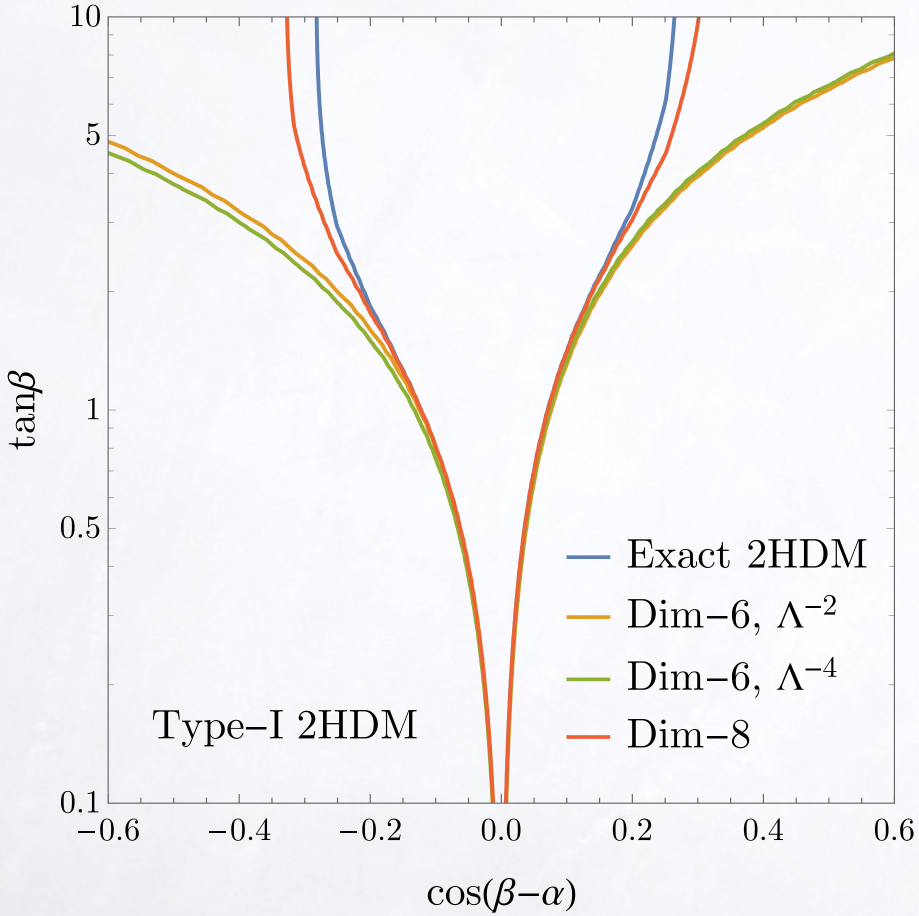

- The inclusion of $\frac{1}{\Lambda^4}$ effects adds an extra solution in some WCs: the *wrong-sign* solution

- Two-parameter limits on WCs:




- Again, two solutions: the SM one and the wrong-sign solution (non-SM)
- There is a large correlation between the two WC
- $C_{t\mathcal{H}}$ is less contrained than in the single-fit parameters

- Now, the fits. Type I:




- For high $\tan\beta$, the dim-6 results are poorly constrained
  - the only WCs are the Yukawa ones
  - $\lambda_f^{(2)} = \frac{\eta_f}{\tan\beta}\lambda_f^{(1)}$

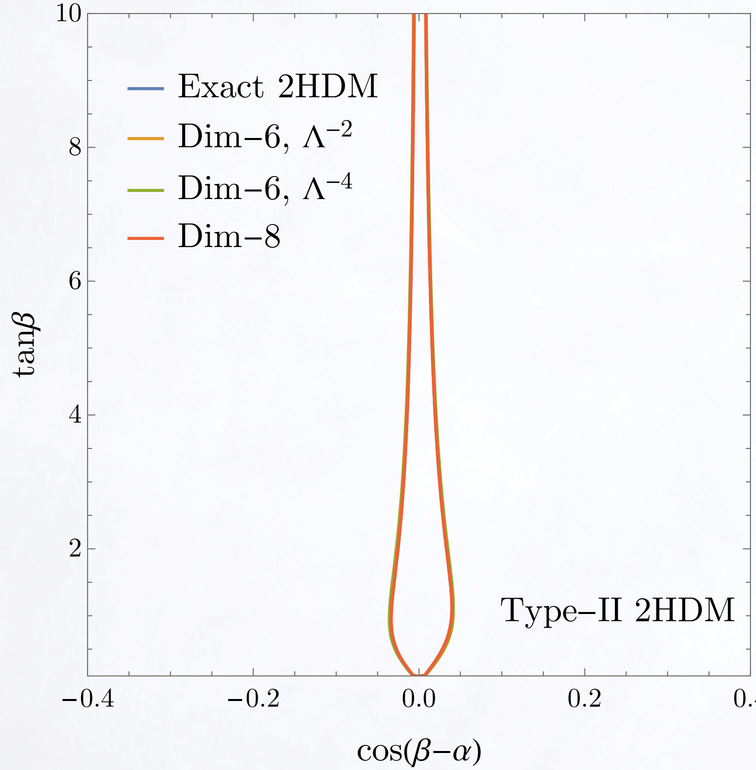
| | Type-I |
|---|---|
| $\eta_u$ | 1 |
| $\eta_d$ | 1 |
| $\eta_l$ | 1 |

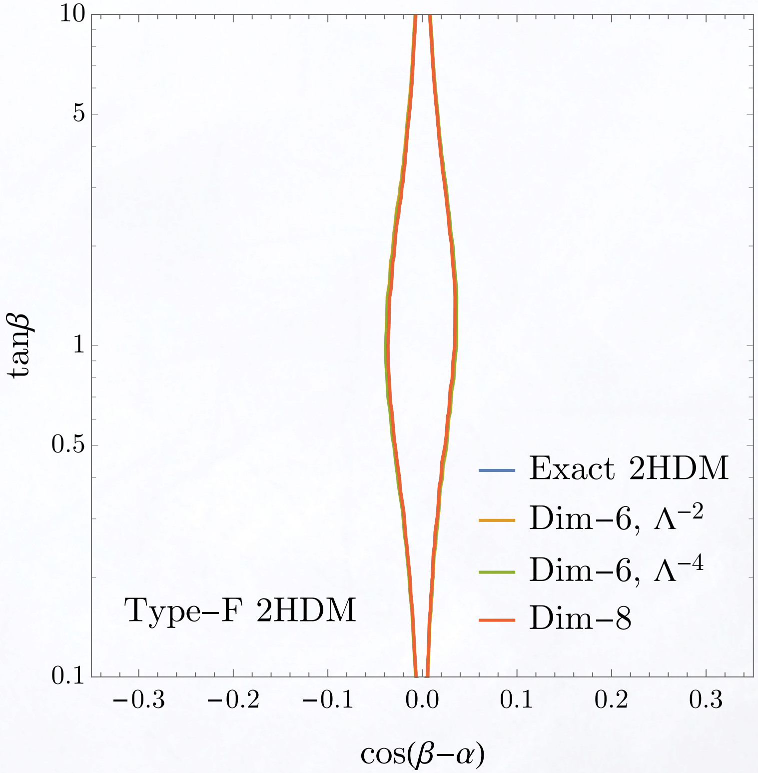
- Obviously, this does not change with the squared terms
- The exact 2HDM has more info than Yukawas
  - → gauge-Higgs interactions
- But that info is contained in the dim-8 results

$$S_{\text{all},8} \ni C_{\mathcal{H}^6}^{(1)} (\mathcal{H}^\dagger \mathcal{H})^2 (D_\mu \mathcal{H})^\dagger (D^\mu \mathcal{H})$$

- The dim-8 EFT is thus a good reproduction of the exact model – whereas dim-6 is clearly insufficient for some regions

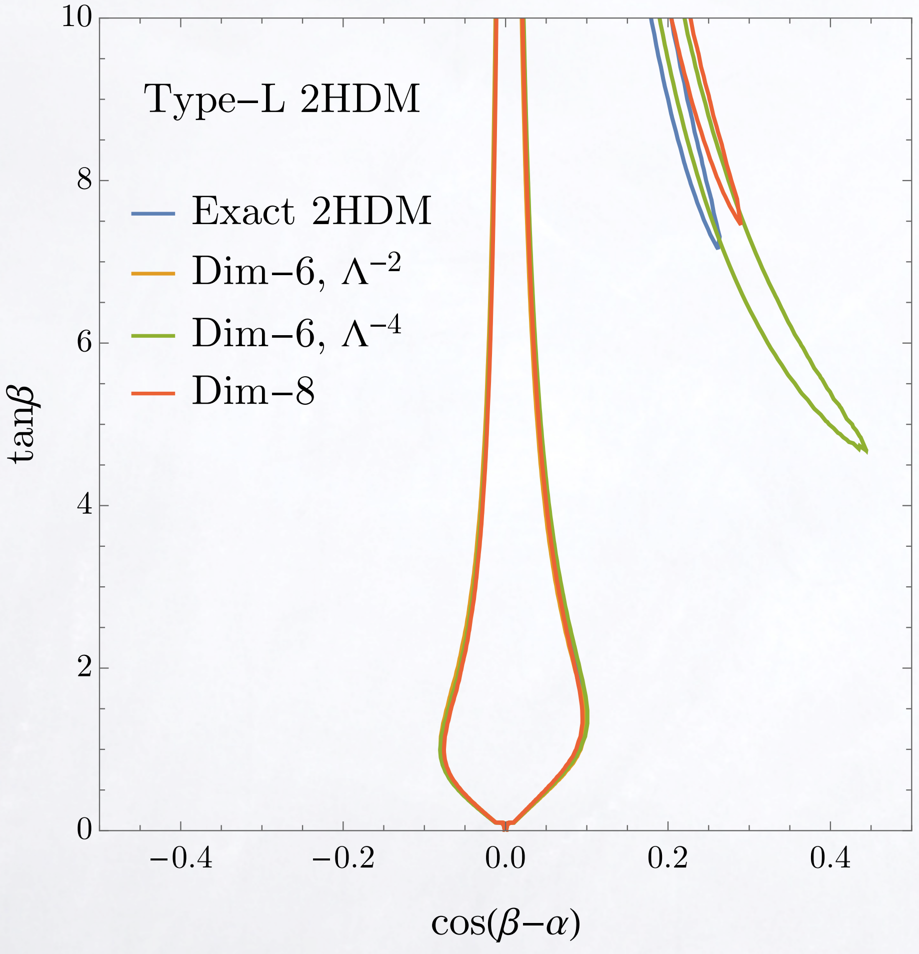
- Types II and F:




- In these models, there is at least one $|\eta_f| \propto \tan^2\beta$
- Therefore, even the dim-6 Yukawa operators are constrained for high $\tan\beta$
- The dim-8 operators are thus irrelevant in these models

- Type L:




- Type-L is still compatible with the wrong-sign
- This solution cannot be captured if only linear effects of dim-6 are kept
- But squared-dim-6 does not accurately describe the full model

  (because, in the exact 2HDM, the large values of $\cos(\beta-\alpha)$ are ruled out by Higgs-gauge interactions)

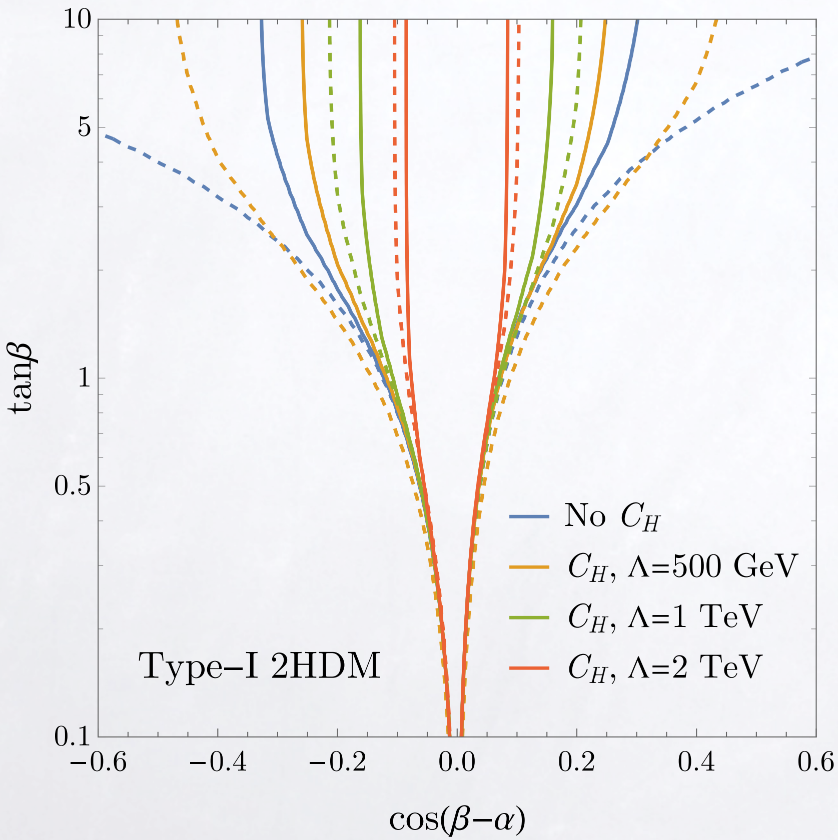
- Info about such couplings comes with dim-8 operators
- The dim-8 EFT is thus a good reproduction of the exact model – whereas dim-6 is clearly insufficient for some regions

- What happens if we include the SMEFT predictions for the trilinear couplings?
  - We calculate higher-order corrections from Higgs self-interactions to single Higgs production or decays (only in SMEFT, not in the 2HDM)
    - higher-order corrections from Higgs self-interactions → $\delta\mu_j$
    - single Higgs production or decays → $\mu_j$

[Degrassi et al, 1607.04251]

[Degrassi et al, 2102.07651]

  - The $\delta\mu_j$ depend on the Higgs self-interactions, which depend on $C_{\mathcal{H}}, C_{\mathcal{H}^8}$
    - $C_{\mathcal{H}}$ → strongly contrained




- We define the combined signal strength as:

$$\mu_j^{\text{comb}} = \mu_j + \delta\mu_j$$

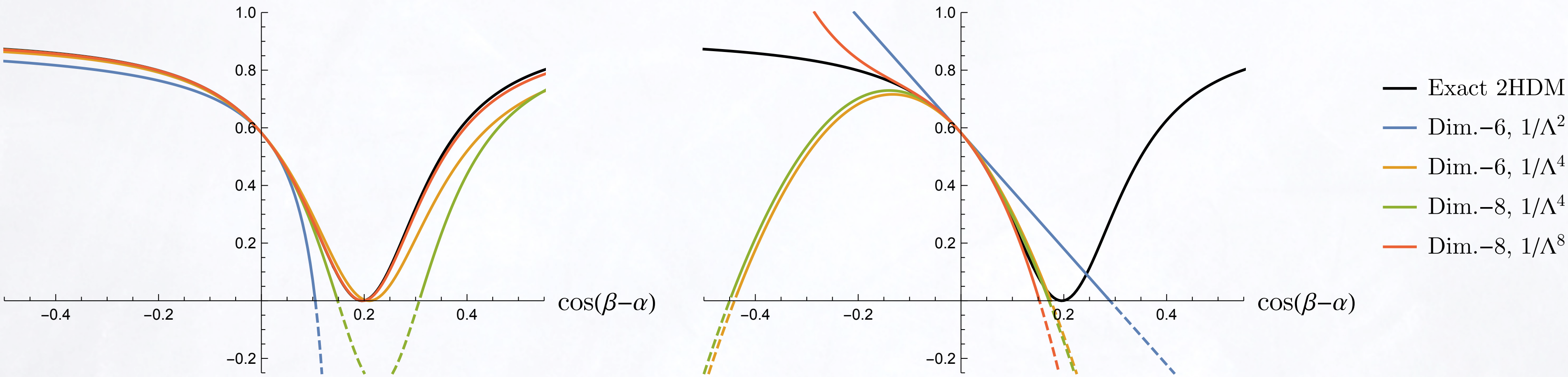
- Because $C_{\mathcal{H}}$ is so contrained, the results are very different
- There is strong dependence on $\Lambda$
- This motivates a study of the one-loop matching in the 2HDM

- SMEFT is very convenient; but *how good* is the usual truncation with dimension-6 operators?
- I considered the 2HDM, and described an EFT for it up to **dimension-8** operators
- After integrating out the heavy doublet, I used several conversions to obtain **SMEFT**
- There are *very few* dimension-6 WCs for LO LHC Higgs physics: $C_{u\mathcal{H}}, C_{d\mathcal{H}}, C_{l\mathcal{H}}$
- The gauge-Higgs interactions appear only with the **dimension-8** operator $(\mathcal{H}^\dagger \mathcal{H})^2 \, (D_\mu \mathcal{H})^\dagger \, (D^\mu \mathcal{H})$
- They turn out to be crucial for the Type-I 2HDM for high $\tan\beta$, where $C_{f\mathcal{H}}$ are suppressed
- **Dimension-8** operators are also relevant for the wrong-sign solution in Type-L
- For other regions and types, dimension-8 operators are irrelevant
- SMEFT NLO Higgs trilinear contributions are quite restrictive

- A note about expansions in power of $1/\Lambda$:
  - When truncating $\mathrm{BR}(h \to b\bar{b}) = \dfrac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \mathrm{all})}$, one can: expand num. and den. separately or expand quotient as whole

$\mathrm{BR}(h \to b\bar{b}); \Gamma(h \to b\bar{b}), \Gamma(h \to \mathrm{all})$ expanded separately

$\mathrm{BR}(h \to b\bar{b}); [\Gamma(h \to b\bar{b})/\Gamma(h \to \mathrm{all})]$ expanded




  - When higher order operators are relevant for $\Gamma(h \to \mathrm{all})$, then $\dfrac{1}{\Gamma(h \to \mathrm{all})}$ does not converge
  - The correct way is thus to expand $\Gamma(h \to b\bar{b})$ and $\Gamma(h \to \mathrm{all})$ separately
  - Neglecting squared effects leads to unreasonable results; but:
    - that is a general consequence of a consistent SMEFT truncation
    - the regions at stake are experimentally excluded anyway