

Is the HEFT matching unique?

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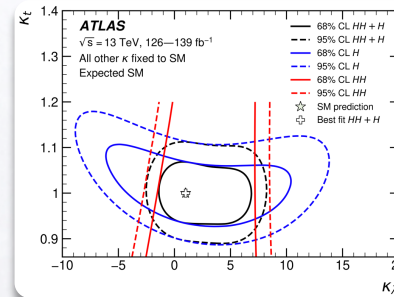
7th General Meeting of the LHC EFT Working Group, CERN

- 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, by looking for deviations from the SM — in a **model-independent** way

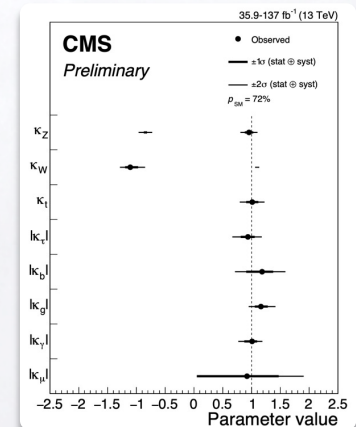
- A usual approach is the **kappa formalism**: [David et al, 1209.0040]
[Heinemeyer et al, 1307.1347]

- 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 :

$$\frac{\sigma_{\text{ggH}}}{\sigma_{\text{ggH}}^{\text{SM}}} = \kappa_g^2, \quad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\text{SM}}} = \kappa_\gamma^2, \quad \frac{\Gamma_{ff}}{\Gamma_{ff}^{\text{SM}}} = \kappa_f^2, \quad \dots$$
- 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**

$$\mathcal{L}_{\text{eff}} = \mathcal{O}(\Lambda^0) + \frac{E}{\Lambda} \mathcal{O}_1 + \left(\frac{E}{\Lambda}\right)^2 \mathcal{O}_2 + \left(\frac{E}{\Lambda}\right)^3 \mathcal{O}_3 + \dots$$

- Consistent Quantum Field Theory for **heavy** BSM, i.e., for small E/Λ
- At each order in E/Λ , all terms consistent with the symmetries are included
- Renormalizable order by order; higher and higher orders become less and less relevant
- It is a general description, that can later be matched to particular BSM models
- Was not mature at LHC Run 1

- Two main **EFT** candidates for **Higgs physics**: **SMEFT** and **HEFT**

- The **SMEFT** takes the SM before SSB and generalizes it: $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}$

SMEFT coefficients

- 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 3 Goldstone bosons are independent of the Higgs, which is a **gauge singlet**
 π^I , imbedded into $U = \exp(i\tau^I \pi^I / v)$ h (instead of part of an SU(2) doublet)
- There is an expansion in the number of (covariant) derivatives. At LO:

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

with:

$$\mathcal{F}(h) = 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \dots, \quad V(h) = \frac{1}{2} m_h^2 h^2 \left(1 + \kappa_3 \frac{h}{v} + \frac{\kappa_4}{4} \frac{h^2}{v^2} + \dots \right)$$

HEFT coefficients

(such that the SM corresponds to $a = b = \kappa_3 = \kappa_4 = 1$)

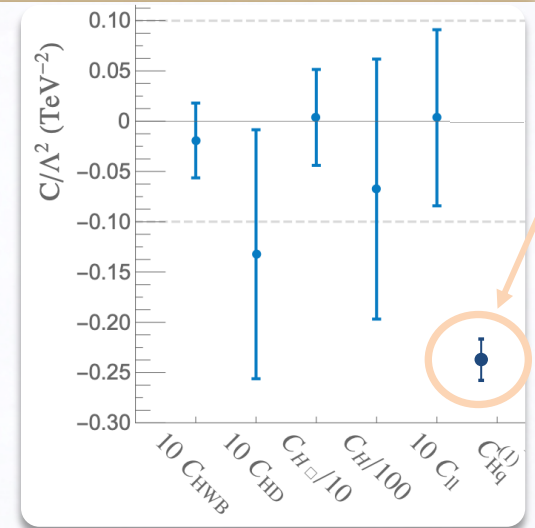
- Because the Higgs is a **gauge singlet**, it has arbitrary couplings: e.g. κ_3 and κ_4 are independent (whereas in the LO **SMEFT** they are related, since h is contained in a doublet)
- The organization of **HEFT** is subtle, since χPT and **SMEFT** have different organizations

- Ultimate goal of any **EFT** framework for BSM physics:

1) Find a pattern of non-zero **EFT coefficients**: ----->

2) Convert (or **match**) them to a **particular BSM model**:

$$\text{BSM1: } C_{Hq}^{(1)} = 2 \sin(\alpha), \quad \text{BSM2: } C_{Hq}^{(1)} = \frac{1}{4} \cos(\beta), \quad \dots$$



- With the matching, we would convert a constraint on an **EFT coefficient** into a constraint on the **parameters** of the **BSM models** (all at once):

$$\text{For } C_{Hq}^{(1)} \simeq -0.24, \text{ then: } \quad \text{BSM1: } \sin(\alpha) \simeq -0.12, \quad \text{BSM2: } \cos(\beta) \simeq -0.06, \quad \dots$$

- The **EFT**, then, is just a tool, and never the ultimate answer
- The matching is thus a crucial part of the **EFT** framework (without it, the EFT is in vain!)
- Even without non-zero **EFT coefficients**, we should understand how matching works

- Understanding matching:

- Recipe:

1. Choose a set of independent **parameters** in the **full theory**
2. Define a small quantity (ξ) to organize the to-be-built **EFT** expansion
3. Decide how each of the independent **parameters** scales with ξ
4. Equate specific amplitudes in the **full theory** and **EFT** order by order in ξ

- If we knew the values of the **parameters**, we would know how to scale them e.g. $\sin(\alpha) \sim \mathcal{O}(\xi^0)$

- But since we do not, we may consider multiple **possibilities** $\sin(\alpha) \sim \mathcal{O}(\xi^0)$ *or* $\sim \mathcal{O}(\xi^1)$ *or* ...

- Each possibility will lead to different expansions or **power countings (PCs)**

- I will consider two **particular BSM models** to be matched to the **HEFT**:

- The real singlet extension of the SM with a Z2 symmetry (Z2RSE)

- The 2 Higgs Doublet Model (2HDM)

(and we will only consider regions allowed
by theoretical and experimental constraints)

- For each of them, we will consider 3 different **PCs**, which differ in how they scale the **parameters**

- The goal is to find the best PC — the fastest to converge to the **BSM model**

- The Z2RSE in a nutshell:

- Add a scalar singlet S to the SM, subject to a Z2 symmetry: $S \rightarrow -S$. The potential reads:

$$V = -\frac{\mu_1^2}{2} \phi^\dagger \phi - \frac{\mu_2^2}{2} S^2 + \frac{\lambda_1}{4} (\phi^\dagger \phi)^2 + \frac{\lambda_2}{4} S^4 + \frac{\lambda_3}{2} \phi^\dagger \phi S^2$$

- The **parameters** $\mu_1^2, \mu_2^2, \lambda_1, \lambda_2, \lambda_3$ are all real, and the fields can be written as:

$$\phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + h_1 + iG_0) \end{pmatrix}, \quad S = \frac{v_s + h_2}{\sqrt{2}}$$

- h_1, h_2 are not yet mass states; they can be diagonalized via a mixing angle χ

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\chi & -s_\chi \\ s_\chi & c_\chi \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

- The fields h, H are then mass states, with masses m, M , respectively
- We can use the relations of the theory to choose two different sets of indep. **parameters**:

- SET_R1: v, m, v_s, M, s_χ

- SET_R2: v, m, μ_2^2, M, s_χ

- For a HEFT approach, we assume $M \gg m$, so that we integrate out H (and we are left with the d.o.f. of the SM after SSB)
- It is then clear that m/M should be small — say, $\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi)$
- But what about the other **parameters**? We consider 3 different **PCs**:

- PC_1^{R} takes SET_R1 as the set of independent **parameters**, and imposes:

$$\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi), \quad \left(\frac{m}{v_s}\right)^2 \sim \mathcal{O}(\xi), \quad s_\chi^2 \sim \mathcal{O}(\xi) \quad (\text{and all the others are } \mathcal{O}(\xi^0))$$

- PC_2^{R} takes SET_R1 as the set of independent **parameters**, and imposes:

$$\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi) \quad (\text{and all the others are } \mathcal{O}(\xi^0))$$

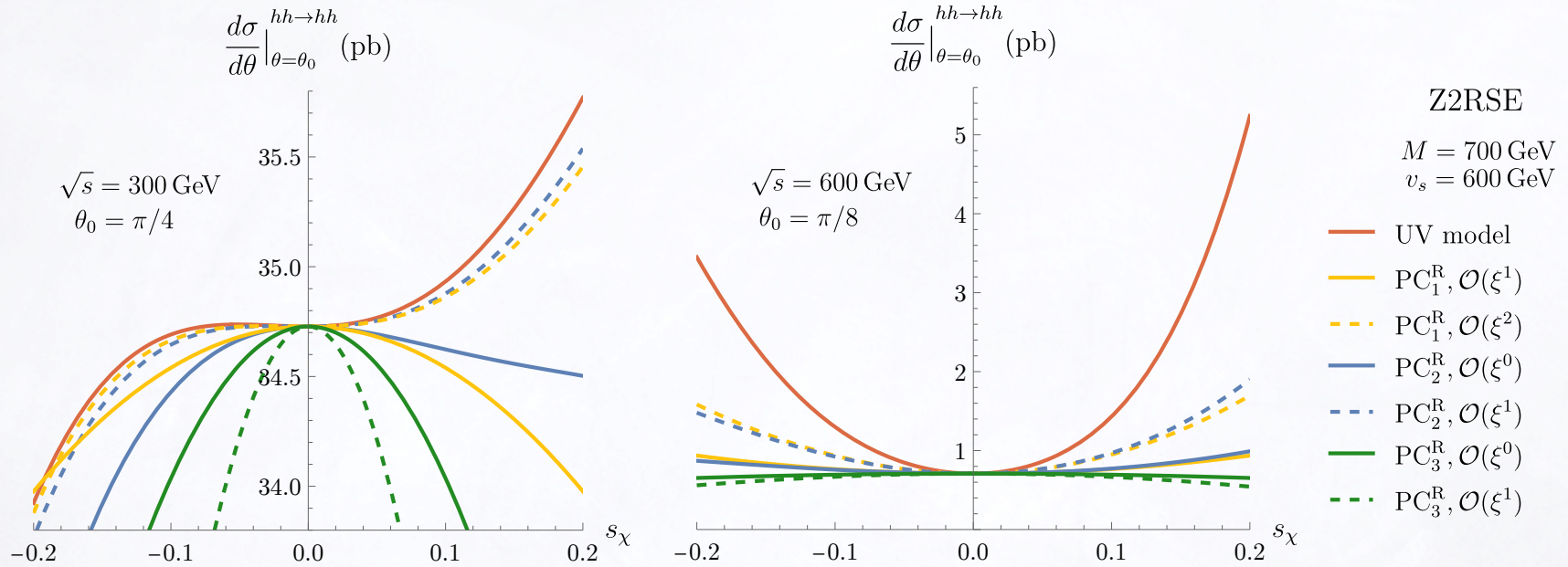
- PC_3^{R} takes SET_R2 as the set of independent **parameters**, and imposes:

$$\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi) \quad (\text{and all the others are } \mathcal{O}(\xi^0))$$

- Example of **matching** for $\mathcal{L}_{\text{HEFT}} \ni -\kappa_3 m_h^2 \frac{h^3}{2v}$. Defining $\Delta\kappa_3 \equiv \kappa_3 - 1$, we find:

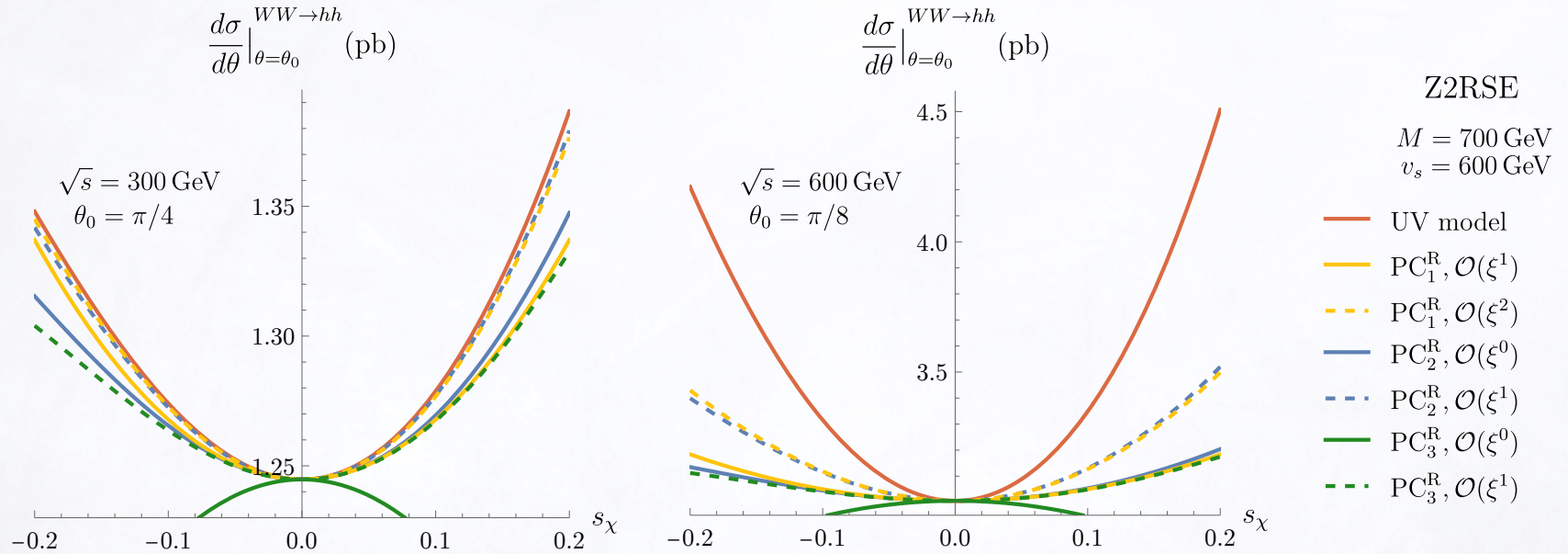
	PC_1^{T}	PC_2^{T}	PC_3^{T}
$\Delta\kappa_3$	$-\xi \frac{3s_\chi^2}{2}$ $+\xi^2 \frac{s_\chi^3}{8v_s} (3s_\chi v_s - 8v)$	$c_\chi^3 - \frac{s_\chi^3 v}{v_s} - 1$	$-1 + c_\chi - \xi \frac{s_\chi^2}{M^2 c_\chi} (m^2 - \mu_2^2)$ $-\xi^2 \frac{m^2 s_\chi^2}{M^4 c_\chi} (m^2 - \mu_2^2)$

- Numerical results for the differential cross section of $hh \rightarrow hh$:



- Close to $s_\chi = 0$, everything works. Elsewhere, there are significant differences
- In particular, even if PC_2^R and PC_3^R only differ by μ_2^2 vs. v_s , PC_2^R is much more accurate
- PC_2^R is the best (quickest to converge) PC, for the entire range of s_χ
- In the right panel, the EFT assumption starts to break down

- Numerical results for the differential cross section of $WW \rightarrow hh$:



- Similar conclusions in a different process
- Clearly, then, even if there are several PCs, PC_2^R is the way to go

(will this also be the case in the 2HDM?)

- Now, the 2HDM. The model in a nutshell:

- Add a second Higgs doublet to the SM. This leads to:

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

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

$$\mathcal{L}_Y = -\lambda_u^{(1)} H_1^\dagger \hat{q}_L u_R - \lambda_u^{(2)} H_2^\dagger \hat{q}_L u_R - \lambda_d^{(1)} \bar{d}_R H_1^\dagger q_L - \lambda_d^{(2)} \bar{d}_R H_2^\dagger q_L - \lambda_l^{(1)} \bar{e}_R H_1^\dagger l_L - \lambda_l^{(2)} \bar{e}_R H_2^\dagger l_L + \text{h.c.} \quad (\hat{q}_L \equiv -i\sigma_2(\bar{q}_L)^T)$$

where Y_i , Z_j and λ_z are real **parameters**, and where the doublets can be written as:

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

with h the scalar found at the LHC, while H, A, H^+ are BSM scalars, assumed to be heavy

- Avoid FCNC via a Z_2 symmetry \longrightarrow 4 types of 2HDM: Type-I, Type-II, Type-L, Type-F
- Take some of the **parameters** as independent:

$$\text{SET_T1: } c_{\beta-\alpha}, Y_2, m_h, m_H, m_A, m_{H^\pm}, \beta, m_f$$

$$\text{SET_T2: } c_{\beta-\alpha}, m_{12}^2, m_h, m_H, m_A, m_{H^\pm}, \beta, m_f$$

- Let us consider the degenerate case, and define $M \equiv m_H = m_A = m_{H^\pm}$

- The PCs to be studied are: (dimensional terms are normalized to m_h)

- PC₁^T takes SET_T1 as the set of independent parameters, and imposes:

$$Y_2 \sim \mathcal{O}(\xi^{-1}), \quad M^2 = Y_2 + \mathcal{O}(\xi^0) \sim \mathcal{O}(\xi^{-1}), \quad c_{\beta-\alpha} \sim \mathcal{O}(\xi)$$

(and all the others are $\mathcal{O}(\xi^0)$)

- PC₂^T takes SET_T1 as the set of independent parameters, and imposes:

$$Y_2 \sim \mathcal{O}(\xi^{-2}), \quad M^2 \sim \mathcal{O}(\xi^{-2}), \quad c_{\beta-\alpha} \sim \mathcal{O}(\xi)$$

(and all the others are $\mathcal{O}(\xi^0)$)

- PC₃^T takes SET_T2 as the set of independent parameters, and imposes:

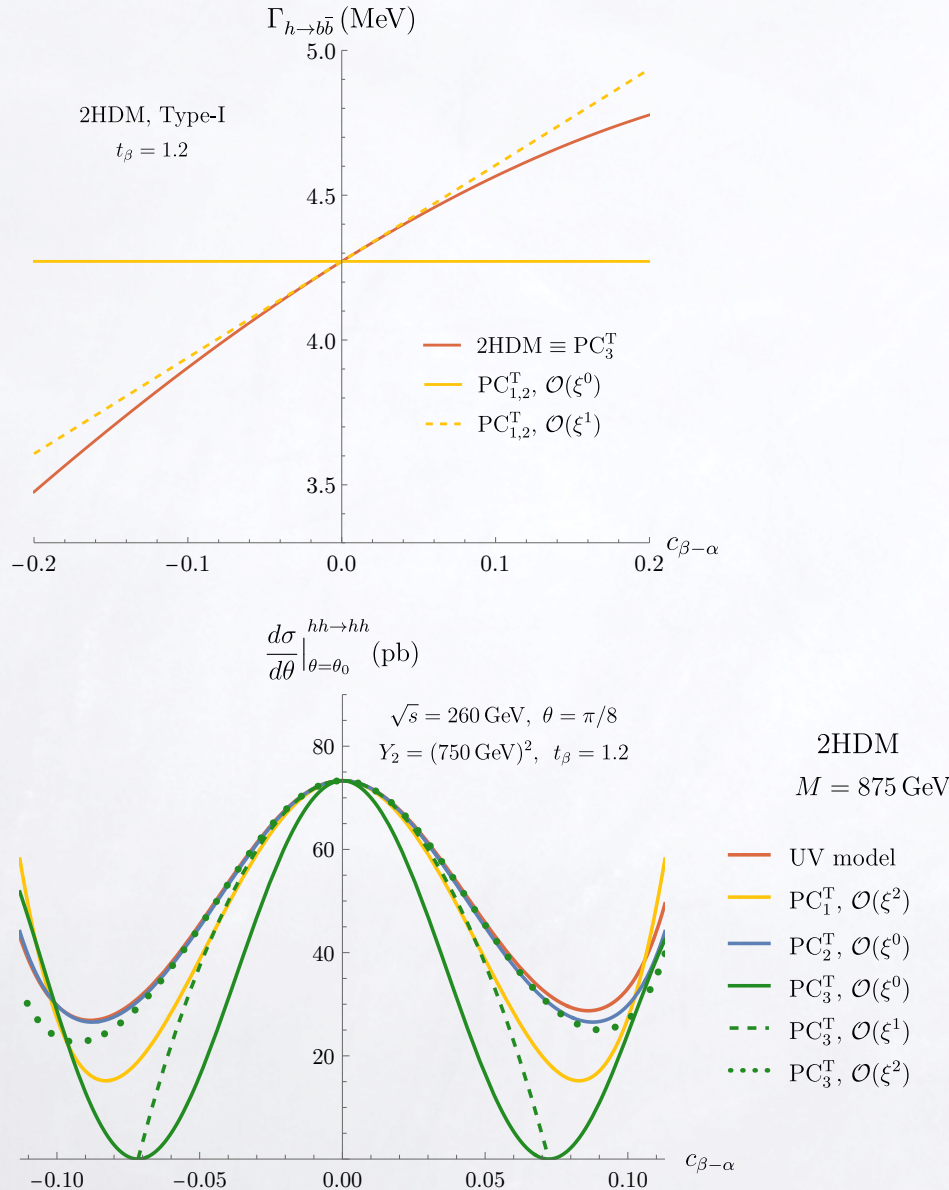
$$M^2 \sim \mathcal{O}(\xi^{-1})$$

(and all the others are $\mathcal{O}(\xi^0)$)

- Example:

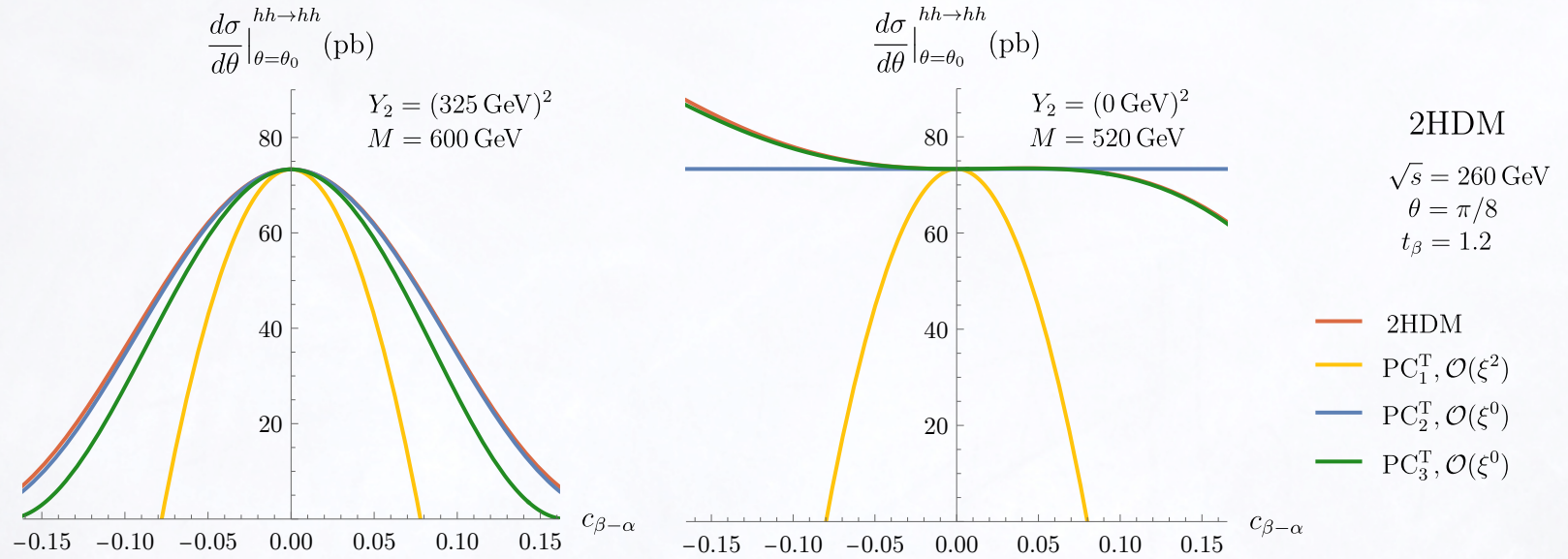
	PC ₁ ^T	PC ₂ ^T	PC ₃ ^T
$\Delta\kappa_3$	$-\xi 2c_{\beta-\alpha}^2 \frac{Y_2}{m_h^2} + \xi^2 \frac{1}{2} c_{\beta-\alpha}^2$	$-\frac{2Y_2 c_{\beta-\alpha}^2}{m_h^2} + \xi \frac{c_{\beta-\alpha}^3}{m_h^2 t_\beta} (t_\beta^2 - 1)(Y_2 - M^2)$ $+ \xi^2 \frac{c_{\beta-\alpha}^2}{2m_h^2 t_\beta^2} \left(c_{\beta-\alpha}^2 \left[M^2 (t_\beta^4 - 4t_\beta^2 + 1) + 2Y_2 t_\beta^2 \right] + m_h^2 t_\beta^2 \right)$	$-1 + s_{\beta-\alpha}(1 + 2c_{\beta-\alpha}^2) + c_{\beta-\alpha}^2 \left[-2s_{\beta-\alpha} m_{12}^2 \right.$ $\left. + 2c_{\beta-\alpha} \cot 2\beta (1 - m_{12}^2) \right]$

Numerical results for two different processes



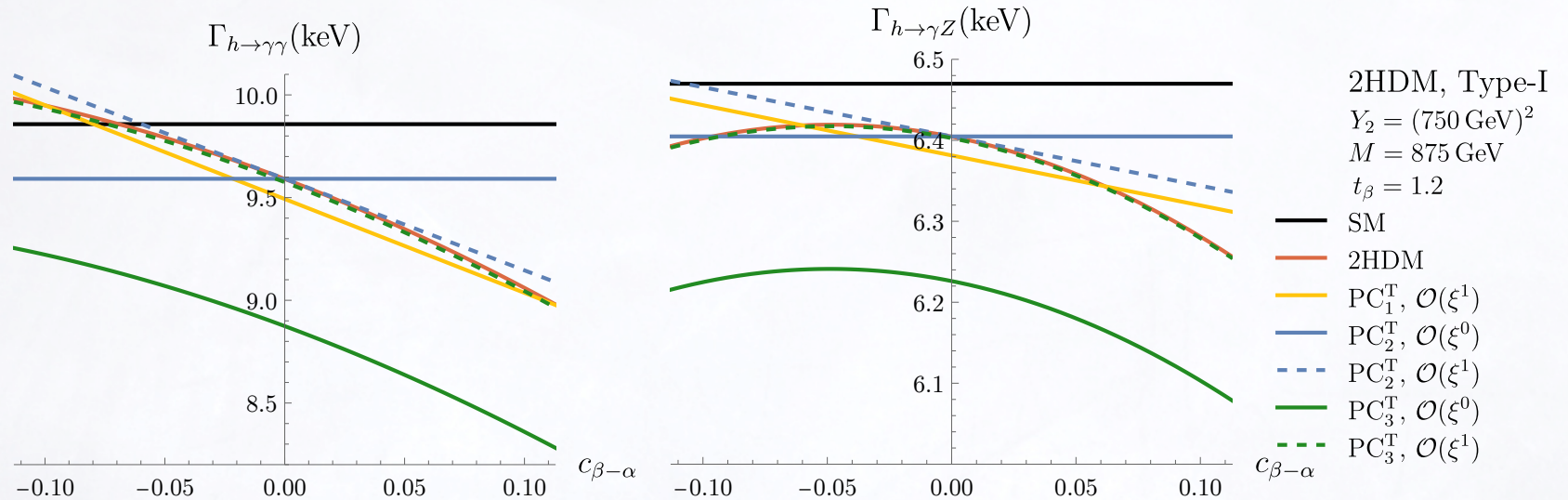
- For an observable like $h \rightarrow b\bar{b}$, PC_3^T is clearly the most convenient, as it is identical to the full model
- PC_1^T and PC_2^T are identical in this case, and they only provide an adequate description at $\mathcal{O}(\xi^1)$
- However, for an observable like $hh \rightarrow hh$, PC_2^T is by far the best choice, providing an excellent replication of the 2HDM result immediately at $\mathcal{O}(\xi^0)$
- PC_3^T can only get closer to that at $\mathcal{O}(\xi^2)$
- Conclusion: according to the process, different PCs should be chosen

- What happens in different regions of parameter space of a certain process?



- In these cases, Y_2 starts to diminish; we thus expect PC_1^T and PC_2^T to fail
- PC_1^T indeed fails. However, in PC_2^T , the scaling of M^2 partially compensates that
- Whereas PC_2^T is still the most adequate PC in the left plot, PC_3^T passes it in the right one
- In sum: the most adequate PC depends not only on the process, but also on the region

• What happens in loop processes?



- In both cases, the SM is not obtained in the 2HDM when $c_{\beta-\alpha} = 0$
 (as the charged Higgs contributions are generally non-zero in that limit)
- PC_1^T is a reasonable description of the 2HDM at $\mathcal{O}(\xi^1)$
 (even though it only has a linear dependence on $c_{\beta-\alpha}$)
- PC_3^T is quite deviated at $\mathcal{O}(\xi^0)$, but provides an excellent replication of the 2HDM at $\mathcal{O}(\xi^1)$
- PC_2^T is not as accurate

- **EFTs** are a consistent and general approach to **BSM models**
- Yet, they are but a tool, that requires matching the EFT **coefficients** to **particular BSM models**
- The **matching** is built based on assumptions about the size of the **parameters** of the **model**
- Since we do not know the sizes, we can consider multiple possibilities or **power countings (PCs)**
- I considered the **HEFT**, and discussed its **matchings** of both of the **Z2RSE** and the **2HDM**
- In both cases, we presented three different **PCs** — leading to three different **matchings**
(the HEFT matching is not unique!)
- In the **Z2RSE**, one of the **PCs** was always preferred
- In the **2HDM**, by contrast, the most adequate **PC** depended on the process and region
- This complicates the interpretation of **HEFT coefficients** in terms of **parameters** of **UV models**