Two-Higgs Doublet Model
Matched to Nonlinear Effective Theory

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Motivation

- Certain parameter ranges of the 2HDM lead to non-decoupling effects
- SMEFT cannot capture non-decoupling effects
- Different EFT approach: Higgs Effective Field Theory (HEFT)
- Non-decoupling effects for $h \to \gamma\gamma$ can be phenomenologically relevant

Two-Higgs Doublet Model

$$\mathcal{L} = (D_\mu \Phi_n)^\dagger (D^\mu \Phi_n) - V + \ldots \qquad n = 1,\, 2$$

Potential with $\lambda_i \in \mathbb{R}$

$$\begin{aligned} V = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 \\ & + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] \end{aligned}$$

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$$\Phi_n = \begin{pmatrix} \varphi_n^+ \\ \frac{1}{\sqrt{2}} (v_n + h_n + i \varphi_n^3) \end{pmatrix}$$

mixing angle β: H^+, A_0, Goldstones

mixing angle α: H_0, h

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- φ_n^+, φ_n^3 → mixing angle β: H^+, A_0, Goldstones
- h_n → mixing angle α: H_0, h

Physical Parameters:

$$v^2 = v_1^2 + v_2^2 \,, \quad t_\beta = \frac{v_2}{v_1} \,, \quad c_{\beta-\alpha} \,, \quad m_h \,, \quad M_0 \,, \quad M_H \,, \quad M_A \,, \quad \overline{m}^2 = \frac{m_{12}^2}{s_\beta c_\beta}$$

Masses and Decoupling

Decoupling limit [Gunion, Haber 2003]

$$\overline{m}^2 = \frac{m_{12}^2}{s_\beta c_\beta} \gg |\lambda_i| v^2 \qquad \text{implies} \qquad c_{\beta-\alpha} = 0$$

Masses:

$$M_0^2,\, M_A^2,\, M_H^2 \simeq \overline{m}^2 + \mathcal{O}(\lambda_i v^2)$$
$$m_h^2 \simeq \mathcal{O}(\lambda_i v^2)$$

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Alternative non-decoupling limit

$$\overline{m}^2 \ll |\lambda_i| v^2\,, \qquad |\lambda_i| < 4\pi$$

Possibility for

$$M_0,\ M_A,\ M_H \simeq \mathcal{O}(M)\,, \qquad m_h,\ \overline{m} \simeq \mathcal{O}(v)$$

Tree-Level Matching

Potential in terms of the mass eigenstates

$$
\begin{aligned}
V = &\frac{1}{2}(m_h^2 h^2 + M_0^2 H_0^2 + M_A^2 A_0^2) + M_H^2 H^+ H^- \\
&- d_1 h^3 - d_2 h^2 H - d_3 h H^2 - d_4 H^3 - d_5 h H^+ H^- \\
&- d_6 h A_0^2 - d_7 H H^+ H^- - d_8 H A_0^2 - z_1 h^4 + \dots
\end{aligned}
$$

Non-decoupling limit: d_i, $z_i \simeq \mathcal{O}(M^2)$

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Non-decoupling limit: d_i, $z_i \simeq \mathcal{O}(M^2)$

EOM from $\mathcal{O}(M^2)$ part of the Lagrangian with solution:

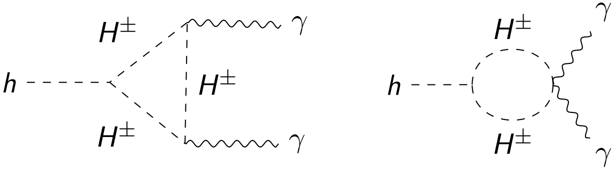
$$H_0(h) = \sum_{k=2}^{\infty} r_k h^k\,, \qquad H^{\pm}(h) = A_0(h) = 0$$

However, all tree-level non-decoupling effects vanish for $c_{\beta-\alpha} = 0$

One-Loop Matching

Non-decoupling EFT contributions to $h \to \gamma\gamma$ through $H^{\pm}$ loops

[Arco, Domenech, Herrero, Morales 2023]



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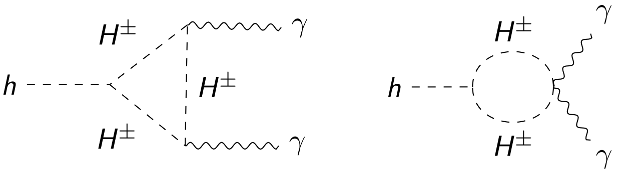

Our strategy: Universal One Loop Effective Action

[Henning, Lu, Murayama 2016; Fuentes-Martin, Portoles, Ruiz-Femenia 2016]

$$\mathcal{L}^{(2)}_{H^\pm} = H^- \Delta H^+ \,, \quad \Delta = -D^2 - M_H^2 - Y\big(h, H_0(h)\big)\,, \quad Y \simeq \mathcal{O}(M_H^2)$$

EFT contribution is given by

$$\mathcal{L}_{1L} = \frac{1}{16\pi^2}\left[\frac{1}{12M_H^2}Y - \frac{1}{24M_H^4}Y^2 + \ldots\right] F_{\mu\nu}F^{\mu\nu} + \ldots$$

Results and Phenomenology

Global HEFT fit [De Blas, Eberhardt, Krause 2018]

$$\mathcal{L}_{fit} = 2c_V m_W^2 W_\mu^+ W^{-\mu} \frac{h}{v} + \frac{e^2}{16\pi} c_{\gamma h}^{(1)} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \ldots$$

with $c_V = 1.01 \pm 0.06$ and $c_{\gamma h}^{(1)} = 0.05 \pm 0.20$ at 68% CL

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2HDM matching gives

$$c_V = s_{\beta-\alpha} \gtrsim 0.95$$
$$c_{\gamma h}^{(1)} = \frac{s_{\beta-\alpha}}{6} \approx 0.16$$

Phenomenologically viable, but could be ruled out with more data

Conclusions

- Non-decoupling effects in 2HDM are possible
- (H)EFT can/should be derived using functional methods
- One-loop non-decoupling effects are phenomenologically relevant
- More data can exclude the non-decoupling limit

Backup: Non-Linear Parameterization

Use the bi-doublet representation:

$$S_n \equiv (\tilde{\Phi}_n, \Phi_n)\,, \quad n = 1,\, 2$$

Parameterization [Dittmaier, Rzehak 2022]

$$S_n \equiv U R_n\,, \quad R_n = \frac{1}{\sqrt{2}}\left[(v_n + h_n)1 + i C_n \sigma_a \rho_a\right], \quad U = \exp\left(i\varphi_a\sigma_a/v\right)$$

with

$$C_1 = -\frac{v_2}{v} \equiv -s_\beta\,, \quad C_2 = \frac{v_1}{v} \equiv c_\beta$$

Mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_0 \\ h \end{pmatrix}, \quad H^\pm = \frac{1}{\sqrt{2}}(\rho_1 \mp i\rho_2)\,, \quad A_0 = \rho_3$$

Backup: Equations of Motion

Split potential parameters as

$$d_i \to \sum_{j=A,H,0} M_j^2 d_{i,j} + \bar{d}_i \,, \qquad z_i \to \sum_{j=A,H,0} M_j^2 z_{i,j} + \bar{z}_i \,,$$

EOM from $\mathcal{O}(M_0^2)$ part of potential

$$(1-d_{3,0}h-2z_{3,0}h^2)H_0 = d_{2,0}h^2+z_{2,0}h^3+(3d_{4,0}+3z_{4,0}h)H_0^2+4z_{5,0}H_0^3$$

Exact solution

$$H_0(h) = \frac{v+\left(\frac{s_\alpha^2 c_\alpha}{s_\beta}-\frac{s_\alpha c_\alpha^2}{c_\beta}\right)h}{\frac{s_\alpha^3}{s_\beta}+\frac{c_\alpha^3}{c_\beta}}\left[\sqrt{1-\frac{\left(\frac{s_\alpha^3}{s_\beta}+\frac{c_\alpha^3}{c_\beta}\right)\left(\frac{s_\alpha c_\alpha^2}{s_\beta}+\frac{s_\alpha^2 c_\alpha}{c_\beta}\right)h^2}{\left(v+\left(\frac{s_\alpha^2 c_\alpha}{s_\beta}-\frac{s_\alpha c_\alpha^2}{c_\beta}\right)h\right)^2}}-1\right]$$

Generate h coefficients by Taylor expanding: $H_0(h) = \sum_k r_k h^k$

Backup: Higher Order UOLEA

Reminder:

$$\mathcal{L}^{(2)}_{H^\pm} = H^- \Delta H^+ \,, \quad \Delta = -D^2 - M_H^2 - Y\big(h, H_0(h)\big) \,, \quad Y \simeq \mathcal{O}(M_H^2)$$

In our case (use EOM to eliminate H_0)

$$\frac{Y}{M_H^2} = 2 s_{\beta-\alpha} \frac{h}{v} + \left[1 - 2c^4_{\beta-\alpha} + 2c^3_{\beta-\alpha} s_{\beta-\alpha} \cot 2\beta)\right] \left(\frac{h}{v}\right)^2 + \mathcal{O}(h^3) + \mathcal{O}(1/M_H^2)$$

One-loop EFT contribution

$$\mathcal{L}_{1L} = \frac{1}{16\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{12n} \operatorname{tr}\left\{ \left(\frac{Y}{M_H^2}\right)^n F_{\mu\nu} F^{\mu\nu} \right\}$$

Careful! Only works if $[Y, F_{\mu\nu}] = 0$