# 2HDM Matched to Nonlinear Effective Theory

## 8th General Meeting of the LHC EFT Working Group

Florian Pandler
work with G. Buchalla, F. König, C. Müller-Salditt
arXiv:2312.13885, Phys. Rev. D 110, 016015

Faculty of Physics, ASC, LMU Munich
F.Pandler@physik.uni-muenchen.de

3 December 2024

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

# Contents

- Motivation
- 2HDM: Basics and Non-decoupling Limit
- Tree- and One-Loop Matching to HEFT
- Phenomenology
- Conclusions

# Motivation

# Motivation

- Is the particle discovered in 2012 the Standard Model (SM) Higgs boson or is it something else?

# Motivation

- Is the particle discovered in 2012 the Standard Model (SM) Higgs boson or is it something else?
- Use Effective Field Theory (EFT) framework to parameterize the indirect effects of new physics: electroweak chiral Lagrangian (HEFT)

# Motivation

- Is the particle discovered in 2012 the Standard Model (SM) Higgs boson or is it something else?
- Use Effective Field Theory (EFT) framework to parameterize the indirect effects of new physics: electroweak chiral Lagrangian (HEFT)
- Take well-known extension of Higgs sector, the Two-Higgs doublet model (2HDM) in the non-decoupling limit, and examine how HEFT is realized as the low-energy EFT

# Motivation

- Is the particle discovered in 2012 the Standard Model (SM) Higgs boson or is it something else?
- Use Effective Field Theory (EFT) framework to parameterize the indirect effects of new physics: electroweak chiral Lagrangian (HEFT)
- Take well-known extension of Higgs sector, the Two-Higgs doublet model (2HDM) in the non-decoupling limit, and examine how HEFT is realized as the low-energy EFT
- Use functional methods

# Motivation

- Is the particle discovered in 2012 the Standard Model (SM) Higgs boson or is it something else?
- Use Effective Field Theory (EFT) framework to parameterize the indirect effects of new physics: electroweak chiral Lagrangian (HEFT)
- Take well-known extension of Higgs sector, the Two-Higgs doublet model (2HDM) in the non-decoupling limit, and examine how HEFT is realized as the low-energy EFT
- Use functional methods
- Non-decoupling effects could be relevant for $h \to \gamma\gamma$ (and $h \to \gamma Z$)

# (Real) Two-Higgs Doublet Model (2HDM)

$$\mathscr{L}_{2HDM} = \left(D_\mu \Phi_n\right)^\dagger \left(D^\mu \Phi_n\right) - V_{2HDM}, \quad n = 1, 2$$

# (Real) Two-Higgs Doublet Model (2HDM)

$$\mathscr{L}_{2HDM} = \left(D_\mu \Phi_n\right)^\dagger \left(D^\mu \Phi_n\right) - V_{2HDM}, \quad n = 1,2$$

$$\begin{aligned} V_{2HDM} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left[\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right] \\ & + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\ & + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{1}{2}\lambda_5 \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right] \end{aligned}$$

# (Real) Two-Higgs Doublet Model (2HDM)

$$\mathscr{L}_{2HDM} = \left(D_\mu \Phi_n\right)^\dagger \left(D^\mu \Phi_n\right) - V_{2HDM}, \quad n = 1,2$$

$$\begin{aligned} V_{2HDM} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left[\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right] \\ & + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\ & + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{1}{2}\lambda_5 \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right] \end{aligned}$$

Polar coordinate representation of $S_n = \left(\tilde{\Phi}_n, \Phi_n\right)$ [Dittmaier and Rzehak 2022]

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

# (Real) Two-Higgs Doublet Model (2HDM)

$$\mathscr{L}_{2HDM} = \left(D_\mu \Phi_n\right)^\dagger \left(D^\mu \Phi_n\right) - V_{2HDM}, \quad n = 1,2$$

$$\begin{aligned} V_{2HDM} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left[\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right] \\ & + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\ & + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{1}{2}\lambda_5 \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right] \end{aligned}$$

Polar coordinate representation of $S_n = \left(\tilde{\Phi}_n, \Phi_n\right)$ [Dittmaier and Rzehak 2022]

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

Physical Parameters

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

# Non-decoupling limit

Phenomenological requirement:

- $M_S \sim M_0, M_H, M_A \gg m_h \sim v$ (new scalars are heavy!)

# Non-decoupling limit

Phenomenological requirement:

- $M_S \sim M_0, M_H, M_A \gg m_h \sim v$ (new scalars are heavy!)

**Decoupling regime (weak coupling): SMEFT scenario**

$$\lambda_i = \mathcal{O}(1), \quad m_h \sim v \ll \overline{m} \sim M_S, \qquad c_{\beta-\alpha} \ll 1$$

# Non-decoupling limit

Phenomenological requirement:

- $M_S \sim M_0, M_H, M_A \gg m_h \sim v$ (new scalars are heavy!)

**Decoupling regime (weak coupling): SMEFT scenario**

$$\lambda_i = \mathcal{O}(1), \quad m_h \sim v \ll \overline{m} \sim M_S, \qquad c_{\beta-\alpha} \ll 1$$

**Non-decoupling regime (strong coupling): HEFT scenario**

$$1 \ll |\lambda_i| \lesssim 16\pi^2, \quad m_h \sim v \sim \overline{m} \ll M_S, \qquad c_{\beta-\alpha} = \mathcal{O}(1)$$

- Phenomenologically we know: $c_{\beta-\alpha} \ll 1$ ($h$ couplings to gauge bosons are close to SM values)

# Tree-Level Matching

**Integrate out heavy scalars at tree-level**

Solve their equations of motion (EOM) and insert the solution back into $\mathscr{L}$

$$V = \frac{m_h^2}{2}h^2 + \frac{M_0^2}{2}H_0^2 + M_H^2 H^+ H^- + \frac{M_A^2}{2}A_0^2 - d_1 h^3 - d_2 h^2 H_0 - d_3 h H_0^2$$
$$- d_4 H_0^3 - d_5 h H^+ H^- - d_6 h A_0^2 - d_7 H^+ H^- H_0 - d_8 H_0 A_0^2 - z_1 h^4 + \cdots$$

Non-decoupling limit: $v\, d_i, v^2 z_i \sim \mathscr{O}(M_S^2)$

# Tree-Level Matching

**Integrate out heavy scalars at tree-level**

Solve their equations of motion (EOM) and insert the solution back into $\mathscr{L}$

$$V = \frac{m_h^2}{2} h^2 + \frac{M_0^2}{2} H_0^2 + M_H^2 H^+ H^- + \frac{M_A^2}{2} A_0^2 - d_1 h^3 - d_2 h^2 H_0 - d_3 h H_0^2$$
$$- d_4 H_0^3 - d_5 h H^+ H^- - d_6 h A_0^2 - d_7 H^+ H^- H_0 - d_8 H_0 A_0^2 - z_1 h^4 + \cdots$$

Non-decoupling limit: $v\, d_i, v^2 z_i \sim \mathcal{O}(M_S^2)$

**Solution to $\mathcal{O}(M_S^2)$ EOM**

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

All tree-level effects vanish for $c_{\beta-\alpha} = 0$!

# Tree-Level Matching: HEFT

Effective theory takes the form of an electroweak chiral Lagrangian (at chiral dimension 2):

$$
\begin{aligned}
\mathscr{L}_{Uh,2} = & \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle (1+F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) \\
& - \Bigg[ \bar{q}_L \left( \mathscr{M}_u + \sum_{n=1}^{\infty} \mathscr{M}_u^{(n)} \left(\frac{h}{v}\right)^n \right) U P_+ q_R \\
& + \bar{q}_L \left( \mathscr{M}_d + \sum_{n=1}^{\infty} \mathscr{M}_d^{(n)} \left(\frac{h}{v}\right)^n \right) U P_- q_R \\
& + \bar{l}_L \left( \mathscr{M}_e + \sum_{n=1}^{\infty} \mathscr{M}_e^{(n)} \left(\frac{h}{v}\right)^n \right) U P_- l_R + h.c. \Bigg]
\end{aligned}
$$

# Tree-Level Matching: HEFT

Effective theory takes the form of an electroweak chiral Lagrangian (at chiral dimension 2):

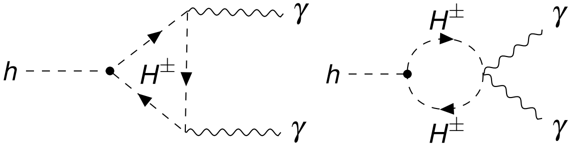
$$\begin{aligned}\mathscr{L}_{Uh,2} =& \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle\left(1+F_U(h)\right)+\frac{1}{2}\partial_\mu h\partial^\mu h - V(h)\\ &-\Bigg[\bar{q}_L\left(\mathscr{M}_u+\sum_{n=1}^{\infty}\mathscr{M}_u^{(n)}\left(\frac{h}{v}\right)^n\right)UP_+q_R\\ &+\bar{q}_L\left(\mathscr{M}_d+\sum_{n=1}^{\infty}\mathscr{M}_d^{(n)}\left(\frac{h}{v}\right)^n\right)UP_-q_R\\ &+\bar{l}_L\left(\mathscr{M}_e+\sum_{n=1}^{\infty}\mathscr{M}_e^{(n)}\left(\frac{h}{v}\right)^n\right)UP_-l_R+h.c.\Bigg]\end{aligned}$$

Tree level matching gives anomalous Higgs couplings e.g.:

$$F_U(h) = 2s_{\beta-\alpha}\frac{h}{v}+\left(1-\frac{s_{2\alpha}}{s_{2\beta}}c_{\beta-\alpha}^2\right)\left(\frac{h}{v}\right)^2-\frac{4}{3}\frac{s_{2\alpha}^2}{s_{2\beta}^2}c_{\beta-\alpha}^2 s_{\beta-\alpha}\left(\frac{h}{v}\right)^3+\cdots$$

# One-Loop Matching

$H^{\pm}$ loops induce $h \to \gamma\gamma$ (and $h \to \gamma Z$) transitions! [Arco et al. 2023]




Integrating out the heavy charged scalar $H^{\pm}$ gives local Higgs-photon operators!

$$\mathscr{L} = \frac{e^2}{16\pi^2}\left(F_{\mu\nu}F^{\mu\nu} + \frac{1-s_W^2}{s_W c_W}F_{\mu\nu}Z^{\mu\nu}\right)F_X\left(\frac{h}{v}\right)$$

Effects survive in the alignment limit ($c_{\beta-\alpha} = 0$)!

# One-Loop Matching: Functional approach

Use functional methods [Fuentes-Martin, Portoles, and Ruiz-Femenia 2016] to integrate out $H^{\pm}$:

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

One loop EFT contribution (assuming $[Y, F_{\mu\nu}] = 0$)

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

Result:

$$F_X\left(\frac{h}{v}\right) = \frac{s_{\beta-\alpha}}{6}\frac{h}{v} - \frac{1}{12}\left(s_{\beta-\alpha}^2 + \frac{s_{2\alpha}}{s_{2\beta}}c_{\beta-\alpha}^2\right)\left(\frac{h}{v}\right)^2 + \mathscr{O}(h^3) \qquad (1)$$

# Phenomenology

## Focus on 2 HEFT couplings

$$\mathscr{L}_{HEFT} \supset 2\, c_V\, m_W^2\, W_\mu^+ W^{-\mu} \frac{h}{v} + \frac{e^2}{16\pi^2} c_\gamma F_{\mu\nu} F^{\mu\nu} \frac{h}{v}$$

## Global HEFT fit (68% CL) [Blas, Eberhardt, and Krause 2018]

$$c_V = 1.01 \pm 0.06, \quad c_\gamma = 0.05 \pm 0.20$$

Results from 2HDM matching:

$$c_V = s_{\beta-\alpha} \gtrsim 0.95$$
$$c_\gamma = \frac{s_{\beta-\alpha}}{6} \approx 0.16$$

Compatible with present data!

# Summary

- (H)EFT matching calculations using functional methods are very efficient!
- Non-decoupling effects are possible in the 2HDM!
- Non-decoupling effects for $h \to \gamma\gamma$ (and $h \to \gamma Z$) are still compatible with present data and could be confirmed or ruled out in the future!

Thank you for your attention!
Questions?

# Backup: Custodial Symmetry Breaking

Scalar potential contains custodial-symmetry violating term:

$$\Delta V_{CSB} = (\lambda_5 - \lambda_4)\langle S_1^\dagger S_2 T_3 \rangle^2$$

Integrating out the heavy scalars this generates the two-derivative operator:

$$\mathscr{L}_{\beta_1} = \beta_1 v^2 \langle U^\dagger D_\mu U T_3 \rangle^2$$

However, this is not a leading order effect, since [Branco et al. 2012]

$$\beta_1 \sim \frac{\lambda_4 - \lambda_5}{16\pi^2} \sim \frac{M_A^2 - M_H^2}{16\pi^2 v^2}$$