When EFT for new physics is not linear

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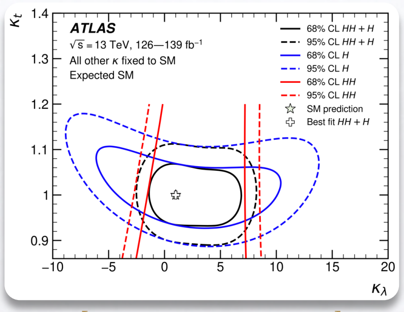
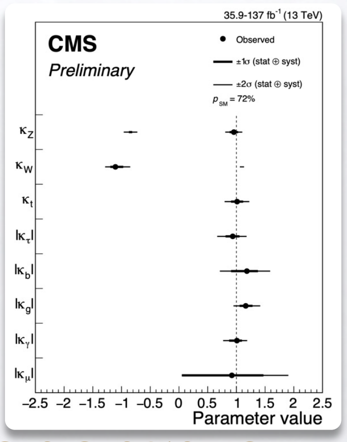
April 25th, 2024

LPC EFT Workshop, Notre Dame, IN

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

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

  - 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 (Standard Model Effective Field Theory) 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: $C_i^{(d)}$)

- The HEFT (Higgs Effective Field Theory) 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 (π^I, imbedded into $U = \exp\left(i\tau^I \pi^I / v\right)$) are independent of the 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:

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

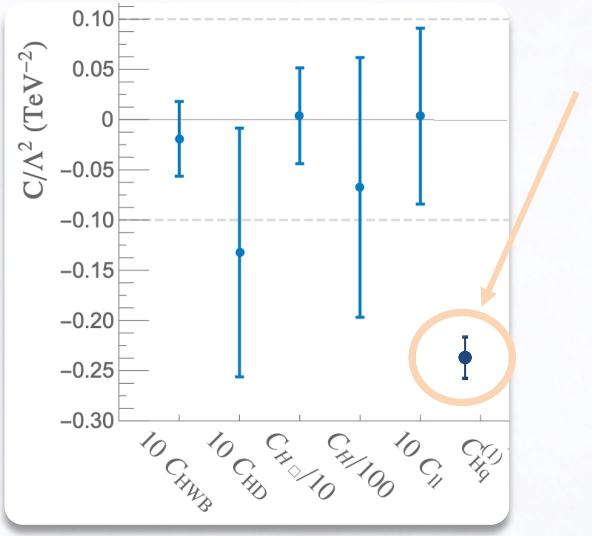
HEFT coefficients: a, b, κ_3, κ_4

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

  - Because h is a **gauge singlet**, it has arbitrary couplings: e.g. κ_3 and κ_4 are independent
  - This does not happen in the SMEFT: the HEFT is more general than the SMEFT
  - Still, 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:

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

- 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):

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

- 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

  → (one of them will correspond to the SMEFT one)
- The goal is to find the best PC — the fastest to converge to the BSM model

- Since one of the PCs is SMEFT-like, we can check if/when linear terms in $\frac{1}{\Lambda^2}$ are enough
  - In that PC, $\frac{1}{\Lambda^2}$ corresponds to $\mathcal{O}(\xi^1)$, $\frac{1}{\Lambda^4}$ corresponds to $\mathcal{O}(\xi^2)$, ...
    - For $\mathcal{A} \propto a_0\, g_{\rm SM} + a_1 \frac{C^{(6)}}{\Lambda^2} + a_2 \frac{C^{(8)}}{\Lambda^4} + \ldots$, it follows:

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

- The Z2RSE in a nutshell:
  - Add a scalar singlet S to the SM, subject to a Z2 symmetry: $S \to -S$. The potential reads:

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

  - 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: $v,\ m,\ v_s,\ M,\ s_\chi$
    - SET_R2: $v,\ m,\ \mu_2^2,\ M,\ s_\chi$

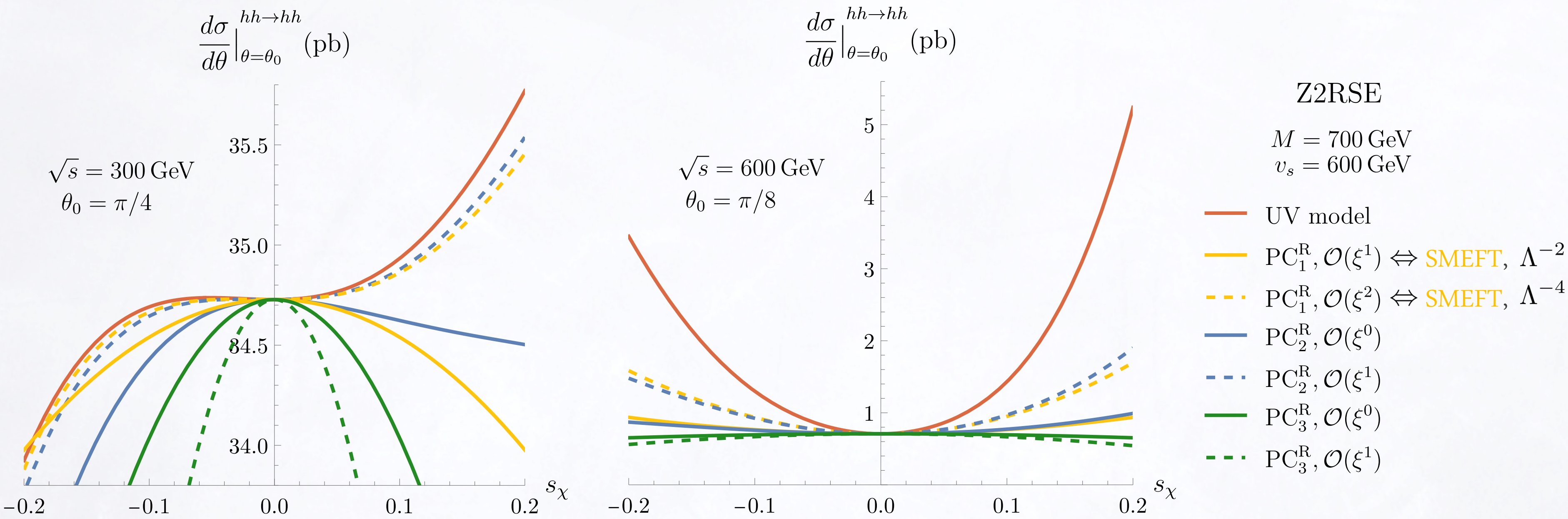
- For a HEFT approach, we assume $M \gg m$, so that we integrate out H (and we are left with the d.o.f. of the SM after SSB)
- It is then clear that m/M should be small — say, $\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi)$

corresponds to the SMEFT: $\mathcal{O}(\xi^1) \leftrightarrow \Lambda^{-2}, \quad \mathcal{O}(\xi^2) \leftrightarrow \Lambda^{-4}, \ldots$

- But what about the other parameters? We consider 3 PCs:
  - PC_1^R takes SET_R1 as the set of independent parameters, and imposes:
  $$\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi), \quad \left(\frac{m}{v_s}\right)^2 \sim \mathcal{O}(\xi), \quad s_\chi^2 \sim \mathcal{O}(\xi)$$
  (and all the others are $\mathcal{O}(\xi^0)$)
  - PC_2^R takes SET_R1 as the set of independent parameters, and imposes:
  $$\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi)$$
  (and all the others are $\mathcal{O}(\xi^0)$)
  - PC_3^R takes SET_R**2** as the set of independent parameters, and imposes:
  $$\left(\frac{m}{M}\right)^2 \sim \mathcal{O}(\xi)$$
  (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:

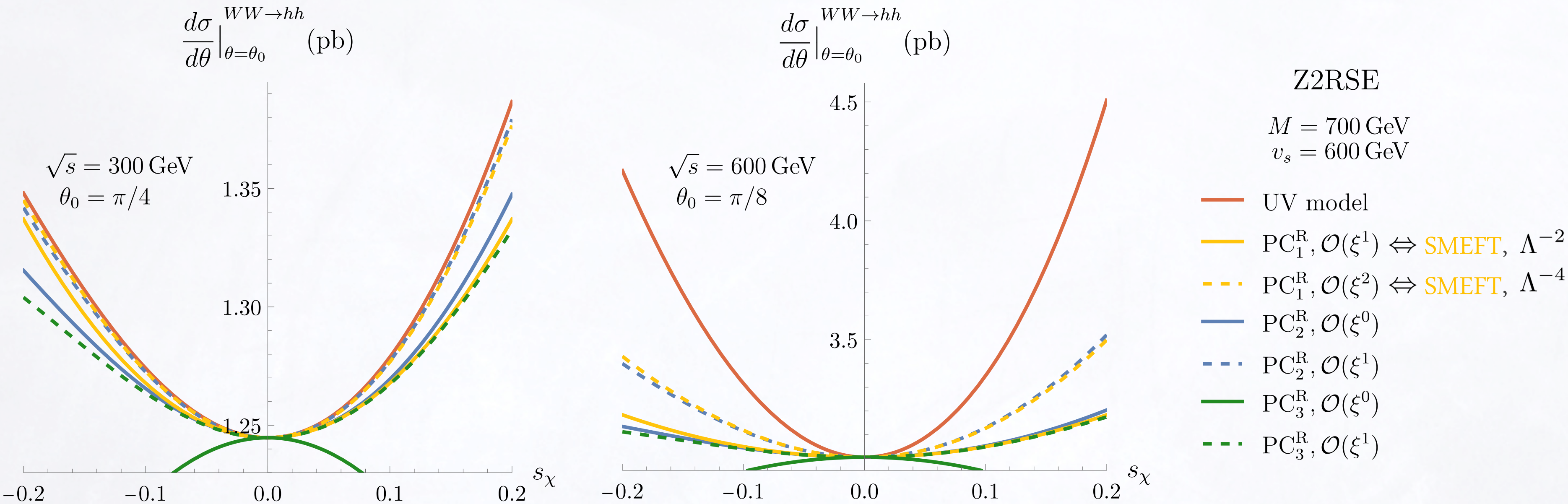
	PC_1^T	PC_2^T	PC_3^T
$\Delta\kappa_3$	$-\xi\frac{3s_\chi^2}{2} + \xi^2\frac{s_\chi^3}{8v_s}\left(3s_\chi v_s - 8v\right)$	$c_\chi^3 - \frac{s_\chi^3 v}{v_s} - 1$	$-1 + c_\chi - \xi\frac{s_\chi^2}{M^2 c_\chi}\left(m^2 - \mu_2^2\right) - \xi^2\frac{m^2 s_\chi^2}{M^4 c_\chi}\left(m^2 - \mu_2^2\right)$

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



  - 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
  - SMEFT at Λ^{-2} is not enough: one needs to go beyond a linear term in Λ^{-2}
  - In the right panel, the EFT assumption starts to break down

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



  - 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:

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

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

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

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

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

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 ➡ 4 types of 2HDM: Type-I, Type-II, Type-L, Type-F
  - Take some of the parameters as independent:
    - SET_T1: $c_{\beta-\alpha}$, Y_2, m_h, m_H, m_A, $m_{H^\pm}$, β, m_f
    - SET_T2: $c_{\beta-\alpha}$, m_{12}^2, m_h, m_H, m_A, $m_{H^\pm}$, β, 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)

corresponds to the SMEFT: $\mathcal{O}(\xi^1) \leftrightarrow \Lambda^{-2}, \quad \mathcal{O}(\xi^2) \leftrightarrow \Lambda^{-4}, \ldots$

  - PC_1^T takes SET_T1 as the set of independent parameters, and imposes:

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

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

  - PC_2^T takes SET_T1 as the set of independent parameters, and imposes:

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

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

  - PC_3^T takes SET_T2 as the set of independent parameters, and imposes:

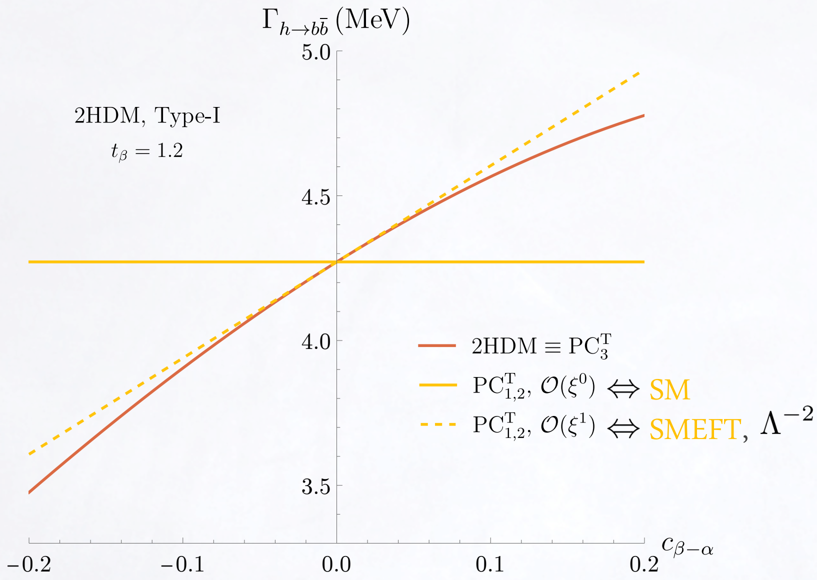
$$M^2 \sim \mathcal{O}(\xi^{-1})$$

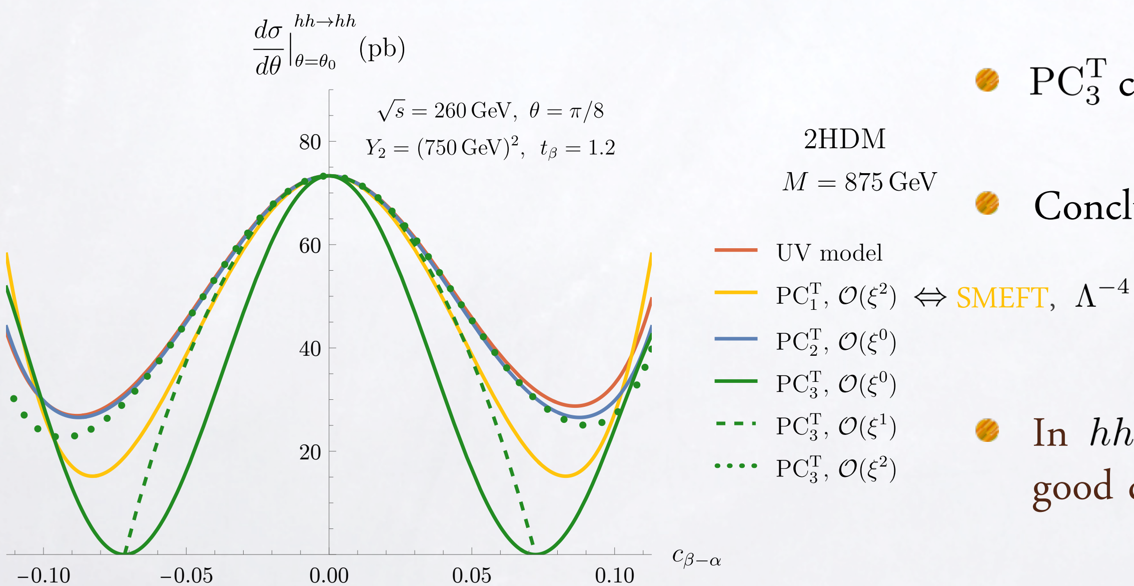
(and all the others are $\mathcal{O}(\xi^0)$)

- Example:

	PC_1^T	PC_2^T	PC_3^T
$\Delta\kappa_3$	$-\xi\, 2c^2_{\beta-\alpha}\dfrac{Y_2}{m_h^2} + \xi^2 \dfrac{1}{2} c^2_{\beta-\alpha}$	$-\dfrac{2Y_2 c^2_{\beta-\alpha}}{m_h^2} + \xi \dfrac{c^3_{\beta-\alpha}}{m_h^2 t_\beta}(t_\beta^2 - 1)(Y_2 - M^2)$ $+\xi^2 \dfrac{c^2_{\beta-\alpha}}{2m_h^2 t_\beta^2}\left(c^2_{\beta-\alpha}\left[M^2(t_\beta^4 - 4t_\beta^2 + 1) + 2Y_2 t_\beta^2\right] + m_h^2 t_\beta^2\right)$	$-1 + s_{\beta-\alpha}(1 + 2c^2_{\beta-\alpha}) + c^2_{\beta-\alpha}\Big[-2s_{\beta-\alpha} m_{12}^2$ $+2c_{\beta-\alpha}\cot 2\beta(1 - m_{12}^2)\Big]$

- Numerical results for two different processes





- For an observable like $h \to b\bar{b}$, 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 $\mathcal{O}(\xi^1)$. SMEFT with Λ^{-2} is ok

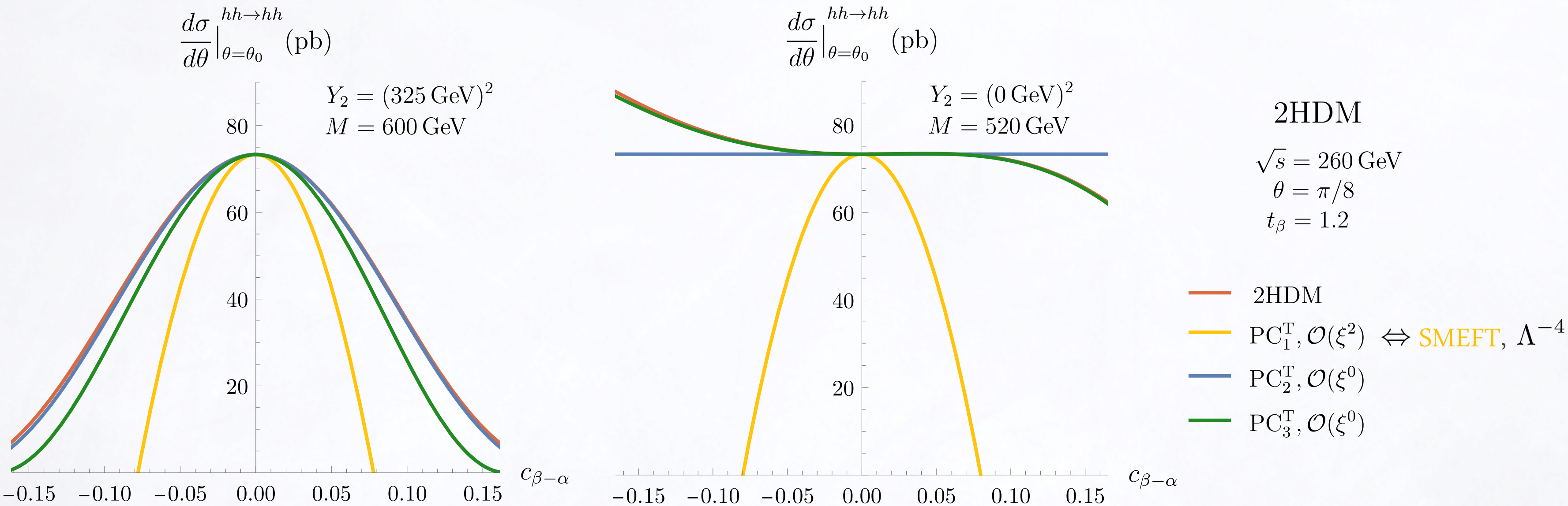
- However, for an observable like $hh \to hh$, PC_2^{T} is by far the best choice, providing an excellent replication of the 2HDM result immediately at $\mathcal{O}(\xi^0)$

- PC_3^{T} can only get closer to that at $\mathcal{O}(\xi^2)$

- Conclusion: according to the process, different PCs should be chosen

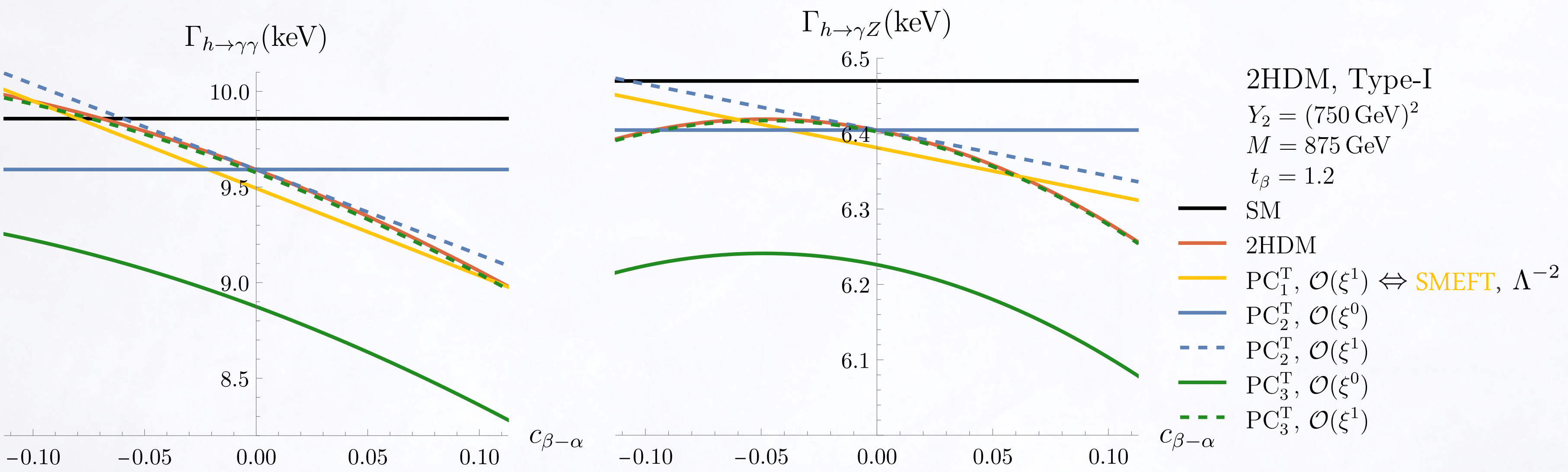
- In $hh \to hh$, not even SMEFT Λ^{-4} provides a good description!

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



- In these cases, Y_2 starts to diminuish; 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} at $\mathcal{O}(\xi^1)$ (SMEFT Λ^{-2}) is a reasonable description
  (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 — one of them corresponding to the SMEFT (the HEFT matching is not unique!)
- In both cases, we found cases where SMEFT with linear terms in Λ^{-2} is not enough
- 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