EFTs for the 2HDM

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and 2305.07689, with Sally Dawson, Carlos Quezada-Calonge and Juan José Sanz-Cillero

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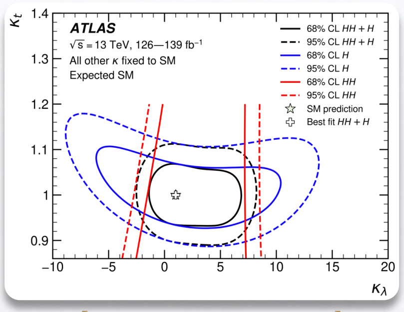
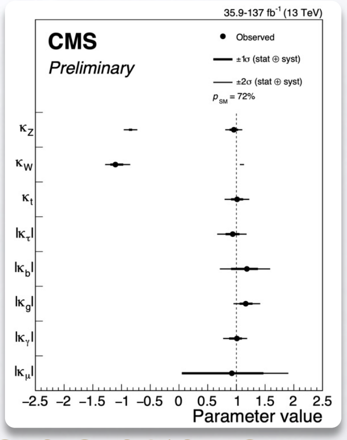
- Although the Standard Model (SM) is extremely powerful, there is physics beyond it (BSM)
- The Higgs sector was inaugurated in 2012, and BSM physics may be found within it
- How to search for physics Beyond the Standard Model (BSM) within the Higgs sector?
  - The dream: direct detection! But if BSM physics is too heavy to be produced, we resort to indirect methods — ideally, in a model-independent way
  - A usual approach is the kappa formalism: [David et al, 1209.0040] [Heinemeyer et al, 1307.1347]
    - A set of scale factors κ_i are defined, such that all decay channels and production x-section of the SM Higgs are rescaled by a κ_i^2: $\dfrac{\sigma_{\text{ggH}}}{\sigma_{\text{ggH}}^{\text{SM}}} = \kappa_g^2, \quad \dfrac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\text{SM}}} = \kappa_\gamma^2, \quad \dfrac{\Gamma_{ff}}{\Gamma_{ff}^{\text{SM}}} = \kappa_f^2, \quad \ldots$
    - ATLAS and CMS have provided (and still provide) limits on the κ_i parameters:



[ATLAS, 2211.01216]



[CMS, CMS-PAS-HIG-19-005]

- But the kappa formalism was explicitly proposed as an *interim solution*:
  - It deliberately ignores tensorial structures not present in the SM
    (so that it becomes model dependent and cannot be used for kinematic distributions)
  - It does not follow from a consistent Quantum Field Theory
    (so that it does not allow higher order, different scales, etc.)
  - It is not an **Effective Field Theory** (EFT)
    (so that it does not represent an IR limit of an UV sector) [Brivio, Trott, 1706.08945]
- The theoretical framework that should be used for a model-independent approach is an **EFT**
  - General & consistent for heavy BSM
  - It was not mature at LHC Run 1
- Two main **EFT** candidates for Higgs physics:

SMEFT HEFT

- What are these two frameworks?

Standard Model Effective Field Theory

- The SMEFT is an **EFT** that takes the SM before SSB and includes higher-order terms:

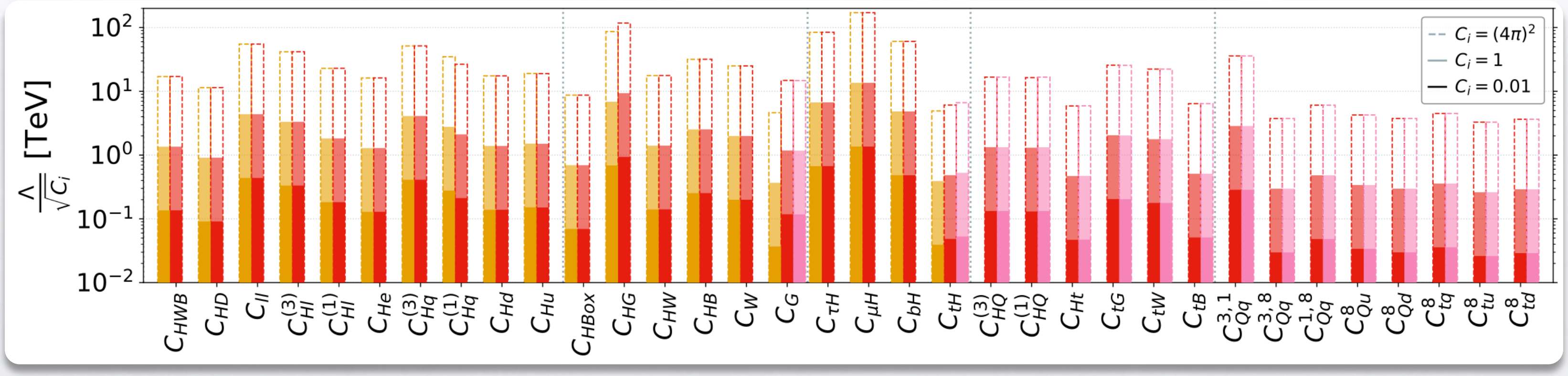
SMEFT (aka Wilson) coefficients

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}, \qquad d > 4$$

is even if lepton and baryon number are conserved

- dof's and symmetries of the SM
- Higgs belongs to a SU(2) doublet
- clear power-counting in $1/\Lambda$

- It is by far the preferred EFT framework at the LHC
- Several observables are correlated at dim-6
- SMEFT at dim-6 has seen an impressive development in the last 10 years
  - In particular, global fits:



[Ellis et al, 2012.02779]

- Significant advances in dim-8 operators have been done in the last ~2 years

Higgs Effective Field Theory

- The HEFT is a fusion of chiral perturbation theory (χPT) (in the scalar sector) with SMEFT (in the fermion and gauge sector). Just as in χPT:
  - The $\underbrace{\text{3 Goldstone}}_{\pi^I\text{, imbedded into } U = \exp\left(i\tau^I\pi^I/v\right)}$ bosons are independent of the $\underbrace{\text{Higgs}}_{h}$, which is a **gauge singlet** (instead of part of an SU(2) doublet)
  - There is an expansion in the number of (covariant) derivatives. At LO:

$$\mathcal{L}_{\text{HEFT}} \supset \frac{v^2}{4}\mathcal{F}(h)\text{Tr}\left\{D_\mu U^\dagger D_\mu U\right\} + \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

with:

HEFT coefficients

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots, \qquad V(h) = \frac{1}{2}m_h^2 h^2\left(1 + d_3\frac{h}{v} + \frac{d_4}{4}\frac{h^2}{v^2} + \dots\right)$$

(such that the SM corresponds to $a = b = d_3 = d_4 = 1$)

- Because the Higgs is a **gauge singlet**, it has arbitrary couplings: e.g. d_3 and d_4 are independent (whereas in the LO SMEFT they are related, since h is contained in a doublet)

- The organization of HEFT is subtle, since χPT and SMEFT have different organizations
  - One sometimes includes the NLO term, since the LO one has a poor structure
  - But there is no agreement in the literature on what is LO and what is NLO [Brivio et al, 1604.06801] [Buchalla, Cata, Krause, 1307,5017]

- Ultimate goal of *any* **EFT** framework for BSM physics:
    - Find a pattern of non-zero deviations in the EFT coefficients
    - Associate (or *match*) that pattern with a particular BSM (a.k.a. UV) model
- So far, no deviations. But several questions:
    - How good is such association? In particular:
    - SMEFT is usually truncated with dim. 6 operators. Is that *enough* to reproduce the UV model?
    - What about the HEFT matching? Is it more cumbersome than the SMEFT one?
    - How exactly to compare the two approaches? Which one is *better* ?
    - And are there several types of SMEFT and HEFT matching?
- Note that the discussion SMEFT vs HEFT has been addressed quite often, albeit in a model-independent (and not so phenomenological) way

[Brivio et al, 1311.1823] [Alonso et al, 1409.1589] [Brivio et al, 1604.06801] [Brivio, PhD thesis, 2016] [Brivio, Trott, 1706.08945] [Falkowski, Rattazzi, 1902.05936] [Cohen et al, 2008.08597] [Cohen et al, 2108.03240] [Alonso, West, 2109.13290] [Banta et al, 2110.02967] [Kanemura, Nagai, 2111.12585] [Banta, 2202.04608] [Ambrosio et al, 2204.01763] [Ambrosio et al, 2207.09848] [Gráf et al, 2211.06275]

- But to address the aforementioned questions, we can look at particular UV models
  - **EFTs** are generic, model-independent (bottom-up approach)
  - (top-down approach)
  - Still, by matching to particular UV models, one may gain insight about the generic approach
  - It is a more phenomenological approach
- Here, I take the 2 Higgs Doublet Model (2HDM) as the UV model
  - Very popular model, sufficiently simple (complex) to allow an economic (interesting) analysis
  - I will focus on the notion of decoupling, which is central in both **EFT**s
  - I shall perform the tree-level matching of both SMEFT and HEFT to the 2HDM
  - I will ascertain the importance of the different **EFT** orders
  - I focus on fits to Higgs signal strengths, as well as on the tree-level processes $WW \to hh$ and $hh \to hh$
  - I will discuss other possible (recently proposed) **EFT** approaches to the 2HDM

- 2HDM in a nutshell:
  - Take the SM, with its scalar doublet (Φ_1) , and add an extra one (Φ_2)
  - Impose a Z_2 symmetry, according to which $\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$
  - Both Φ_1 and Φ_2 have vevs: $\frac{v_1}{\sqrt{2}}$ and $\frac{v_2}{\sqrt{2}}$; then, define β 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,

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

N.B.: Z2 is imposed to avoid FCNC. Yet, an exact Z2 prevents decoupling. So, we allow Z2 to be softly broken

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

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

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

$\widehat{q}_L \equiv -i\sigma_2(\bar{q}_L)^{\mathrm{T}}$, 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
η_u	1	1	1	1
η_d	1	$-\tan^2\beta$	1	$-\tan^2\beta$
η_l	1	$-\tan^2\beta$	$-\tan^2\beta$	1

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

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

Then:

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

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

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

where h is the scalar found at the LHC, and H, A, H^+ are new scalars

- Take some of the parameters as independent: $c_{\beta-\alpha},\ Y_2,\ m_h,\ m_{H_0},\ m_A,\ m_{H^\pm},\ \beta,\ m_f$

- In order to build an **EFT** from the 2HDM, this model needs a separation of scales: $\Lambda \gg v$
  - We thus assume that the BSM scalars decouple: $m_H \simeq m_A \simeq m_{H^+} \gg m_h = 125$ GeV
  - But we do not want the couplings constants too large: we want perturbativity

$$m_h^2 = \frac{c_{\beta-\alpha}^2}{2\,c_{\beta-\alpha}^2 - 1} Y_2 + \frac{2\,(c_{\beta-\alpha}^2 - 1) Z_1 + c_{\beta-\alpha}^2 Z_{345}}{4\,c_{\beta-\alpha}^2 - 2} v^2, \qquad m_A^2 = Y_2 + \frac{Z_{345} - 2Z_5}{2} v^2,$$

$$m_H^2 = \frac{(c_{\beta-\alpha}^2 - 1)}{2\,c_{\beta-\alpha}^2 - 1} Y_2 + \frac{c_{\beta-\alpha}^2 (2Z_1 + Z_{345}) - Z_{345}}{4\,c_{\beta-\alpha}^2 - 2} v^2 \qquad m_{H^+}^2 = Y_2 + \frac{Z_3}{2} v^2$$

with $Z_{345} \equiv Z_3 + Z_4 + Z_5$

  - Clearly, while taking Y_2 large and keeping the Z's fixed, A and H^+ become heavy
  - Besides, $c_{\beta-\alpha}$ must be small, so that h can be light and H can be heavy
  - Then, the decoupling limit $m_H \simeq m_A \simeq m_{H^+} \gg m_h$ can be obtained in a way consistent with perturbativity if:

$$Y_2 = \Lambda^2, \qquad m_H^2 = \Lambda^2 + \Delta m_H^2, \quad m_A^2 = \Lambda^2 + \Delta m_A^2, \quad m_{H^+}^2 = \Lambda^2 + \Delta m_{H^+}^2,$$

$$\Lambda^2 \gg v^2, \qquad m_h^2 \sim \mathcal{O}(v^2), \qquad \Delta m_H^2, \Delta m_A^2, \Delta m_{H^+}^2 \sim \mathcal{O}(v^2),$$

$$c_{\beta-\alpha} \sim \mathcal{O}(v^2/\Lambda^2)$$

[Gunion, Haber, 0207010]

- This (decoupling) limit can be used to perform *expansions*. To do that, we introduce ξ such that the power-counting that organizes the expansion is:

$$v^2/\Lambda^2 \sim \mathcal{O}(\xi), \qquad c_{\beta-\alpha} \sim \mathcal{O}(\xi)$$

- The expansion is in powers of ξ. The trivial order, $\mathcal{O}(\xi^0)$, yields SM couplings for the Higgs boson: the alignment limit, $\mathbf{c}_{\beta-\alpha} = \mathbf{0}$

- Both the SMEFT and the HEFT matchings to the **2HDM** will follow this expansion
  - It is true that the SMEFT and the HEFT are in general different
  - More than that, the SMEFT and HEFT matchings to the 2HDM follow different prescriptions:

integrate out the physical states H, A, H^+

integrate out the doublet H_2

SMEFT/HEFT matching to the 2HDM:
integrate out the heavy dof's before/after SSB

  - Yet, if they match a perturbative 2HDM with heavy masses and with our choice of independent parameters, they follow the same power-counting

- To obtain the an **EFT** from the 2HDM, the heavy states must be integrated out
- To obtain the SMEFT matching, the integration out must happen before SSB:
  - Write the equation of motion (EoM) for the whole doublet H_2
  - We want to obtain the matching up to dim-8 operators
  - Then, assume a solution of the form $H_{2c} = {H_2}_c^{(0)} + \frac{{H_2}_c^{(1)}}{Y_2} + \frac{{H_2}_c^{(2)}}{{Y_2}^2}$
  - Replace H_2 by H_{2c} in the Lagrangian. The effective Lagrangian reads:

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

or canonical

and we label both the absolute dimension and the effective dimension;

[Egana-Ugrinovic, Thomas, 1512.00144]

example:

$$\frac{F_{8,4}}{Y_2^2} \ni \underbrace{\frac{Y_3^2}{Y_2^2}}_{\text{eff dim. 8}} \underbrace{\boxed{\left(D_\mu H_1\right)^\dagger \left(D^\mu H_1\right)}}_{\text{abs. dim. 4}}$$

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

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

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

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

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

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

operators with 4 fermions will not be relevant

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

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

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

- 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

[Grzadkowski et al, 1008.4884]

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

- We want to write it in the SMEFT format, and render the matching explicit

[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:

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

- Identifying Y_2 with Λ^2, the resulting (effective) Lagrangian is:

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

$$\begin{aligned} S_{\text{all},6} &= C_{\mathcal{H}}(\mathcal{H}^\dagger\mathcal{H})^3 + \left\{C_{u\mathcal{H}}\,(\mathcal{H}^\dagger\mathcal{H})\,\bar{q}_L u_R \tilde{\mathcal{H}} + C_{d\mathcal{H}}\,(\mathcal{H}^\dagger\mathcal{H})\,\bar{q}_L d_R \mathcal{H} + \text{h.c.}\right\} + 4\text{F} \\ S_{\text{all},8} &= C_{\mathcal{H}^8}(\mathcal{H}^\dagger\mathcal{H})^4 + C^{(1)}_{\mathcal{H}^6}(\mathcal{H}^\dagger\mathcal{H})^2\,(D_\mu\mathcal{H})^\dagger\,(D^\mu\mathcal{H}) \\ &\quad + \left\{C_{qu\mathcal{H}^5}(\mathcal{H}^\dagger\mathcal{H})^2\bar{q}_L u_R \tilde{\mathcal{H}} + C_{qd\mathcal{H}^5}(\mathcal{H}^\dagger\mathcal{H})^2\bar{q}_L d_R \mathcal{H} + \text{2D2H2F} + \text{h.c.}\right\} + 4\text{F}, \end{aligned}$$

- The explicit matching is:

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

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

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

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

- We can rewrite these relations in terms of the independent parameters

$(c_{\beta-\alpha},\, Y_2,\, m_h,\, m_H,\, m_A,\, m_{H^\pm},\, \beta,\, m_f)$

  - Write the dependent parameters in terms of them
  - Use the scaling in ξ and expand to $\mathcal{O}(\xi^2)$. We find:

$$\begin{aligned}
\frac{C_{\mathcal{H}}}{\Lambda^2} &= c^2_{\beta-\alpha}\,(\sqrt{2}G_F)^2\Big[\Lambda^2 - 4\,(m_h^2 - \Delta m_H^2)\Big] + \mathcal{O}(\xi^3),\\
\frac{C_{\mathcal{H}^8}}{\Lambda^4} &= 2\,c^2_{\beta-\alpha}\,(\sqrt{2}G_F)^3\,\left(m_h^2 - \Delta m_H^2\right) + \mathcal{O}(\xi^3),\\
\frac{C^{(1)}_{\mathcal{H}^6}}{\Lambda^4} &= -c^2_{\beta-\alpha}\,(\sqrt{2}G_F)^2 + \mathcal{O}(\xi^3)\\
&(\ldots)
\end{aligned}$$

- Remarks:
  - Among the non-4F dim-6 opers. of the Warsaw basis, only 4 show up in the matching
  - In particular, the hVV interaction only shows up at dim-8

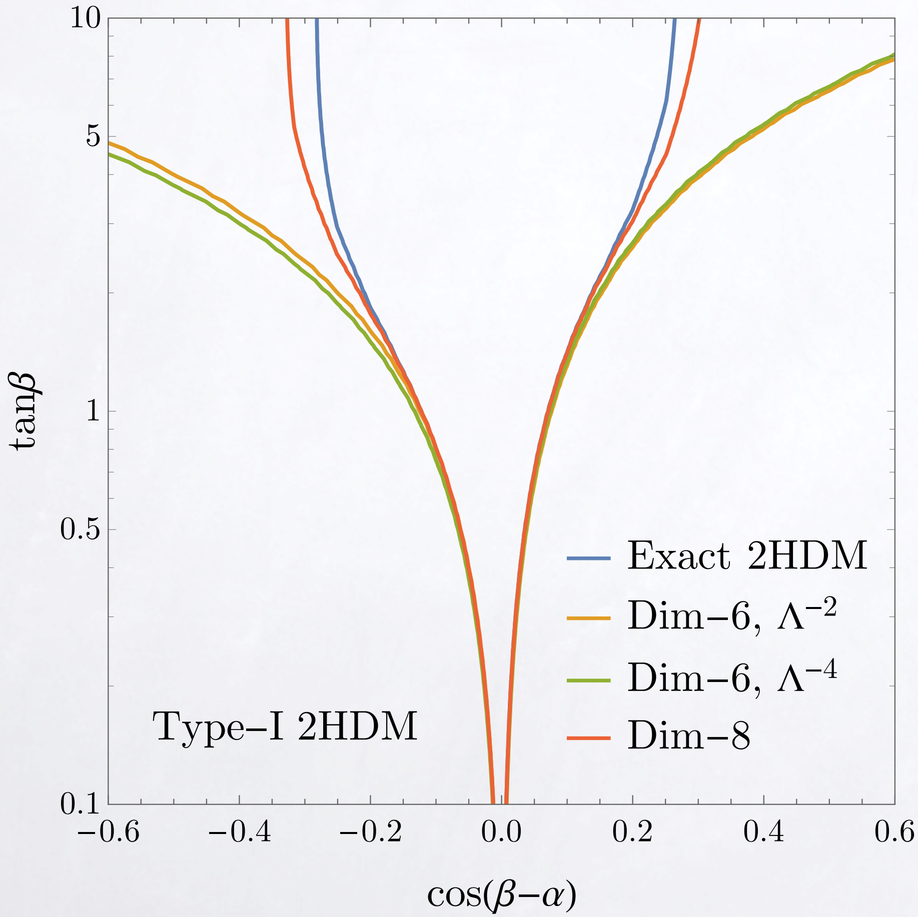
- Higgs signal strengths: $$\mu^P_{pp\to h\to f} = \frac{\sigma^P(pp\to h)}{\sigma^P(pp\to h)_{\rm SM}} \times \frac{{\rm BR}(h\to f)}{{\rm BR}(h\to f)_{\rm SM}}$$

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

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

- SMEFT fits, assuming $m_H = m_A = m_{H^+}$

Type-I:

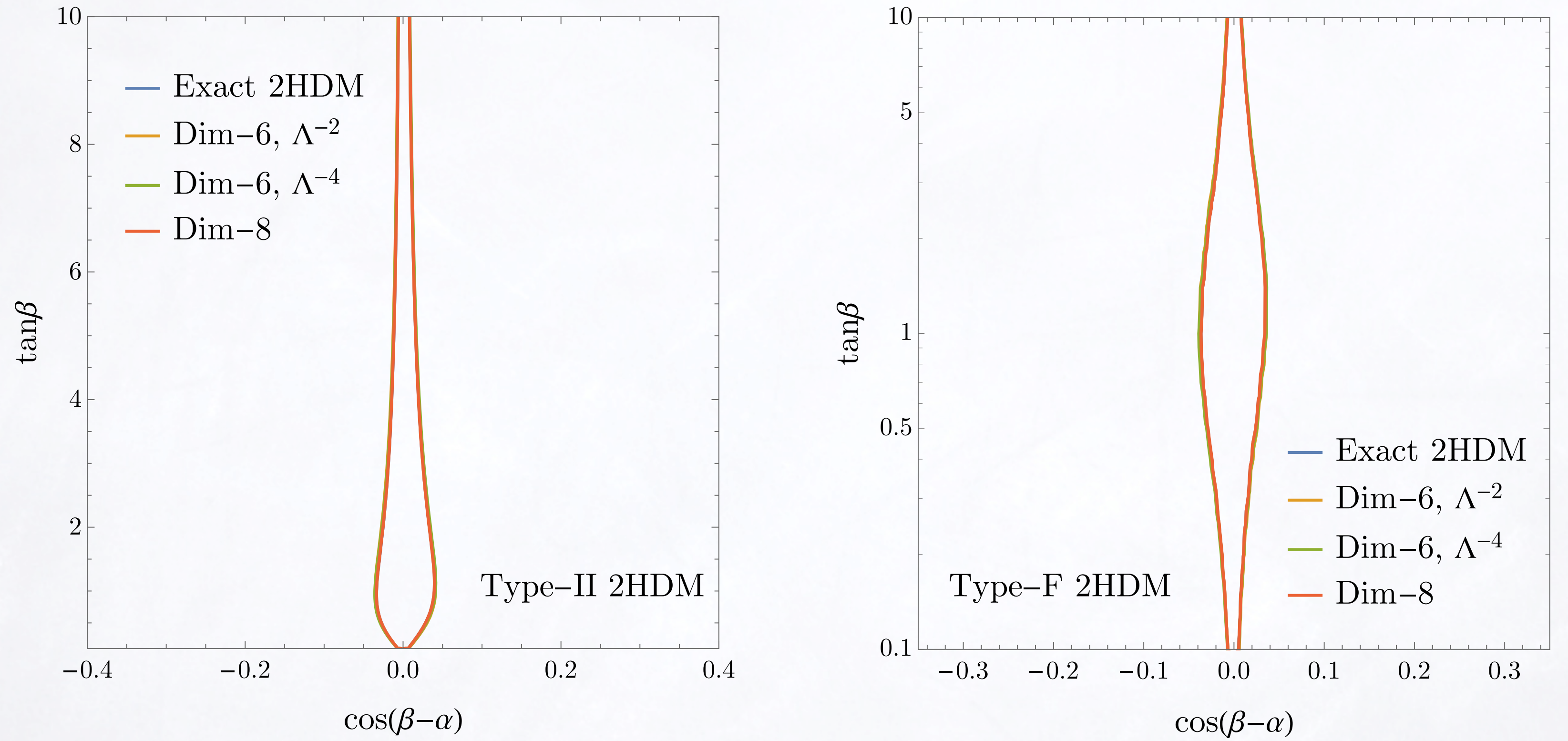


- For high $\tan\beta$, the dim-6 results are poorly constrained
  - the only WCs are the Yukawa ones, which in Type-I are $\propto 1/\tan\beta$
- The exact 2HDM has more info than Yukawas

  gauge-Higgs interactions
- But that info is contained in the dim-8 results

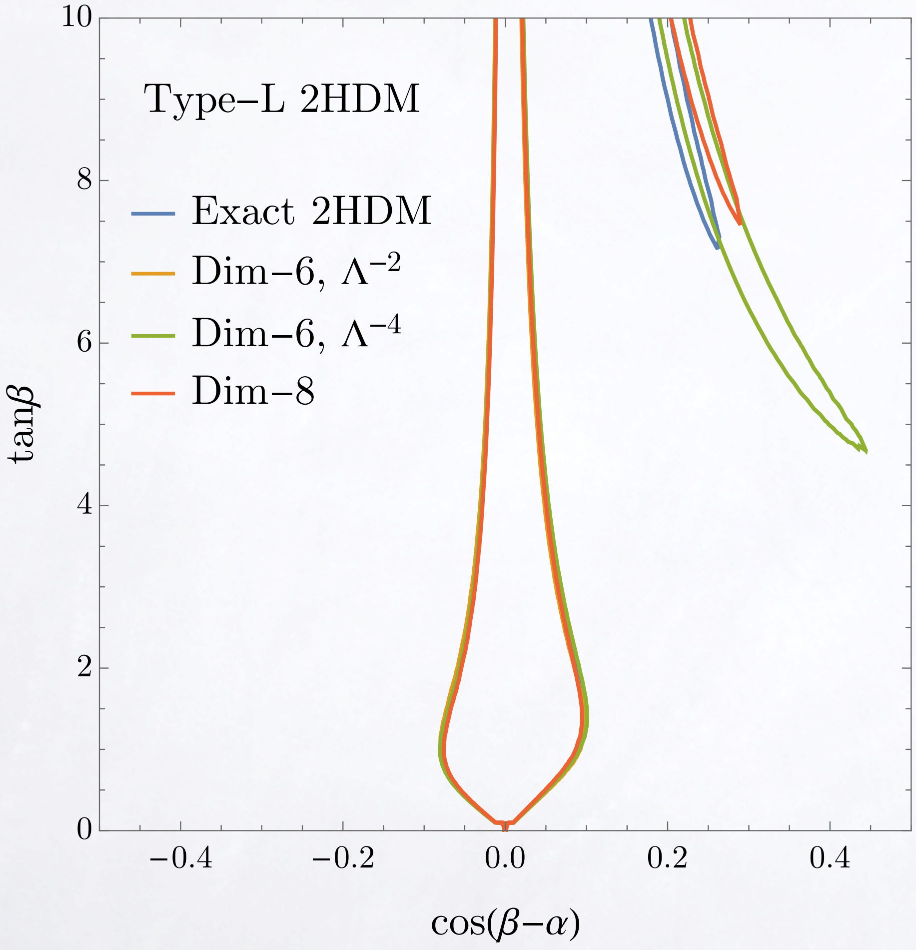
  $$S_{\rm all,8} \ni C^{(1)}_{\mathcal{H}^6} (\mathcal{H}^\dagger \mathcal{H})^2 (D_\mu \mathcal{H})^\dagger (D^\mu \mathcal{H})$$
- The dim-8 EFT is thus a good reproduction of the exact model – whereas dim-6 is clearly insufficient for some regions

- Type-II and Type-F:



- In these models, there is at least one of the Yukawas scales with $\tan\beta$
- 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

- Now the HEFT. Here, we start from the 2HDM after SSB, and only then do we perform the integration out of heavy states
- We've seen that, given our choice of independent parameter, the HEFT will also follow the power counting in ξ , such that $m_H^2 = \Lambda^2 + \Delta m_H^2, \quad v^2/\Lambda^2 \sim \mathcal{O}(\xi), \quad c_{\beta-\alpha} \sim \mathcal{O}(\xi)$
- But why? Can't we simply ignore the scaling of $c_{\beta-\alpha}$ and perform an expansion simply in inverse powers of the heavy physical masses?
  - Let us consider the h^3 interaction
  - Like any other 3-point function, the interaction in the HEFT Lagrangian is obtained trivially from the same interaction in the 2HDM one:

$$\mathcal{L}_{\text{2HDM}} = \underbrace{\_\_ H^2}_{\text{2-point}} + \underbrace{\_\_ Hh^2 + \_\_ HW^\mu W_\mu + \ldots}_{\text{3-point}} \quad \Longrightarrow \quad \text{EoM: } H = \underbrace{\_\_ h^2 + \_\_ W^\mu W_\mu + \ldots}_{\text{2-point}}$$

So, replacing the the solution of the EoM in $\mathcal{L}$ generates at least 4-point functions

Hence, a certain 3-point function in the HEFT Lagrangian is obtained simply by:

a) considering the same interaction in the 2HDM Lagrangian,

b) applying the EFT expansion

- Now, the h^3 interaction in the 2HDM with our independent parameters reads:

$$\frac{3i\csc^2(2\beta)}{2v}\Big\{ s_{\beta-\alpha}\cos(4\beta)\Big[-3c_{\beta-\alpha}^4 m_H^2 - 2c_{\beta-\alpha}^2 Y_2 + \big(3c_{\beta-\alpha}^4 + c_{\beta-\alpha}^2 + 1\big)\, m_h^2\Big] + c_{\beta-\alpha}^3 \sin(4\beta)$$
$$\times\Big[\big(1-3c_{\beta-\alpha}^2\big)\, m_h^2 + \big(3c_{\beta-\alpha}^2 - 2\big)\, m_H^2 + 2Y_2\Big] + s_{\beta-\alpha}\Big[2c_{\beta-\alpha}^2 Y_2 - c_{\beta-\alpha}^4 m_H^2 + \big(c_{\beta-\alpha}^4 - c_{\beta-\alpha}^2 - 1\big)\, m_h^2\Big]\Big\}$$

  - But since this rule scales with *positive* powers of m_H, we can't just expand in $1/m_H$
  - Conversely, if we apply the ξ scaling (according to which $c_{\beta-\alpha}$ scales), h^3 is well behaved
- Hence, we describe HEFT using the power counting in ξ
- Just as h^3, all the 3-point functions are obtained trivially from the 2HDM ones
- For >3-point, however, we need to integrate out the three heavy states:
  - We write the Lagrangian by separating the light (i.e. SM) fields from the heavy (i.e. BSM) ones:

$$\mathcal{L}_{\text{2HDM}} \supset \frac{1}{2}(\partial_\mu H^a)^2 - \frac{1}{2}(M^2)^{ab} H^a H^b + J_0 + J_1^a H^a$$
$$+ J_2^{ab} H^a H^b + J_3^{abc} H^a H^b H^c + J_4^{abcd} H^a H^b H^c H^d,$$

where J_k only has light (i.e. SM) fields, and H^a only heavy (i.e. BSM) ones:

$$H^a = (H,\ A,\ H_3,\ H_4), \ \ \text{with} \ \ H^\pm \equiv (H_3 \mp i H_4)/\sqrt{2}$$

- Each physical heavy scalar H^a is integrated out at tree-level by solving its EoM

- Replacing those solutions back in the 2HDM Lagrangian yields the HEFT Lagrangian for the 2HDM. Comparing with the general HEFT Lagrangian,

$$\mathcal{L}_{\rm HEFT} \supset \frac{v^2}{4}\mathcal{F}(h)\mathrm{Tr}\left\{D_\mu U^\dagger D_\mu U\right\} + \frac{1}{2}(\partial_\mu h)^2 - V(h), \qquad \mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots, \qquad V(h) = \frac{1}{2}m_h^2 h^2\left(1 + d_3\frac{h}{v} + \frac{d_4}{4}\frac{h^2}{v^2} + \ldots\right)$$

we find the HEFT matching expressions:

N.B.: the matching in general requires higher order terms in the derivative expansion. I do not show them.

$$\begin{aligned}
\Delta a^2 \equiv a^2 - 1 &= -c_{\beta-\alpha}^2\,,\\
\Delta b \equiv b - 1 &= -3c_{\beta-\alpha}^2 + 4c_{\beta-\alpha}^2\frac{\Delta m_H^2}{\Lambda^2} + \mathcal{O}(\xi^4)\,,\\
\Delta d_3 \equiv d_3 - 1 &= -2c_{\beta-\alpha}^2\frac{\Lambda^2}{m_h^2} + \frac{1}{2}c_{\beta-\alpha}^2 + c_{\beta-\alpha}^3\left[-\cot(2\beta)\left(1 - \frac{2\Delta m_H^2}{m_h^2}\right) + 2c_{\beta-\alpha}\cot^2(2\beta)\frac{\Lambda^2}{m_h^2}\right] + \mathcal{O}(\xi^4)\,,\\
\Delta d_4 \equiv d_4 - 1 &= -12c_{\beta-\alpha}^2\frac{\Lambda^2}{m_h^2} + c_{\beta-\alpha}^2\left(\frac{16\Delta m_H^2}{m_h^2} - 11\right)\\
&\quad + c_{\beta-\alpha}^2\left[2c_{\beta-\alpha}^2\frac{\Lambda^2}{m_h^2}\left(22\cot^2(2\beta) - 17\right) - 22c_{\beta-\alpha}\cot(2\beta)\left(1 - \frac{2\Delta m_H^2}{m_h^2}\right)\right.\\
&\qquad\left. + 16\frac{\Delta m_H^2}{\Lambda^2}\left(\frac{2 - \Delta m_H^2}{m_h^2}\right)\right] + \mathcal{O}(\xi^4)\,.
\end{aligned}$$

- We considered the HEFT matching up to $\mathcal{O}(\xi^3)$, whereas the SMEFT one up to $\mathcal{O}(\xi^2)$

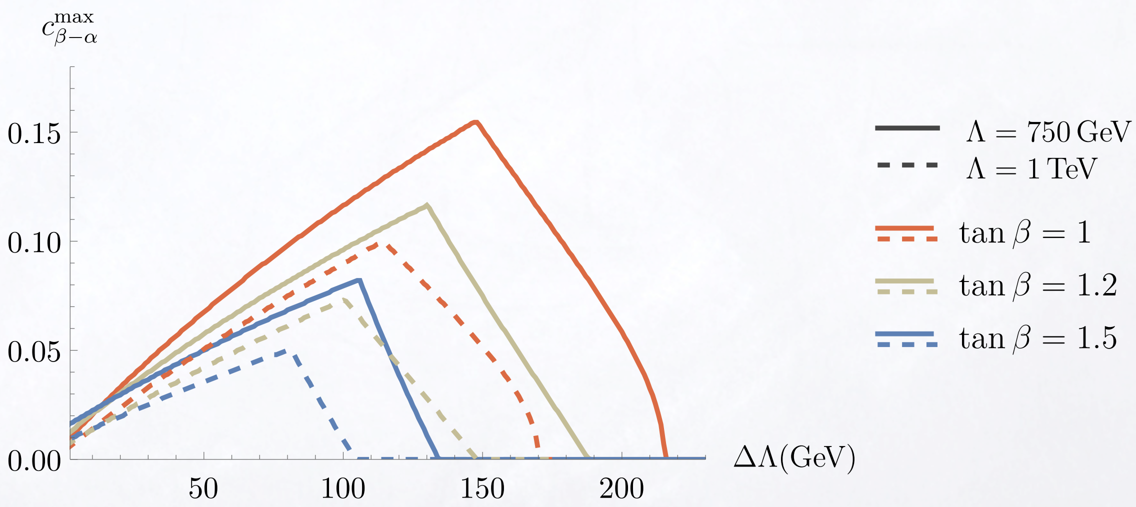
- In what follows, we still assume that the heavy masses are degenerate, but such that:

$$m_H = m_A = m_{H^+} = \Lambda + \Delta\Lambda$$

Since $Y_2 = \Lambda^2$ and $m_A^2 = Y_2 + f_A(Z_j)\,v^2$, $m_{H^+}^2 = Y_2 + f_{H^+}(Z_j)\,v^2$, the new parameter $\Delta\Lambda$ measures the amount of mass in m_A, m_{H^+} that comes from the vev

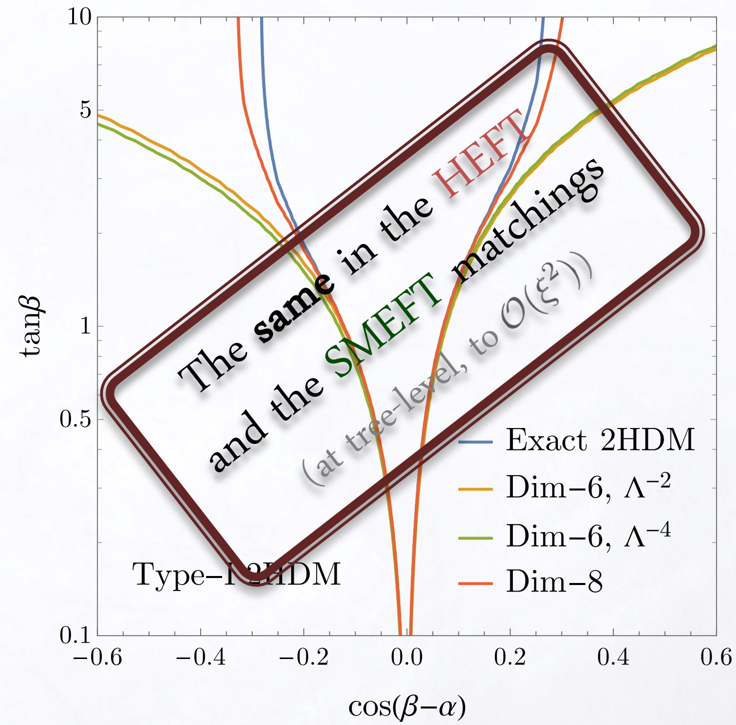
- We require the 2HDM to obey theoretical constraints of perturbativity, boundedness from below and EW precision measurements via S, T, U
    - What is the impact of these contraints on the 2HDM parameter space?

- For these large values of Λ , the 2HDM is forced to be close to the alignment limit
- Larger values of Λ (or of $\tan\beta$) would require even narrower a window of $c_{\beta-\alpha}^{\max}$
- In all curves, the segment with positive slope is constrained by boundedness from below, whereas that with negative slope by perturbativity



- The 2HDM parameter space is also contrained from experiments, especially Higgs couplings measurements, b meson decays and searches for heavy Higgses $\Longrightarrow$ $\boxed{\tan\beta = 1.2}$

- We now compare the (tree-level) SMEFT and HEFT matchings to the 2HDM at $\mathcal{O}(\xi^2)$
  - Recall that, since we require the 2HDM to have decoupling, the SMEFT and the HEFT matchings follow the same power-counting
  - Hence, even if they are structurally different, their results end up being very similar
  - For example, the couplings hVV and $h\bar{f}f$ are the **same** in both approaches to $\mathcal{O}(\xi^2)$, as are the one-loop processes $gg \to h$ and $h \to \gamma\gamma$
    - So, the fits to global Higgs signal strenghts are the **same** in the two approaches

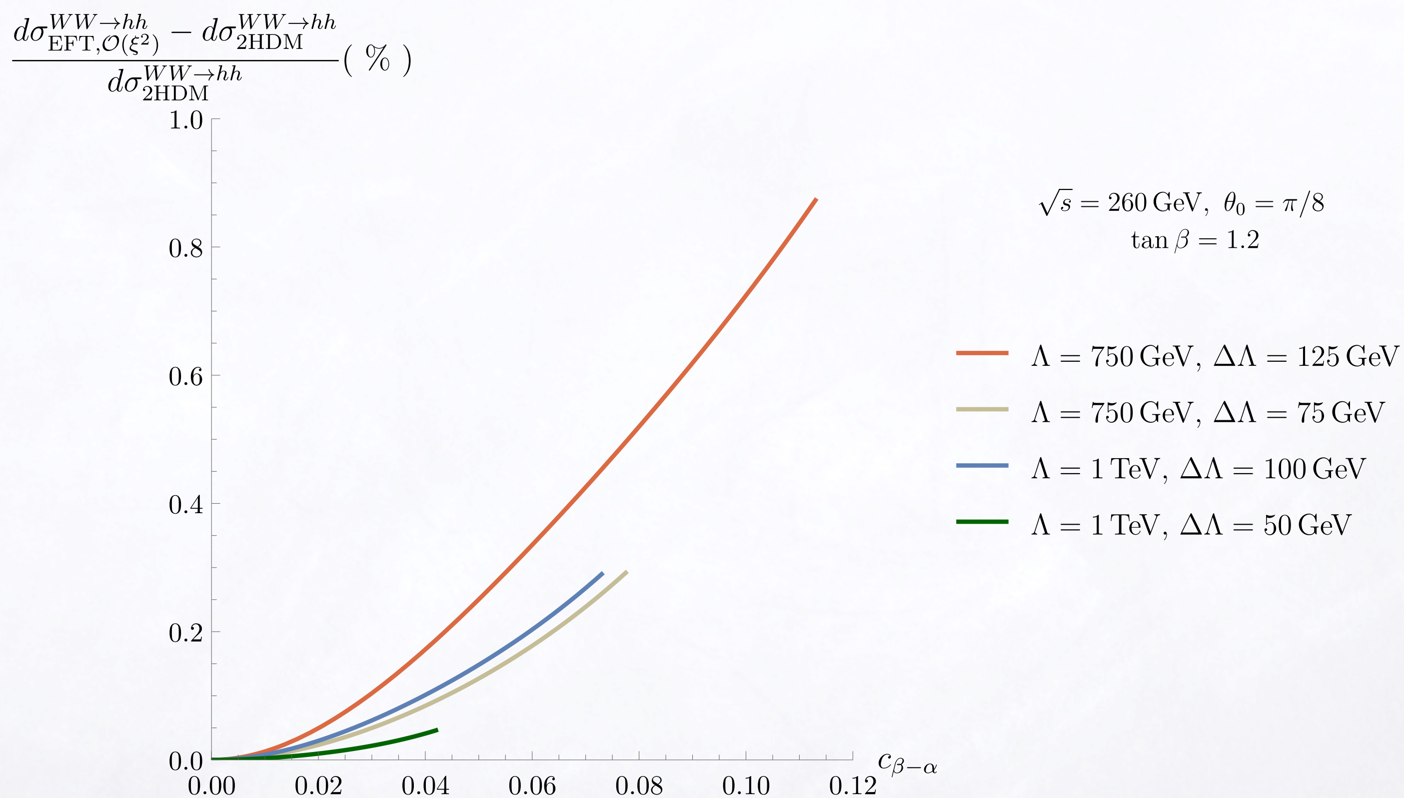


  - Actually, the tree-level scatterings $WW \to hh$ and $hh \to hh$ are also the **same** at $\mathcal{O}(\xi^2)$!
    - This holds, even if the individual Feynman diagrams different

i.e. there is a field redefinition from the HEFT to the SMEFT matching

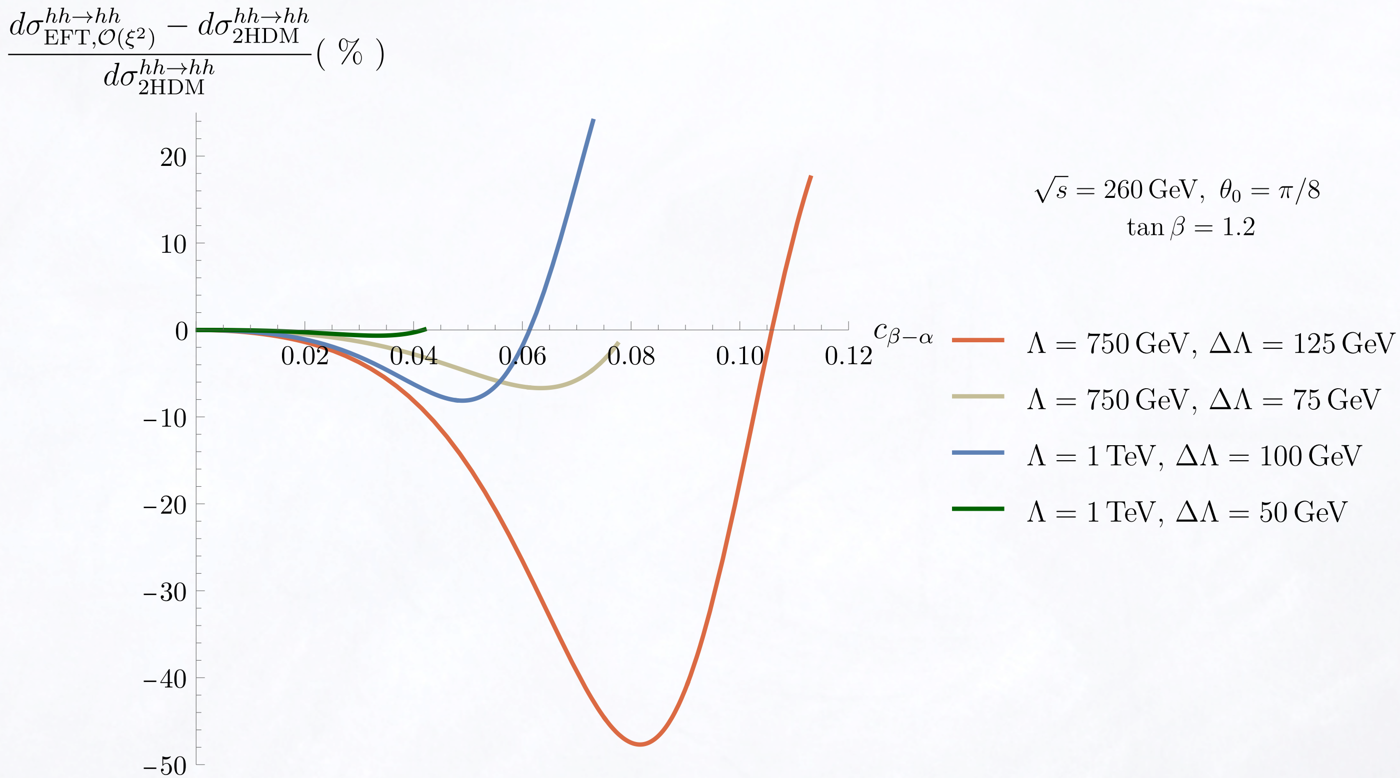
    - In the following, we refer to the two identical matchings at $\mathcal{O}(\xi^2)$ simply as the EFT matching

- Let's start with $WW \to hh$. Using the short notation $d\sigma \equiv \frac{d\sigma}{d\theta}|_{\theta=\theta_0}$, and showing only the range of (positive values of) $c_{\beta-\alpha}$ allowed by the theoretical constraints, we find:



- The EFT matching reproduces the 2HDM quite well, with relative differences below 1%

- The case $hh \to hh$ is very different:

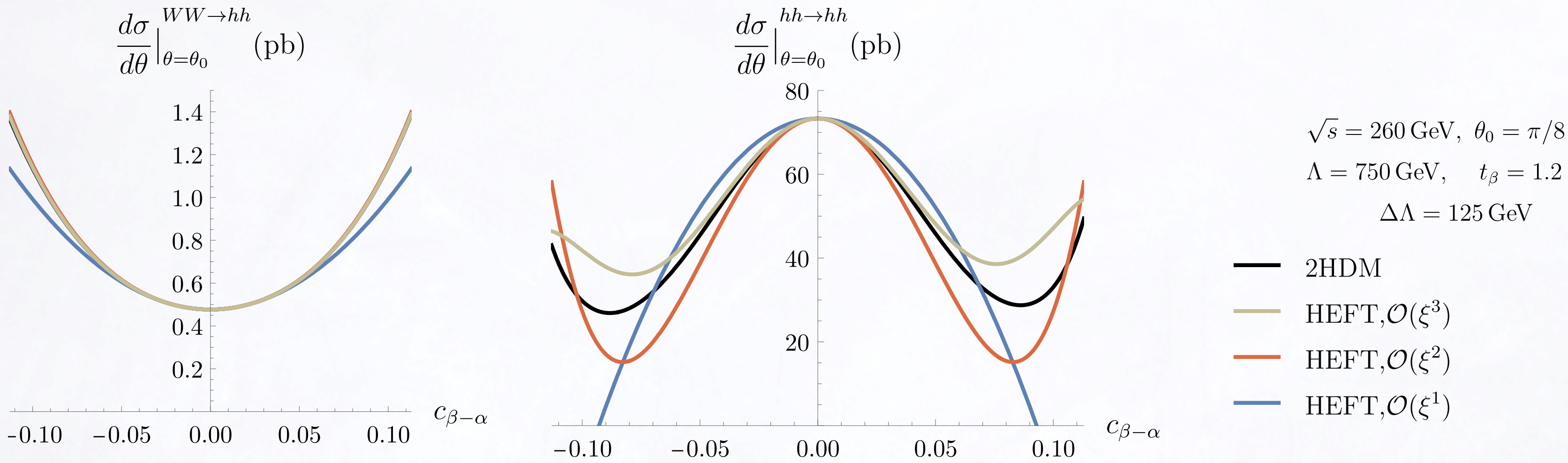


- There are regions where the relative differences (in modulus) is >40%

- In these regions, therefore, $\mathcal{O}(\xi^2)$ is not enough to faithfully replicate the 2HDM results

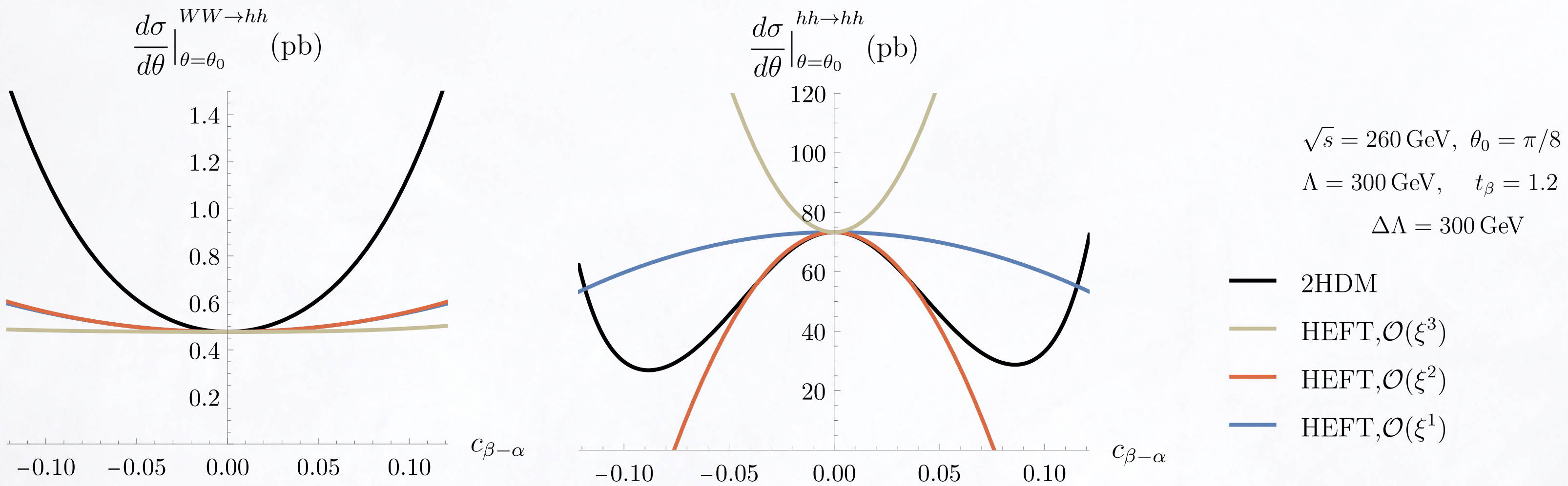
in terms of SMEFT operators, this means that even dim-8 operators are not enough!

- We can present the results for both $WW \to hh$ and $hh \to hh$ in a different way:



  - The plots show the HEFT matching now, which we performed up to $\mathcal{O}(\xi^3)$, but which we are only assured of being equal to the SMEFT one up to $\mathcal{O}(\xi^2)$
  - In both plots, the $\mathcal{O}(\xi^1)$ curve does not replicate the 2HDM result away from $\mathbf{c}_{\beta-\alpha} = \mathbf{0}$
  - But whereas in $WW \to hh$ the $\mathcal{O}(\xi^2)$ curve does, in $hh \to hh$ not quite
    - For larger values of $c_{\beta-\alpha}$ in $hh \to hh$, the ξ expansion is quite slow

- What happens if decoupling is lost?



  - The choice $\Lambda = 300\,\mathrm{GeV}$ is a blatant violation of the decoupling assumption $\Lambda^2 \gg v^2$
  - Hence, even if $m_H = m_A = m_{H^+} = \Lambda + \Delta\Lambda = 600\,\mathrm{GeV}$, the expansion does not converge

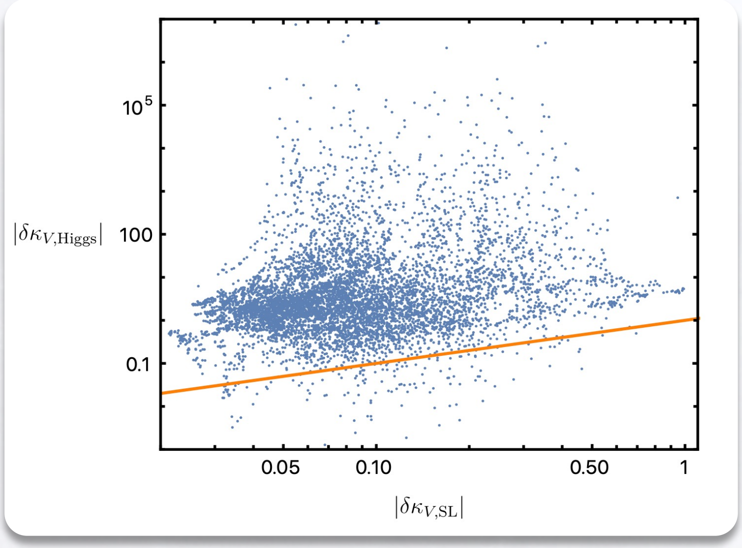
- Recently, two papers proposed alternative EFT approaches to the 2HDM:
- Banta, Cohen, Craig, Lu, Sutherland (arXiv: 2304.09884)
  - The authors propose a novel basis of the 2HDM, as an alternative to the Higgs basis
  - The new basis — straight-line (SL) basis — is such that (the zero-derivative part of) the classical solution of the heavy Higgs doublet is a *linear* function of the light Higgs doublet
    - In the Higgs basis, this is not the case: $Y_2 H_2 = -H_1 Y_3 \underbrace{- Z_6 H_1^\dagger H_1^2 - \frac{\eta_f}{\tan\beta}\bar{f}_R Y_f f_L}_{\text{non-linear}}$
  - The EFT is then obtained by integrating out the heavy doublet of the SL basis
  - The EFT is both SMEFT-like and not:
    - It is SMEFT-like, in the sense that it is the whole doublet that is integrated out
    - It is not SMEFT-like, in the sense that:

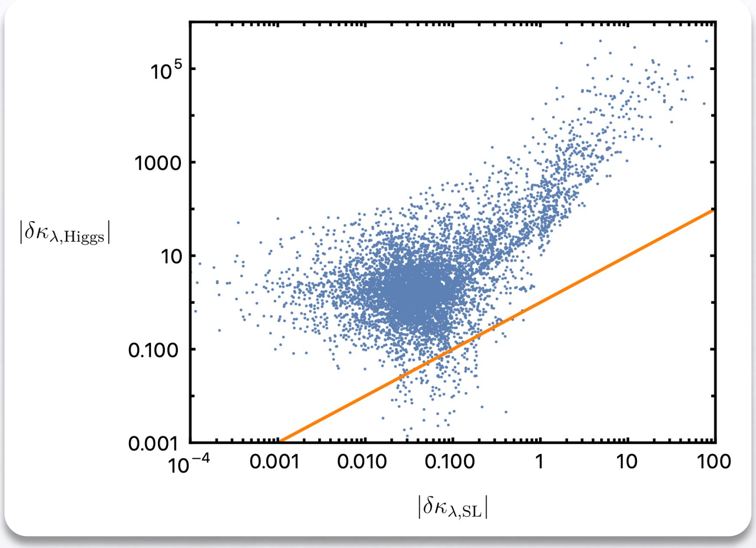
      a) it has its own power-counting, very different from the SMEFT one

      b) the trivial order of the EFT expansion does not correspond to the SM

- In the decoupling limit, the SL-basis EFT and the Higgs-basis EFT are equivalent
- In general, however, the SL-basis EFT replicates the 2HDM much faster
    - Defining κ_V as the shift in the hWW coupling, and κ_λ as the shift in the h^3 coupling, such that

$$\delta\kappa_{i,\mathrm{EFT}} \equiv \frac{\kappa_{i,\mathrm{EFT}} - \kappa_{i,\mathrm{UV}}}{\kappa_{i,\mathrm{UV}} - 1}$$, they find:





Yet, since the SL-basis EFT is not SMEFT-like in the sense described above, how can it be matched to the WCs of a bottom-up SMEFT approach used at the LHC?

And if it cannot, how useful is it?

- Arco, Domenech, Herrero, Morales (arXiv: 2307.15693)
  - The authors perform a HEFT approach to the 2HDM, but without Y_2 as independent
  - Instead, they use m_{12}^2, a parameter of the original basis (to which the Z_2 symmetry is applied):

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{ h.c. } \right] + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right)$$
$$+ \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{ h.c. } \right] + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \text{ h.c. } \right]$$

  - With this parameter, the h^3 interaction reads:

$$s_{\beta-\alpha} \left(1 + 2c_{\beta-\alpha}^2\right) \frac{m_h^2}{2} - s_{\beta-\alpha} c_{\beta-\alpha}^2 \frac{m_{12}^2}{s_\beta c_\beta} + c_{\beta-\alpha}^3 \cot 2\beta \left(m_h^2 - \frac{m_{12}^2}{s_\beta c_\beta} \right)$$

    so that it does not scale with positive powers of the heavy masses. Hence, one can build a consistent expansion simply in inverse powers of the heavy masses, without scaling $c_{\beta-\alpha}$
  - The result is a consistent HEFT, very different from — and much more quickly convergent to the 2HDM than — the one proposed above (which was equivalent to SMEFT)

What happens at loop level? Doesn't this scaling lead to an inconsistent expansion?

- Conclusions:
  - I discussed EFT approaches to the 2HDM, focusing on the SMEFT and the HEFT
  - Requiring the 2HDM to have decoupling (and perturbativity), I obtained an expansion in ξ which I applied to both the SMEFT and the HEFT matchings
  - Choosing Y_2 and $c_{\beta-\alpha}$ as independent, we must take into account that $c_{\beta-\alpha} \sim \mathcal{O}(\xi)$
  - I performed the SMEFT and the HEFT matchings to $\mathcal{O}(\xi^2)$ at tree-level...

    ... and found <u>no differences</u> between the two approaches
  - For the LHC Higgs signal strength fits, dim-6 operators are enough, except in some regions in Type-I and Type-L, where dim-8 operators do become important
  - I studied $WW \to hh$ and $hh \to hh$ at $\mathcal{O}(\xi^2)$. Whereas the former replicates the 2HDM results for all the allowed range of $c_{\beta-\alpha}$, the latter does not
  - The expansion in ξ clearly does not converge if decoupling is lost
  - I discussed recent alternative EFT approaches to the 2HDM

- We considered the HEFT matching up to $\mathcal{O}(\xi^3)$, whereas the SMEFT one up to $\mathcal{O}(\xi^2)$. This is because the HEFT approach is much simpler to implement (for our purposes)

  - In the SMEFT approach, higher order terms contain the scalar doublet, which includes the vev. Hence, 2-point functions are in general affected

    (which means that kinetic terms and relations between masses and Lag. parameters need to be redefined)

    In the HEFT approach, this never happens, for the integration out of heavy states affects only >3-point functions, as seen before

  - Besides, 3-point function in the HEFT approach are trivially obtained, but not in the SMEFT one

  - For simple processes (as the ones considered here), the HEFT results can be obtained starting from the Feynman diagrams for the 2HDM, and applying the ξ expansion