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SM extensions and matching to SMEFT and HEFT

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based on 2305.07689 and 2311.16897, in collaboration with S. Dawson, D. Fontes and J.J Sanz-Cillero

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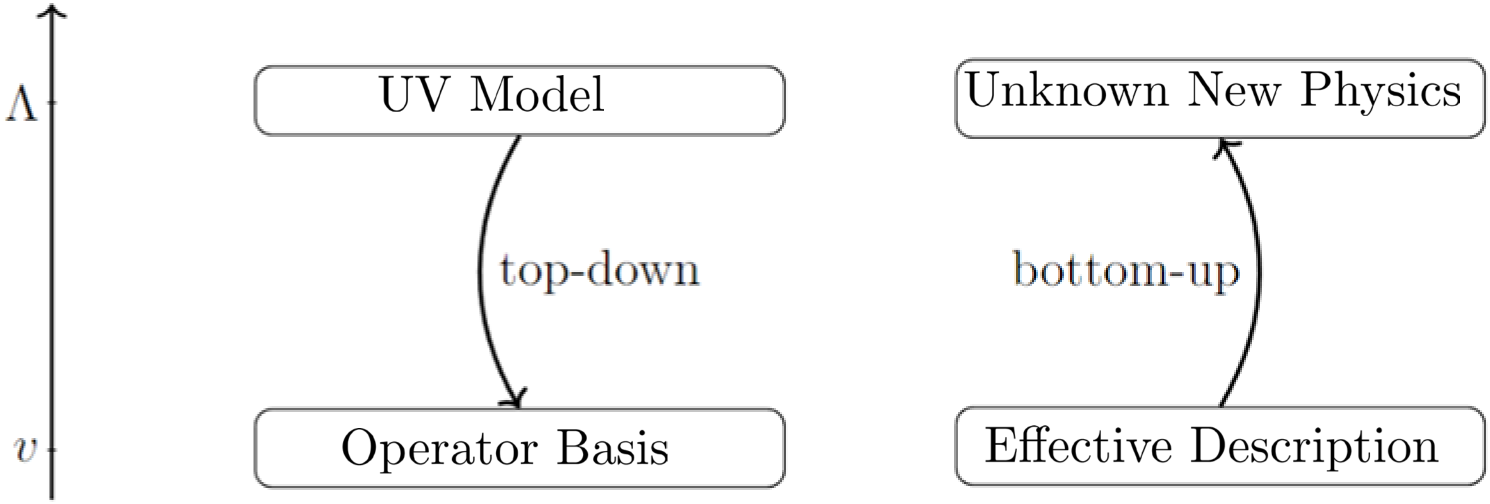
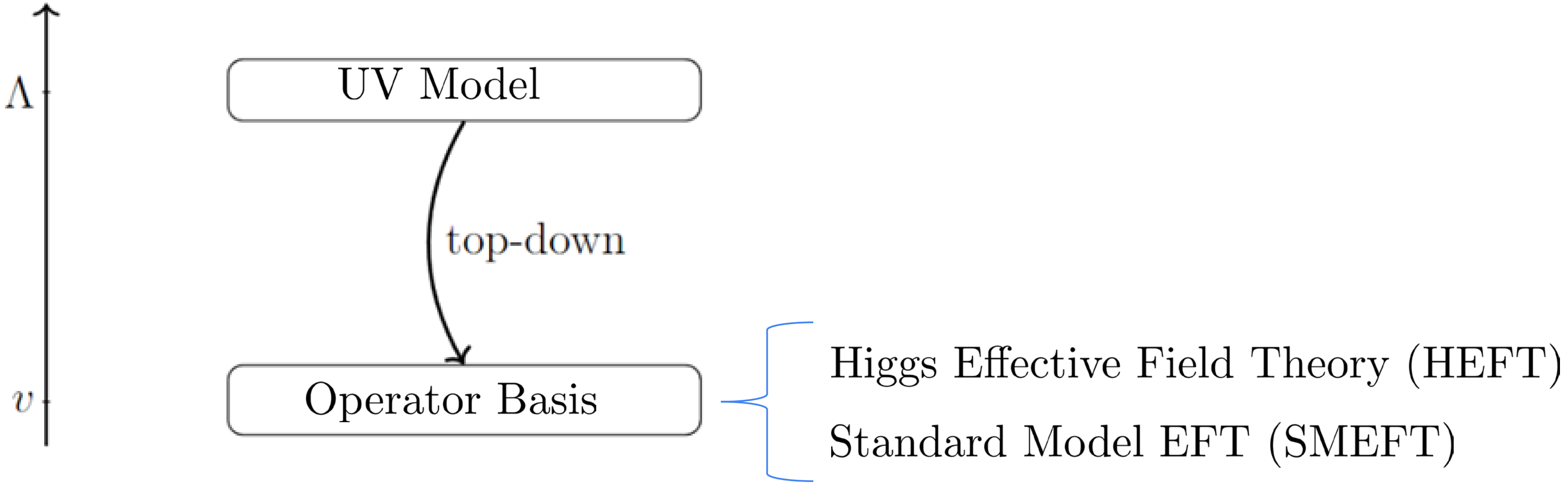
Outline

1. Introduction:

The search for physics Beyond the Standard Model (BSM) can be carried out in two approaches:



The search for physics Beyond the Standard Model (BSM) can be carried out in two approaches:



1. HEFT and SMEFT:

2. Higgs Effective Field Theory (HEFT) and Standard Model Effective Field Theory (SMEFT)

[Brivio,Trott,2017]

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \mathcal{L}^{(8)} \ldots, \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4$$

Each term $\mathcal{L}^{(d)}$ is written in the unbroken phase (before EW symmetry breaking) in terms of the complex doublet Φ

[Feruglio,1992]

$$\mathcal{L}_{HEFT} = \mathcal{L}_2 + \mathcal{L}_{(4)} + \mathcal{L}_{(6)} + \ldots, \quad \text{expansion in chiral dimensions}$$

Each term $\mathcal{L}_{(d)}$ of HEFT is written in the broken phase (after EW symmetry breaking) in terms of the Higgs and Goldstone fields

Chiral counting

$$\partial_\mu,\ M_W,\ M_Z,\ M_h \sim \mathcal{O}(p)$$
$$D_\mu U,\ V_\mu,\ g' v \mathcal{T},\ \hat{W}_\mu,\ \hat{B}_\mu \sim \mathcal{O}(p)$$
$$\hat{W}_{\mu\nu},\ \hat{B}_{\mu\nu} \sim \mathcal{O}(p^2)$$

The lagrangian at lowest order (chiral dimension 2)

Equivalence Theorem

$$\mathcal{L}_2 = \frac{v^2}{4}\mathcal{F}(h)\,\mathrm{Tr}\left[(D_\mu U)^\dagger D^\mu U\right] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + i\bar{Q}\partial Q - v\mathcal{G}(h)\left[\bar{Q}'_L U H_Q Q'_R + \mathrm{h.c.}\right]$$

[Castillo,Delgado Dobado,Llanes-Estrada,2016]

ω^a (GB) + h
+ Yukawa sector

Spherical parametrization for the GB

$$U = \sqrt{1 - \frac{\omega^2}{v^2}} + i\frac{\bar{\omega}}{v} \qquad \bar{\omega} = \tau^a \omega^a \qquad Q^{(\prime)} = \begin{pmatrix} \mathscr{U}^{(\prime)} \\ \mathscr{D}^{(\prime)} \end{pmatrix}$$

$$\mathcal{U}' = (u, c, t)' \qquad \mathcal{D}' = (d, s, b)'$$

Quarks

Analytic functions of powers of the Higgs field. Inspired by most of low energy HEFT models.

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots \qquad \mathcal{G}(h) = 1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \dots$$

$$V(h) = \frac{1}{2}M_h^2 h^2 + d_3\frac{M_h^2}{2v}h^3 + d_4\frac{M_h^2}{8v^2}h^4 + \dots$$

Modifications on the Higgs SM couplings and beyond

Recover the SM

$a = b = 1$

$d_3 = d_4 = 1$

$c_1 = 1$

rest $\kappa_{HEFT} = 0$

3. Matching UV models: 2HDM, RSE and CSE

We will consider three UV models: Real Scalar Singlet Extension (RSE), Two Higgs Doublet Model (2HDM) and the Complex Scalar Extension (CSE).

For these models we will consider the matching to HEFT/SMEFT in scenarios where the BSM masses are not the only large parameters. This defines the three power countings (PCs) we will use for the three models.

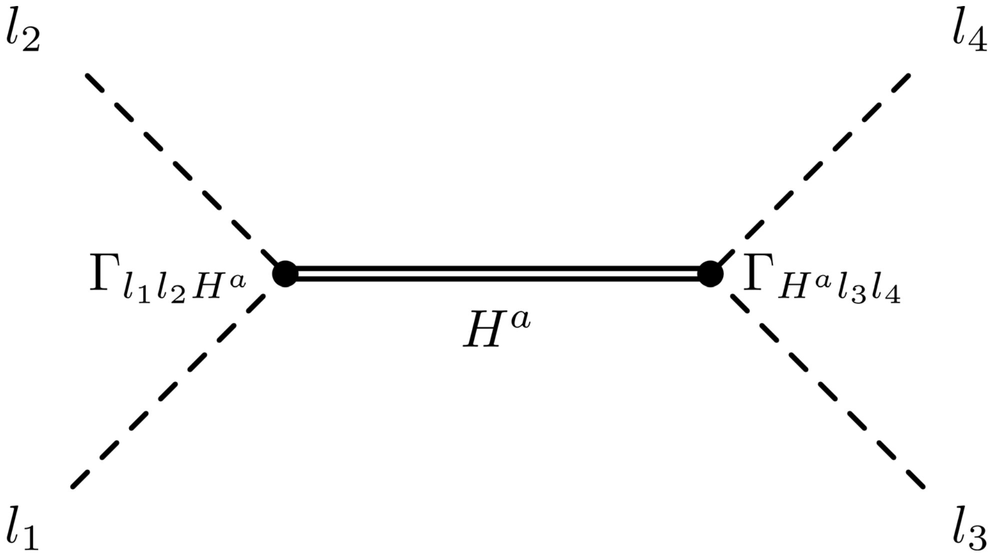
The PCs are chosen so PC1 always reproduces the SMEFT results and another PC always shows non-decoupling effects.

In practice we will organize our EFTs by ξ:

$$\frac{1}{\Lambda^2} \to \frac{\xi}{\Lambda^2}$$

We will calculate the LECs necessary for $W^+W^- \to W^+W^-$, $W^+W^- \to hh$ and $hh \to hh$,$h \to b\bar{b}$, $h \to \gamma\gamma$ and $h \to \gamma Z$ in HEFT and SMEFT.

Large parameters: BSM masses



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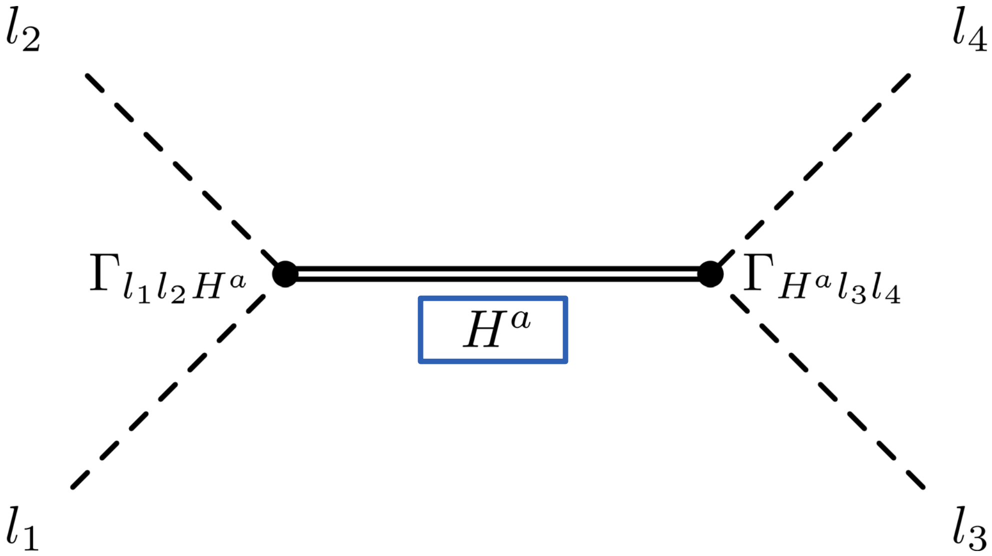
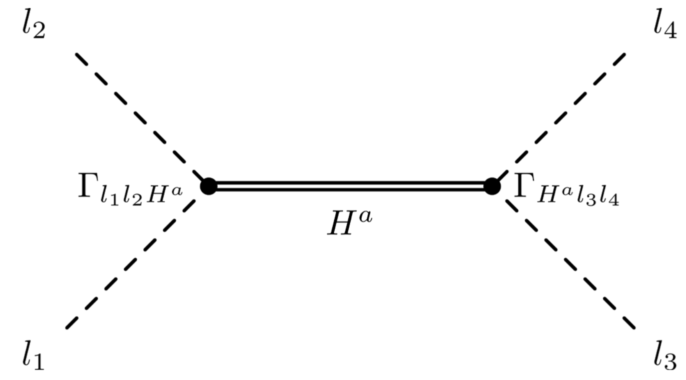
Large parameters: BSM masses

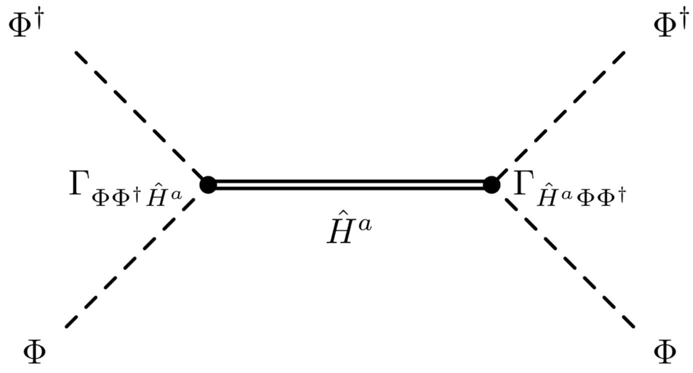
$$\frac{i}{p^2 - m_H^2} \sim -\frac{i}{m_H^2} - \frac{ip^2}{m_H^4} + \mathcal{O}\left(\left(\frac{p^2}{m_H^2}\right)^3\right)$$



Matching in HEFT
Physical fields



Matching in SMEFT
Unbroken phase (PC1)



4. 2HDM

4. 2HDM

Let us the 2HDM as a test to exemplify the results for all models

$$V_{2\mathrm{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left[\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right] + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2\right]$$

"Higgs basis"
where H_2 does not get a vev.

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

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

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

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

4. 2HDM

However, the h and H are not eigenstates. The physical states are obtained by a introducing another mixing angle.

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} s_{\beta-\alpha} & c_{\beta-\alpha} \\ c_{\beta-\alpha} & -s_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} h_1^{\mathrm{H}} \\ h_2^{\mathrm{H}} \end{pmatrix}$$

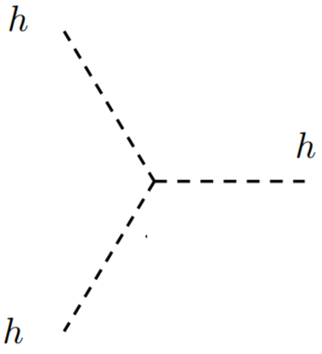
Finally, all fields are physical and we are left with 8 independent parameters:

$$\cos_{\beta-\alpha}, \tan\beta, v, m_h, Y_2, m_H, m_A, m_{H^\pm}$$

Since we are in the unbroken phase, the integration out of the BSM states generates a HEFT lagrangian.

4. 2HDM

Nonetheless, further inspection of this limit shows a divergent behaviour for the cubic Higgs coupling:



$$= \kappa_{hhh} = \frac{3i\csc^2(2\beta)}{2v}\Big\{ s_{\beta-\alpha}\cos(4\beta)\left[-3c^4_{\beta-\alpha}m_H^2 - 2c^2_{\beta-\alpha}Y_2 + \left(3c^4_{\beta-\alpha}+c^2_{\beta-\alpha}+1\right)m_h^2\right]$$
$$+c^3_{\beta-\alpha}\sin(4\beta)\left[\left(1-3c^2_{\beta-\alpha}\right)m_h^2 + \left(3c^2_{\beta-\alpha}-2\right)m_H^2 + 2Y_2\right]$$
$$+s_{\beta-\alpha}\left[2c^2_{\beta-\alpha}Y_2 - c^4_{\beta-\alpha}m_H^2 + \left(c^4_{\beta-\alpha} - c^2_{\beta-\alpha} - 1\right)m_h^2\right]\Big\}$$

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

$$\left.\begin{array}{c} m_H, m_{H^+}, m_A \to \infty \\ Y_2 \to \infty \end{array}\right\} \kappa_{hhh} \to \infty$$

This indicates that in this particular basis, additional assumptions need to be included.

4. 2HDM

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

We define the decoupling limit that reproduces the SMEFT results

$$Y_2 = \Lambda^2, \qquad m_H^2 = \Lambda^2 + \Delta m_H^2, \quad m_A^2 = \Lambda^2 + \Delta m_A^2, \quad m_{H^+}^2 = \Lambda^2 + \Delta m_{H^+}^2$$
$$\Lambda^2 \gg v^2, \qquad m_h^2 \sim \mathcal{O}(v^2), \qquad \Delta m_H^2, \Delta m_A^2, \Delta m_{H^+}^2 \sim \mathcal{O}(v^2),$$
$$c_{\beta-\alpha} \sim \mathcal{O}(v^2/\Lambda^2),$$

In practice this means that the value of $c_{\beta-\alpha}$ will be suppressed

$$\frac{1}{\Lambda^2} \to \frac{\xi}{\Lambda^2}, \qquad c_{\beta-\alpha} \to \xi\, c_{\beta-\alpha};$$

Now we can proceed to integrate out the heavy BSM fields.

4. 2HDM

We write the lagrangian in a way that makes the BSM fields explicit $H^a = H, H^+, A$.

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

The Equation of Motion (EoM) for each field then takes the form

$$J_1^a + (-\partial^2 - M^2 + 2J_2)^{ab} H^b + 3J_3^{abc} H^b H^c + 4J_4^{abcd} H^b H^c H^d = 0$$

We solve order by order in our expansion parameter ξ

$$H = \sum_{i=0}^{\infty} H_{(\xi^i)}, \qquad H^+ = \sum_{i=0}^{\infty} H^+_{(\xi^i)}$$

4. 2HDM

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

$$
\begin{aligned}
H_{(\xi^0)} &= H^+_{(\xi^0)} = 0, \\
H_{(\xi^1)} &= -\frac{3c_{\beta-\alpha}h^2}{2v}, \\
H^+_{(\xi^1)} &= 0, \\
H_{(\xi^2)} &= \frac{2c_{\beta-\alpha}}{v\Lambda^2}\Delta m_H^2 h^2 + \frac{2c_{\beta-\alpha}}{v\Lambda^2} m_W^2 W_\mu W^{\dagger\mu} + \frac{3c_{\beta-\alpha}}{v\Lambda^2}\left[(\partial^\mu h \partial_\mu h) + h\left(\partial^2\, h\right)\right], \\
H^+_{(\xi^2)} &= -\frac{ic_{\alpha-\beta}M_W}{2v\Lambda^2}\left[h\left(\partial_\mu W^\mu\right) + 2W_\mu\left(\partial^\mu h\right)\right], \\
H_{(\xi^3)} &= \frac{c_{\beta-\alpha}h^2}{4t_\beta^2 v\Lambda^4}\left[c^2_{\beta-\alpha}\left(3t_\beta^4 - 2t_\beta^2 + 3\right)\Lambda^4 - 3c_{\beta-\alpha}\left(t_\beta^2 - 1\right)t_\beta\Lambda^2 2(2\Delta m_H^2 - m_h^2) - 8\Delta m_H^2{}^2 t_\beta^2\right] \\
&\quad -\frac{7\Delta m_H^2 c_{\beta-\alpha}}{\Lambda^4 v}\left[\left(\partial^\mu h\right)\left(\partial_\mu h\right) + h\left(\partial^2 h\right)\right] - \frac{3c_{\beta-\alpha}}{\Lambda^4 v}\left[\left(\partial^2 h\right)\left(\partial^2 h\right) + h\left(\partial^2\partial^2 h\right)\right] \\
&\quad -\frac{6c_{\beta-\alpha}}{\Lambda^4 v}\left[(\partial^\mu h \partial^\nu h)(\partial_\mu h \partial_\nu h) + \left(\partial_\mu h\right)(\partial^\mu \partial^2 h) + (\partial_\nu h)\left(\partial^2 \partial^\nu h\right)\right] \\
&\quad -\frac{2c_{\beta-\alpha}m_W^2}{v\Lambda^4}\left[W^{\dagger\nu}\left(\Delta m_H^2 W_\nu + \partial^2 W_\nu\right) + 2\left(\partial^\mu W^\nu\right)\left(\partial_\mu W^\dagger_\nu\right) + W_\nu\left(\partial^2 W^{\dagger\nu}\right)\right], \\
H^+_{(\xi^3)} &= -\frac{im_W c_{\beta-\alpha}}{v\Lambda^4}\left[h(\partial^2\partial^\nu W_\nu) + (\partial^2 h)(\partial^\nu W_\nu)\right] \\
&\quad +\frac{ic_{\beta-\alpha}m_W}{v\Lambda^4}\left[h\left(\partial^2\partial^\nu W_\nu\right) + 2W^\nu\left(\partial^2\partial_\nu h\right)\right] - \frac{4im_W c_{\beta-\alpha}}{v\Lambda^4}\left(\partial^\mu\partial^\nu h\right)\left(\partial_\mu W_\nu\right) \\
&\quad -\frac{ic_{\beta-\alpha}\Delta m_{H_+}^2 m_W}{v\Lambda^4}\left[h\left(\partial^\nu W_\nu\right) + 2W^\nu\left(\partial_\nu h\right)\right].
\end{aligned}
$$

4. 2HDM

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

$$\text{set 1} \qquad \cos_{\beta-\alpha}, \tan\beta, v, m_h, Y_2, m_H, m_A, m_{H^\pm}$$

$$\text{set 2} \qquad \cos_{\beta-\alpha}, \tan\beta, v, m_h, m_{12}^2, m_H, m_A, m_{H^\pm}$$

- PC_1 takes set 1 as independent parameters, and imposes the decoupling (SMEFT) scaling:

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

- PC_2 takes set 1 as independent parameters, and imposes:

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

- PC_3 takes set 2 as independent parameters, and imposes:

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

We collect the HEFT coefficients

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

PC	Δb	Δd_3	Δd_4
$\mathrm{PC}_1^{\mathrm{T}}$	$-\xi^2\, 3c^2_{\beta-\alpha}$	$-\xi\, 2c^2_{\beta-\alpha}\dfrac{Y_2}{m_h^2} + \xi^2\dfrac{1}{2}c^2_{\beta-\alpha}$	$-\xi\, 12c^2_{\beta-\alpha}\dfrac{Y_2}{m_h^2} + \xi^2 c^2_{\beta-\alpha}\left(\dfrac{16\Delta m_H^2}{m_h^2} - 11\right)$
$\mathrm{PC}_2^{\mathrm{T}}$	$-\xi^2\, 3c^2_{\beta-\alpha}$	$-\dfrac{2Y_2 c^2_{\beta-\alpha}}{m_h^2} + \xi\dfrac{c^3_{\beta-\alpha}}{m_h^2 t_\beta}(t_\beta^2-1)(Y_2-M^2) + \xi^2\dfrac{c^2_{\beta-\alpha}}{2m_h^2 t_\beta^2}\left(c^2_{\beta-\alpha}\left[M^2(t_\beta^4-4t_\beta^2+1)+2Y_2 t_\beta^2\right] + m_h^2 t_\beta^2\right)$	$\dfrac{4Y_2 c^2_{\beta-\alpha}}{m_h^2 M^2}(M^2-4Y_2) + \xi\dfrac{2c^3_{\beta-\alpha}}{m_h^2 M^2 t_\beta}\left(t_\beta^2-1\right)(M^2-12Y_2)(M^2-Y_2) + \mathcal{O}(\xi^2)$
$\mathrm{PC}_3^{\mathrm{T}}$	$c^2_{\beta-\alpha}\left(1-2c^2_{\beta-\alpha} + 2c_{\beta-\alpha}s_{\beta-\alpha}\cot 2\beta\right) + \mathcal{O}(\xi)$	$-1 + s_{\beta-\alpha}(1+2c^2_{\beta-\alpha}) + c^2_{\beta-\alpha}\left[-2s_{\beta-\alpha}m_{12}^2 + 2c_{\beta-\alpha}\cot 2\beta(1-m_{12}^2)\right]$	$\dfrac{c^2_{\beta-\alpha}}{3}\Big(-7+64c^2_{\beta-\alpha}-76c^4_{\beta-\alpha}+12(1-6c^2_{\beta-\alpha}+6c^4_{\beta-\alpha})\bar{m}_{12}^2 + 4c_{\beta-\alpha}s_{\beta-\alpha}\cot 2\beta\left[-13+38c^2_{\beta-\alpha}-3(-5+12c_{\beta-\alpha})\bar{m}_{12}^2\right] + 4c^2_{\beta-\alpha}\cot^2 2\beta\left[3c^2_{\beta-\alpha}-16s^2_{\beta-\alpha}+3(-1+6s^2_{\beta-\alpha})\bar{m}_{12}^2\right]\Big) + \mathcal{O}(\xi)$

4. 2HDM

$\Delta b = 3\Delta a^2 + \mathcal{O}(\xi^3)$ SMEFT D=8 correlations [Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,Sanz-Cillero,22]

$\Delta d_4 = 6\Delta d_3 + \mathcal{O}(\xi^2)$ SMEFT D=6 correlations [Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

PC	Δb	Δd_3	Δd_4
$\mathrm{PC}_1^{\mathrm{T}}$	$-\xi^2\, 3c_{\beta-\alpha}^2$	$-\xi\, 2c_{\beta-\alpha}^2 \frac{Y_2}{m_h^2} + \xi^2 \frac{1}{2} c_{\beta-\alpha}^2$	$-\xi\, 12c_{\beta-\alpha}^2 \frac{Y_2}{m_h^2} + \xi^2 c_{\beta-\alpha}^2 \left(\frac{16\Delta m_H^2}{m_h^2} - 11 \right)$
$\mathrm{PC}_2^{\mathrm{T}}$	$-\xi^2\, 3c_{\beta-\alpha}^2$	$-\frac{2Y_2 c_{\beta-\alpha}^2}{m_h^2} + \xi \frac{c_{\beta-\alpha}^3}{m_h^2 t_\beta}(t_\beta^2 - 1)(Y_2 - M^2) + \xi^2 \frac{c_{\beta-\alpha}^2}{2m_h^2 t_\beta^2} \left(c_{\beta-\alpha}^2 \left[M^2(t_\beta^4 - 4t_\beta^2 + 1) + 2Y_2 t_\beta^2 \right] + m_h^2 t_\beta^2 \right)$	$\frac{4Y_2 c_{\beta-\alpha}^2}{m_h^2 M^2}(M^2 - 4Y_2) + \xi \frac{2c_{\beta-\alpha}^3}{m_h^2 M^2 t_\beta} \left(t_\beta^2 - 1\right)(M^2 - 12Y_2)(M^2 - Y_2) + \mathcal{O}(\xi^2)$
$\mathrm{PC}_3^{\mathrm{T}}$	$c_{\beta-\alpha}^2 \left(1 - 2c_{\beta-\alpha}^2 + 2c_{\beta-\alpha} s_{\beta-\alpha} \cot 2\beta \right) + \mathcal{O}(\xi)$	$-1 + s_{\beta-\alpha}(1 + 2c_{\beta-\alpha}^2) + c_{\beta-\alpha}^2 \left[-2s_{\beta-\alpha} m_{12}^2 + 2c_{\beta-\alpha} \cot 2\beta (1 - m_{12}^2) \right]$	$\frac{c_{\beta-\alpha}^2}{3} \Big(-7 + 64c_{\beta-\alpha}^2 - 76c_{\beta-\alpha}^4 + 12(1 - 6c_{\beta-\alpha}^2 + 6c_{\beta-\alpha}^4)\bar{m}_{12}^2 + 4c_{\beta-\alpha} s_{\beta-\alpha} \cot 2\beta \left[-13 + 38c_{\beta-\alpha}^2 - 3(-5 + 12c_{\beta-\alpha})\bar{m}_{12}^2 \right] + 4c_{\beta-\alpha}^2 \cot^2 2\beta \left[3c_{\beta-\alpha}^2 - 16s_{\beta-\alpha}^2 + 3(-1 + 6s_{\beta-\alpha}^2)\bar{m}_{12}^2 \right] \Big) + \mathcal{O}(\xi)$

[Arco,Domenech,Herrero,Morales,23]

4. 2HDM

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$\Delta d_4 = 6\Delta d_3 + \mathcal{O}(\xi^2)$ SMEFT D=6 correlations [Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

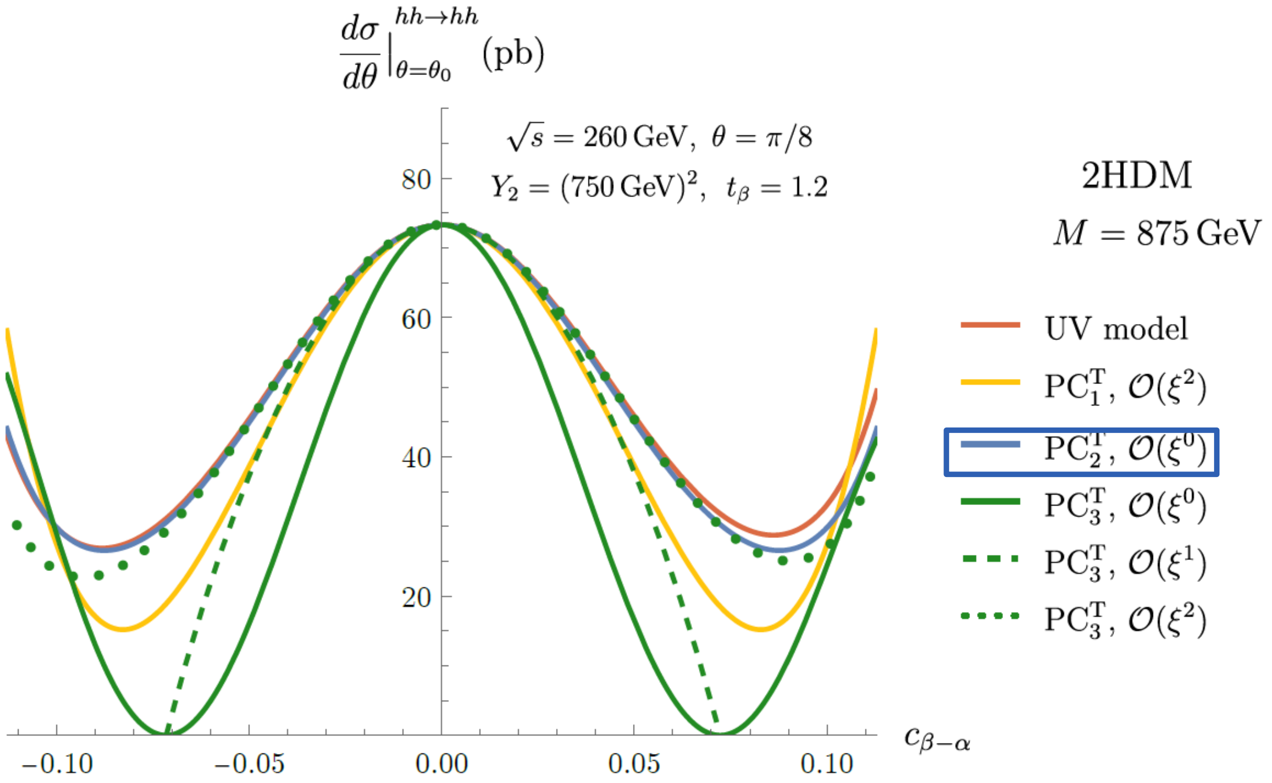
PC	Δa	Δc_1	$a_{h\gamma\gamma}$	$a_{h\gamma Z}$
$\mathrm{PC}_1^{\mathrm{T}}$	$-\xi^2 \frac{c^2_{\beta-\alpha}}{2}$	$1 + \xi \frac{c_{\beta-\alpha}}{\tan\beta} - \xi^2 \frac{c^2_{\beta-\alpha}}{2}$	$-\xi \frac{\Delta m_H^2}{48\pi^2 Y_2} + \mathcal{O}(\xi^2)$	$\xi \frac{\Delta m^2_{H^+} (m_Z^2 - 2m_W^2)}{96\pi^2 m_W^2 Y_2} + \mathcal{O}(\xi^2)$
$\mathrm{PC}_2^{\mathrm{T}}$	$-\xi^2 \frac{c^2_{\beta-\alpha}}{2}$	$1 + \xi \frac{c_{\beta-\alpha}}{\tan\beta} - \xi^2 \frac{c^2_{\beta-\alpha}}{2}$	$\frac{1}{48\pi^2 Y_2}(Y_2 - M^2) + \xi \frac{c_{\beta-\alpha}\cot 2\beta}{48\pi^2 M^2}(Y_2 - M^2) + \mathcal{O}(\xi^2)$	$-\frac{(M^2 - Y2)(2m_W^2 - m_Z^2)}{96\pi^2 M^2 m_W^2} - \xi \frac{\cot(2\beta)(M^2 - Y_2) c_{\beta-\alpha} (2m_W^2 - m_Z^2)}{96\pi^2 M^2 m_W^2} + \mathcal{O}(\xi^2)$
$\mathrm{PC}_3^{\mathrm{T}}$	$s_{\beta-\alpha} - 1$	$\frac{1}{\tan\beta}(c_{\beta-\alpha} + \tan\beta\, s_{\beta-\alpha})$	$-\frac{s_{\beta-\alpha}}{48\pi^2} + \xi \frac{m_{12}^2}{48\pi^2 M^2} \csc(\beta)\sec(\beta)\left(\cot(2\beta)c_{\beta-\alpha} + s_{\beta-\alpha}\right) - \xi \frac{m_h^2}{1440\pi^2 M^2}\left(30\cot(2\beta)c_{\beta-\alpha} + 19 s_{\beta-\alpha}\right) + \mathcal{O}(\xi^2)$	$\frac{s_{\beta-\alpha}}{96 m_W^2 \pi^2}(m_Z^2 - 2m_W^2) - \xi \frac{(2m_W^2 - m_Z^2)}{2880\pi^2 M^2 m_W^2}\left[30\cot(2\beta)c_{\beta-\alpha}(m_h^2 - m_{12}^2\csc(\beta)\sec(\beta)) + s_{\beta-\alpha}(19m_h^2 - 30m_{12}^2\csc(\beta)\sec(\beta) + 2m_Z^2)\right] + \mathcal{O}(\xi^2)$

4. 2HDM

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

Each PC replicates the model show different convergence

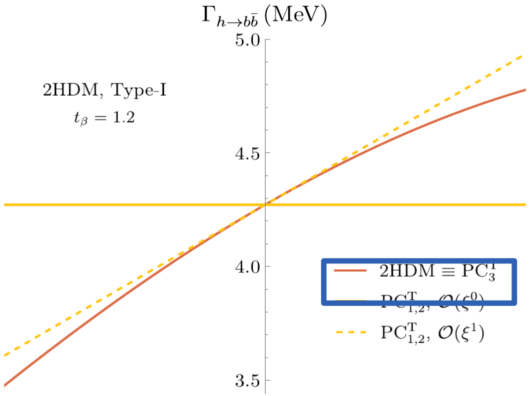
At order ξ^2 PC_2 fits better the UV model.



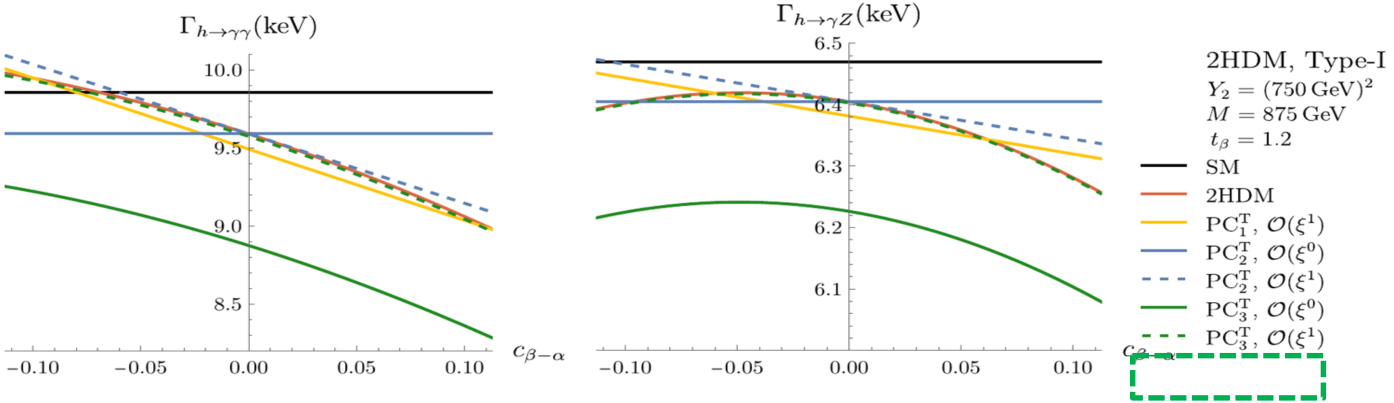
4. 2HDM

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

$h \to b\bar{b}$, $h \to \gamma\gamma$ and $h \to \gamma Z$



At LO in ξ PC_3 converges faster



5. Real Singlet Extension (RSE)

5. RSE

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

Real Singlet Extension (RSE): SM + one real scalar

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

set 1	$v,\ m,\ v_s,\ M,\ s_\chi$
set 2	$v,\ m,\ \mu_2^2,\ M,\ s_\chi$

- PC_1 takes set 1 and imposes the decoupling (SMEFT) scaling:

$$M^2 \sim \mathcal{O}(\xi^{-1}), \quad v_s^2 \sim \mathcal{O}(\xi^{-1}), \quad s_\chi^2 \sim \mathcal{O}(\xi).$$

- PC_2 also takes set 1 imposes:

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

- PC_3 takes set 2 and imposes:

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

5. RSE

We collect the HEFT coefficients [Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

PC	Δa	Δb	$\Delta\kappa_3$	$\Delta\kappa_4$
$\mathrm{PC}_1^{\mathrm{R}}$	$-\xi\frac{s_\chi^2}{2} - \xi^2\frac{s_\chi^4}{8}$	$-2\xi s_\chi^2 + \xi^2 s_\chi^2\left(s_\chi^2 - \frac{2m^2}{M^2} - \frac{v_s s_\chi}{v_s}\right)$	$-\xi\frac{3s_\chi^2}{2} + \xi^2\frac{s_\chi^3}{8v_s}\left(3s_\chi v_s - 8v\right)$	$-\xi\frac{25s_\chi^2}{3} - \xi^2\frac{s_\chi^2}{3M^2 v_s}\left[28m^2 v_s - M^2 s_\chi\left(41 s_\chi v_s - 38v\right)\right]$
$\mathrm{PC}_2^{\mathrm{R}}$	$c_\chi - 1$	$c_\chi^4 - s_\chi^3 c_\chi\frac{v}{v_s} - 1 + \xi\frac{2m^2 s_\chi^2}{M^2 v_s}\left(s_\chi^2 v_s - v_s - c_\chi s_\chi v\right)$	$c_\chi^3 - \frac{s_\chi^3 v}{v_s} - 1$	$-1 - \frac{19c_\chi^2 s_\chi^2\left(c_\chi v_s + s_\chi v\right)^2}{3v_s^2} + \frac{\left(c_\chi^4 v_s^2 + s_\chi^4 v^2\right)}{v_s^2} - \xi\frac{28c_\chi^2 m^2 s_\chi^2\left(c_\chi v_s + s_\chi v\right)^2}{3M^2 v_s^2} - \xi^2\frac{16c^2 m^4 s_\chi^2\left(c_\chi v_s + s_\chi v\right)^2}{3M^4 v_s^2}$
$\mathrm{PC}_3^{\mathrm{R}}$	$c_\chi - 1$	$-s_\chi^2 + \xi\frac{s_\chi^2}{M^2}\left(m^2 - \mu_2^2\right) + \xi^2\frac{3m^2 s_\chi^2}{M^4}\times\left(m^2 - \mu_2^2\right)$	$-1 + c_\chi - \xi\frac{s_\chi^2}{M^2 c_\chi}\left(m^2 - \mu_2^2\right) - \xi^2\frac{m^2 s_\chi^2}{M^4 c_\chi}\left(m^2 - \mu_2^2\right)$	$-s_\chi^2 + \xi\frac{2s_\chi^2}{M^2}\left(m^2 - \mu_2^2\right) + \xi^2\frac{s_\chi^2}{3c_\chi M^4}\left(m^2 - \mu_2^2\right)\left[m^2\left(13s_\chi^2 - 10\right) + \mu_2^2\left(16 - 19s_\chi^2\right)\right]$

[Buchalla,Cata,Celis,Krause,16]

Table 1: HEFT couplings for the Z2RSE. All the couplings are shown up to $\mathcal{O}(\xi^2)$.

5. RSE

$$\Delta b = 2\Delta a^2 + \mathcal{O}(\xi^2)$$
$$\Delta d_4 = 6\Delta d_3 - 4/3\Delta a + \mathcal{O}(\xi^2)$$

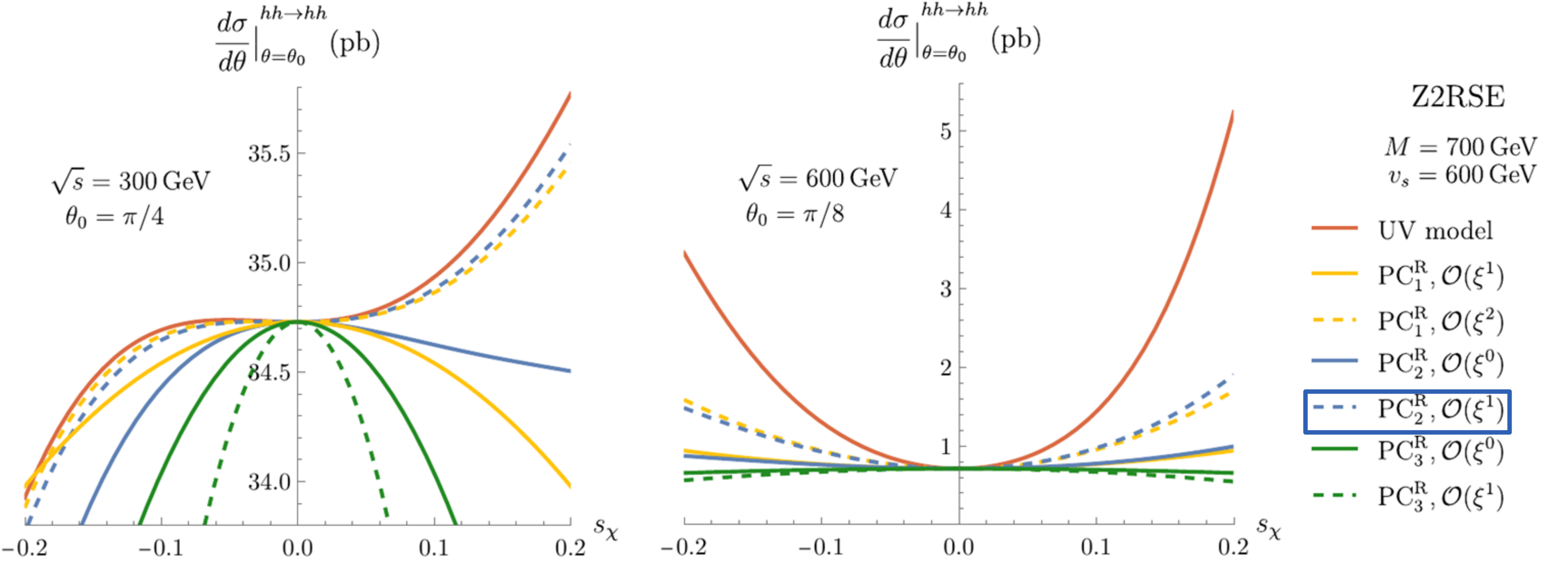
SMEFT D=6 correlations

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

PC	Δa	Δb	$\Delta\kappa_3$	$\Delta\kappa_4$
$\mathrm{PC}_1^{\mathrm{R}}$	$-\xi\frac{s_\chi^2}{2} - \xi^2\frac{s_\chi^4}{8}$	$-2\xi s_\chi^2 + \xi^2 s_\chi^2\left(s_\chi^2 - \frac{2m^2}{M^2} - \frac{v_s s_\chi}{v_s}\right)$	$-\xi\frac{3s_\chi^2}{2} + \xi^2\frac{s_\chi^3}{8v_s}\left(3s_\chi v_s - 8v\right)$	$-\xi\frac{25s_\chi^2}{3} + \xi^2\frac{s_\chi^2}{3M^2v_s}\left[28m^2v_s - M^2s_\chi\left(41s_\chi v_s - 38v\right)\right]$
$\mathrm{PC}_2^{\mathrm{R}}$	$c_\chi - 1$	$c_\chi^4 - s_\chi^3 c_\chi\frac{v}{v_s} - 1 + \xi\frac{2m^2s_\chi^2}{M^2v_s}\left(s_\chi^2 v_s - v_s - c_\chi s_\chi v\right)$	$c_\chi^3 - \frac{s_\chi^3 v}{v_s} - 1$	$-1 - \frac{19c_\chi^2 s_\chi^2\left(c_\chi v_s + s_\chi v\right)^2}{3v_s^2} + \frac{\left(c_\chi^4 v_s^2 + s_\chi^4 v^2\right)}{v_s^2} - \xi\frac{28c_\chi^2 m^2 s_\chi^2\left(c_\chi v_s + s_\chi v\right)^2}{3M^2v_s^2} - \xi^2\frac{16c^2m^4s_\chi^2\left(c_\chi v_s + s_\chi v\right)^2}{3M^4v_s^2}$
$\mathrm{PC}_3^{\mathrm{R}}$	$c_\chi - 1$	$-s_\chi^2 + \xi\frac{s_\chi^2}{M^2}\left(m^2 - \mu_2^2\right) + \xi^2\frac{3m^2s_\chi^2}{M^4} \times \left(m^2 - \mu_2^2\right)$	$-1 + c_\chi - \xi\frac{s_\chi^2}{M^2c_\chi}\left(m^2 - \mu_2^2\right) - \xi^2\frac{m^2s_\chi^2}{M^4c_\chi}\left(m^2 - \mu_2^2\right)$	$-s_\chi^2 + \xi\frac{2s_\chi^2}{M^2}\left(m^2 - \mu_2^2\right) + \xi^2\frac{s_\chi^2}{3c_\chi M^4}\left(m^2 - \mu_2^2\right)\left[m^2\left(13s_\chi^2 - 10\right) + \mu_2^2\left(16 - 19s_\chi^2\right)\right]$

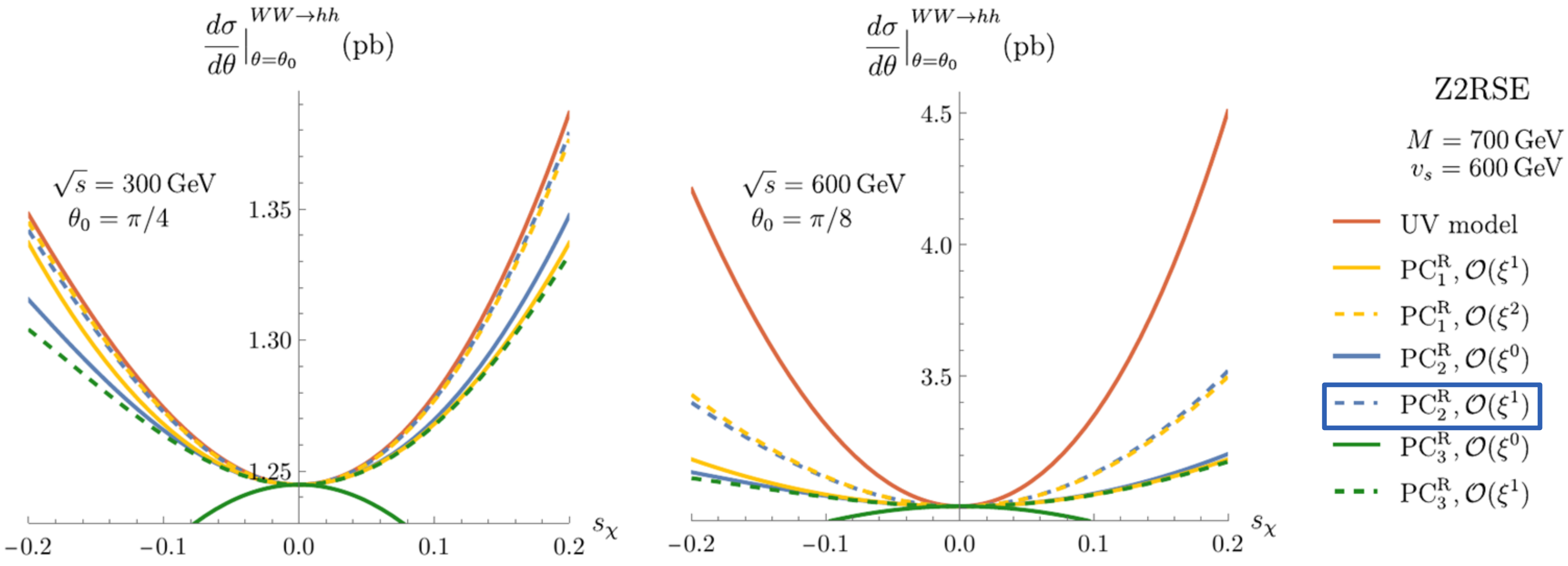
Table 1: HEFT couplings for the Z2RSE. All the couplings are shown up to $\mathcal{O}(\xi^2)$.

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]



5. RSE

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]



4. Complex Scalar Extension (CSE)

CSE: SM + one Complex Scalar

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

$$V = -\frac{\mu^2}{2}\phi^\dagger\phi + \frac{\lambda}{4}\left(\phi^\dagger\phi\right)^2 + \frac{1}{2}b_2\left|S_c\right|^2 + \frac{\delta_2}{2}\phi^\dagger\phi\left|S_c\right|^2 + \frac{1}{4}\rho_2\left(\left|S_c\right|^2\right)^2 + \left[a_1 S_c + \frac{1}{4}b_1 S_c^2\right.$$

$$\left. + \frac{1}{6}e_1 S_c^3 + \frac{1}{6}e_2 S_c\left|S_c\right|^2 + \frac{1}{8}\rho_1 S_c^4 + \frac{1}{8}\rho_3 S_c^2\left|S_c\right|^2 + \frac{1}{4}\delta_1\phi^\dagger\phi S_c + \frac{1}{4}\delta_3\phi^\dagger\phi S_c^2 + \text{h.c.}\right]$$

set $\quad v, m, M, \theta_1, \theta_2, \delta_2, \delta_3, \rho_1, \rho_2, \rho_3, e_1, e_2$

- PC_1 imposes the decoupling (SMEFT) scaling:

$$M^2 \sim \mathcal{O}(\xi^{-1}), \quad s_1 \sim \mathcal{O}(\xi).$$

- PC_2 imposes:

$$M^2 \sim \mathcal{O}(\xi^{-1}), \quad s_1^2 \sim \mathcal{O}(\xi), \quad e_1^2 \sim \mathcal{O}(\xi^{-1}), \quad e_2^2 \sim \mathcal{O}(\xi^{-1}).$$

- PC_3 imposes:

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

6 CSE

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

PC	Δa	Δb	Δd_3	Δd_4
$\mathrm{PC}_1^{\mathrm{C}}$	$-\xi^2\frac{s_1^2}{2}$	$-\xi^2\, 2s_1^2$	$\xi^2\frac{s_1^2}{2m_1^2}\left(v^2\bar{\delta}_{23}-3m_1^2\right)$	$\xi^2\frac{s_1^2}{3m_1^2}\left(9v^2\bar{\delta}_{23}-25m_1^2\right)$
$\mathrm{PC}_2^{\mathrm{C}}$	$-\xi\frac{s_1^2}{2} - \xi^2\frac{s_1^4}{8}$	$-\xi\, 2s_1^2 + \mathcal{O}(\xi^2)$	$-\xi\frac{s_1^2}{6m_1^2}\left(9m_1^2-3v^2\bar{\delta}_{23} + \sqrt{2}s_1 v\, e_{12\mathrm{R}}\right) + \xi^2\frac{s_1^4}{8m_1^2}\left(3m_1^2-2v^2\bar{\delta}_{23}\right)$	$\xi\frac{s_1^2}{3m_1^2}\left(9v^2\bar{\delta}_{23}-3\sqrt{2}s_1 v\, e_{12\mathrm{R}} - 25m_1^2\right)+\mathcal{O}(\xi^2)$
$\mathrm{PC}_3^{\mathrm{C}}$	c_1-1	$c_1^4-1 +\mathcal{O}(\xi)$	$-\frac{v}{24m_1^2}\left[3c_1 v(c_1^2-3s_1^2-1)\bar{\delta}_{23} + \sqrt{2}s_1(-3c_1^2+s_1^2+3)e_{12\mathrm{R}}\right] + \frac{c_1}{4}\left(c_1^2-3s_1^2+3\right)-1+$	$\frac{s_1^2 v}{2m_1^2}\left[s_1^2 v\left(-6(c_1^2+1)\bar{\delta}_{23}+\rho_{13\mathrm{R}} +\rho_2\right)+6v\bar{\delta}_{23}-2\sqrt{2}c_1^3 s_1 e_{12\mathrm{R}}\right] + c_1^4\left(1-\frac{19s_1^2}{3}\right)-1+\mathcal{O}(\xi)$

6 CSE

$$\Delta b = 2\Delta a^2 + \mathcal{O}(\xi^2)$$
$$\Delta d_4 = 6\Delta d_3 - 4/3\Delta a + \mathcal{O}(\xi^2)$$

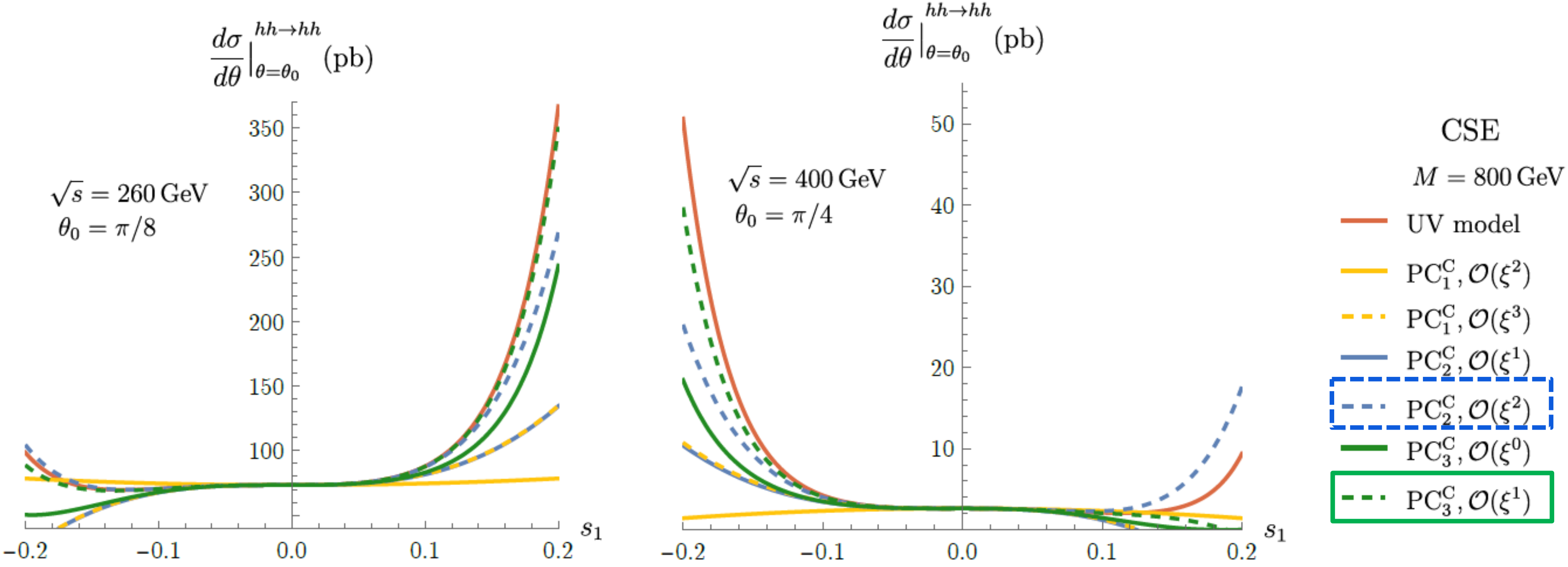
SMEFT D=6 correlations

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]

PC	Δa	Δb	Δd_3	Δd_4
PC_1^{C}	$-\xi^2 \frac{s_1^2}{2}$	$-\xi^2 2s_1^2$	$\xi^2 \frac{s_1^2}{2m_1^2}\left(v^2\bar{\delta}_{23} - 3m_1^2\right)$	$\xi^2 \frac{s_1^2}{3m_1^2}\left(9v^2\bar{\delta}_{23} - 25m_1^2\right)$
PC_2^{C}	$-\xi \frac{s_1^2}{2} - \xi^2 \frac{s_1^4}{8}$	$-\xi\, 2s_1^2 + \mathcal{O}(\xi^2)$	$-\xi \frac{s_1^2}{6m_1^2}\left(9m_1^2 - 3v^2\bar{\delta}_{23} + \sqrt{2}s_1 v\, e_{12\text{R}}\right) + \xi^2 \frac{s_1^4}{8m_1^2}\left(3m_1^2 - 2v^2\bar{\delta}_{23}\right)$	$\xi \frac{s_1^2}{3m_1^2}\left(9v^2\bar{\delta}_{23} - 3\sqrt{2}s_1 v\, e_{12\text{R}} - 25m_1^2\right) + \mathcal{O}(\xi^2)$
PC_3^{C}	$c_1 - 1$	$c_1^4 - 1 + \mathcal{O}(\xi)$	$-\frac{v}{24m_1^2}\left[3c_1 v(c_1^2 - 3s_1^2 - 1)\bar{\delta}_{23} + \sqrt{2}s_1(-3c_1^2 + s_1^2 + 3)e_{12\text{R}}\right] + \frac{c_1}{4}\left(c_1^2 - 3s_1^2 + 3\right) - 1 +$	$\frac{s_1^2 v}{2m_1^2}\left[s_1^2 v\left(-6(c_1^2+1)\bar{\delta}_{23} + \rho_{13\text{R}} + \rho_2\right) + 6v\bar{\delta}_{23} - 2\sqrt{2}c_1^3 s_1 e_{12\text{R}}\right] + c_1^4\left(1 - \frac{19s_1^2}{3}\right) - 1 + \mathcal{O}(\xi)$

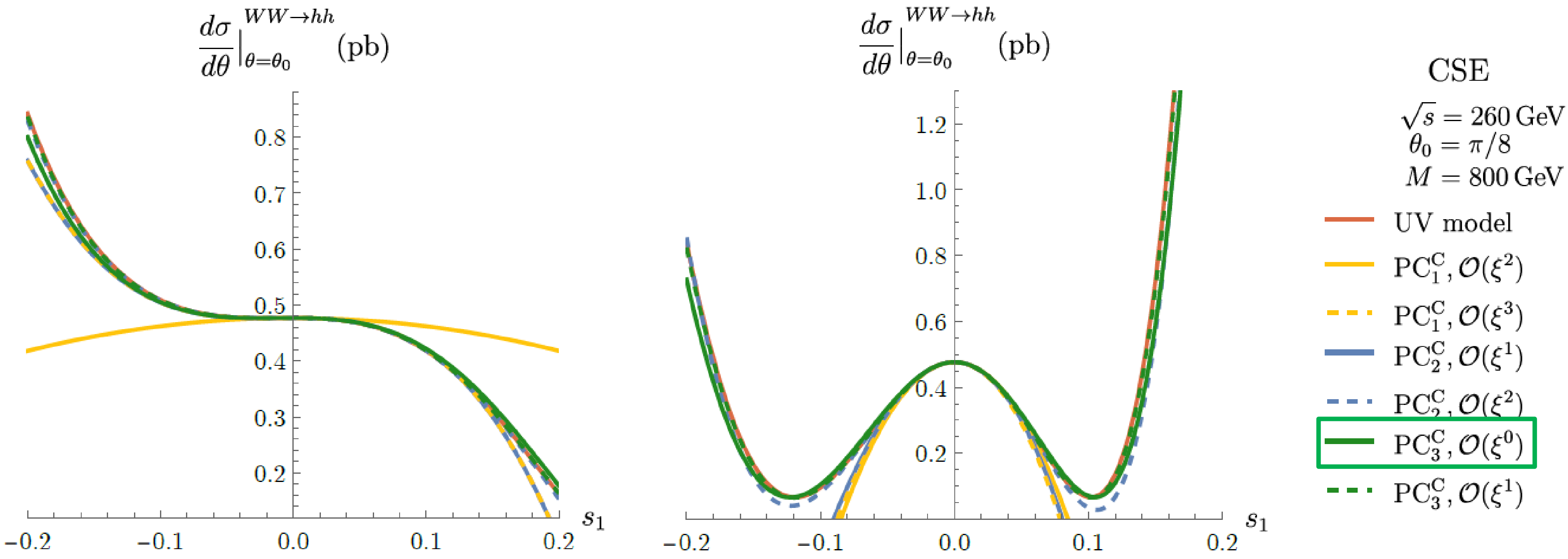
6 CSE

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]



6 CSE

[Dawson,Fontes,Quezada-Calonge,Sanz-Cillero,23]



Conclusions

We have studied the matching of UV models to HEFT/SMEFT for different choice of UV parameters and PCs that result in different low-energy theories. Some aspects of the models and PCs used are:

- **2HDM.** We have shown that different PCs are more suited for a given observable . PC_3 is most adequate for $h \to \gamma\gamma$ and $h \to \gamma Z$, PC_2 is clearly more accurate for some regions of processes such as $hh \to hh$.

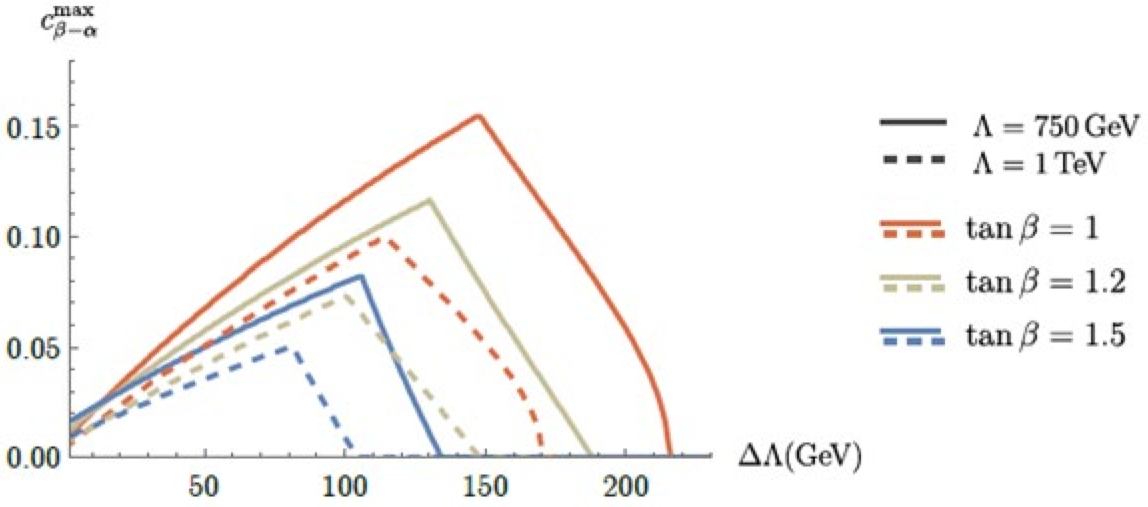
- **Complex Singlet Extension.** All PCs considered show similar results around a $\pm$ 0.1 deviation from the alignment limit. PC_3 is able to reproduce the behavior of the CSE in for $s_1 \leq 0.2$.

- **Real Singlet Extension.** We showed that two PCs perform an expansion only on inverse powers of the heavy physical mass for $WW \to hh$ lead to very different results. This is the case for PC_2 and PC_3 where v_s and μ_2^2 are used. $hh \to hh$ does not show this acute difference, except for the first order of PC_3.

Questions?

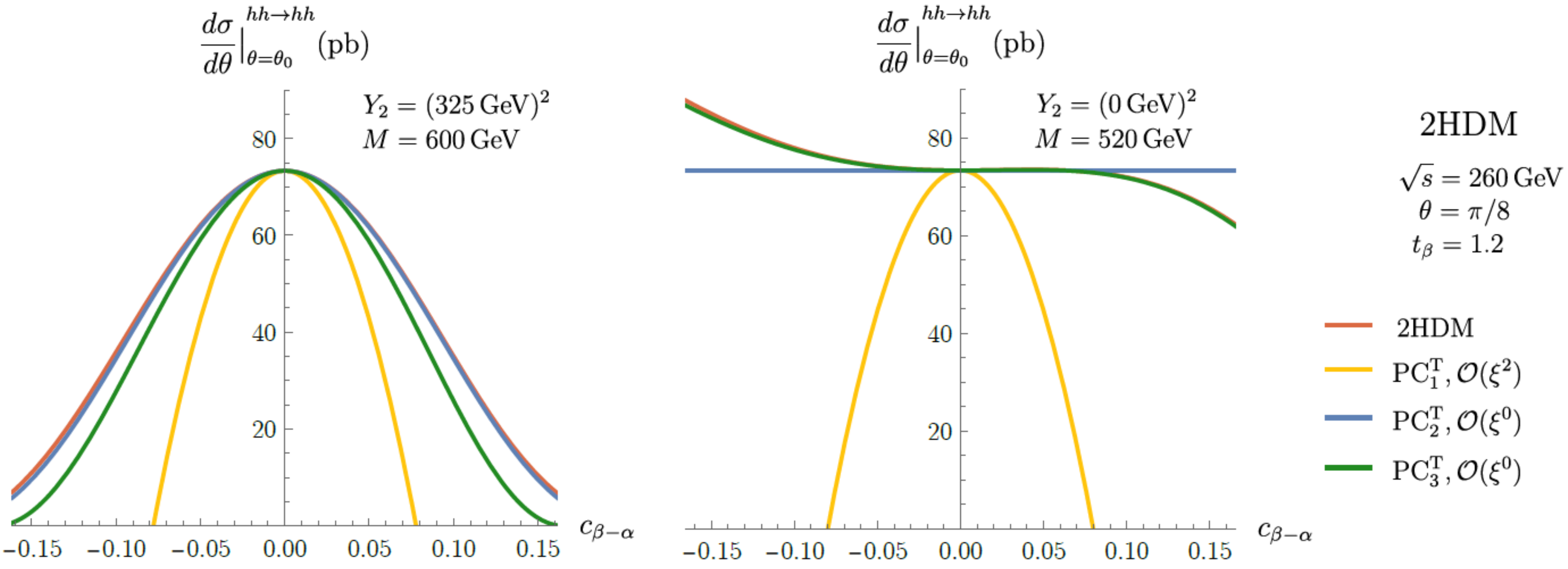
Backup slides

Constraints

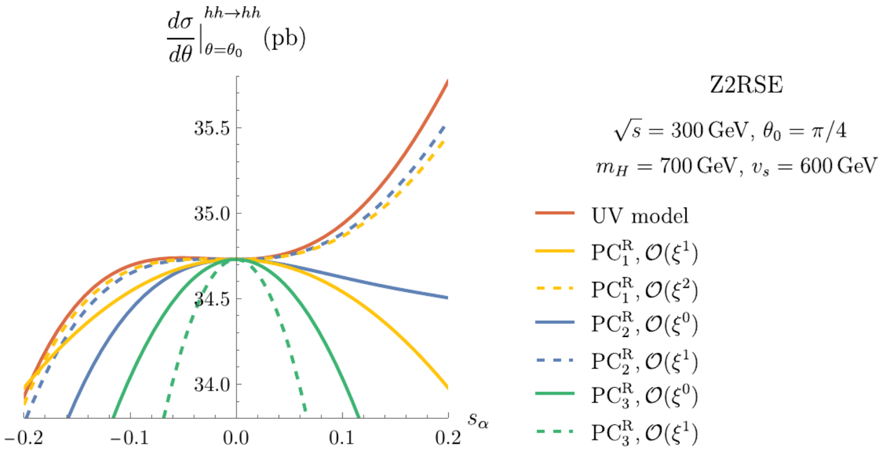


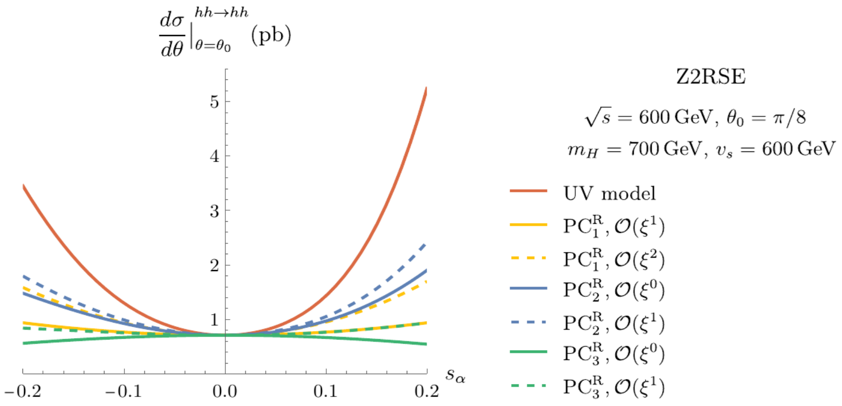
Perturbativity and positivity

Backup slides



Backup slides





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The Straight-line Basis

$$\Phi_2^\alpha\Big|_{\text{vev}} = k\,\Phi_1^\alpha\Big|_{\text{vev}}$$

$$-\left.\frac{\partial \mathcal{L}_0}{\partial \Phi_2^\dagger}\right|_{\Phi_2=\Phi^{(0)}_{2,\mathbf{c}}(\Phi_1)} = Y_{2b}\Phi_b\Big|_{\Phi_2=\Phi^{(0)}_{2,\mathbf{c}}(\Phi_1)} + Z_{2bcd}\Phi_b\left(\Phi_c^\dagger\Phi_d\right)\Big|_{\Phi_2=\Phi^{(0)}_{2,\mathbf{c}}(\Phi_1)} = 0$$

$$\Phi_{2,\mathbf{c}}[\Phi_1] = \Phi^{(0)}_{2,\mathbf{c}}(\Phi_1) + O\left(\partial^2\right)$$