

# Matching Two-Higgs Doublet Models with Higgs EFT

Hermès BÉLUSCA-MAÏTO

[hermes.belusca@th.u-psud.fr](mailto:hermes.belusca@th.u-psud.fr)

in collaboration with Adam Falkowski (LPT), and

Duarte Fontes, Jorge Romão and João P. Silva (CFTP Lisbon)



Laboratoire de Physique Théorique  
Université Paris-Sud XI, ORSAY, France

Rencontres de Physique des Particules, 25–27 janvier 2016, Annecy

Based on [HBM, A. Falkowski, D. Fontes, J. Romão and J.P. Silva, *Work in preparation*]

# Overview

① Introduction: Motivation, EFT, 2HDM

② Higgs EFT & The setup

③ Results & Comments

④ Conclusion

# Overview

① Introduction: Motivation, EFT, 2HDM

② Higgs EFT & The setup

③ Results & Comments

④ Conclusion

# Motivation

## The context

- SM certainly needs to be completed by physics BSM.
- No direct signs of new physics @ LHC.
- If new physics decoupled enough from SM  $\Rightarrow$  EFT.

*Does EFT always work?*

Our aim: (partly...) answer the question

Use one of the simplest BSM model: the 2HDM. Write an EFT at dimension-6+ from the 2HDM and see how best it captures features of the 2HDM, or how/why it fails to do so (see also [[Gorbahn et al. \(1502.07352\)](#)] and [[Brehmer et al. \(1510.03443\)](#)] for similar works studying CP-conserving 2HDM with  $d = 6$  EFT only, and other models).

# Motivation

## The context

- SM certainly needs to be completed by physics BSM.
- No direct signs of new physics @ LHC.
- If new physics decoupled enough from SM  $\Rightarrow$  EFT.

*Does EFT always work?*

## Our aim: (partly...) answer the question

Use one of the simplest BSM model: the 2HDM. Write an EFT at dimension-6+ from the 2HDM and see how best it captures features of the 2HDM, or how/why it fails to do so (see also [[Gorbahn et al. \(1502.07352\)](#)] and [[Brehmer et al. \(1510.03443\)](#)] for similar works studying CP-conserving 2HDM with  $d = 6$  EFT only, and other models).

# SM Effective Approach in a nutshell

- Suppose new degrees of freedom @ high energy  
⇒ **Separation of scales:**  $m(\text{NP}) \gg m(\text{EW})$ .
- At lower energies, NP modifies interactions of SM fields (modify SM predictions).  
Formally: NP fields are integrated out, generation of (non-renormalisable) dim.  $\geq 5$  effective operators.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d \geq 5} \frac{\mathcal{C}^{(d)}}{\Lambda_{\text{NP}}^{d-4}} \mathcal{O}^{(d)} (\{\text{SM fields}\}) = \mathcal{L}_{D=5} + \mathcal{L}_{D=6} + \dots$$

- $\mathcal{L}_{\text{SM}}$ : the Standard-Model Lagrangian.
- $\Lambda_{\text{NP}}$ : energy scale of NP;  
 $\mathcal{C}^{(d)}$ : dimensionless effective coupling ("Wilson coefficient");  
 $\mathcal{O}^{(d)}$ : effective operator, *function of SM fields only*.
- $\mathcal{L}_{D=5}$  (Weinberg operator): masses for neutrinos.
- $\mathcal{L}_{D=6}$  etc... is the interesting part!

# Why looking at 2HDM?

- Motivated extensions of the SM such as SUSY having an extended scalar sector.
- Ex. in SUSY: two Higgs superfields couple separately to up and down-type fermions. Needed to cancel anomalies due to higgsinos; holomorphicity of superpotential.
- Composite models can generate two doublets, with a coupling structure different from SUSY [Mrazek et al. ([arXiv:1105.5403](#))].
- It's one simple SM extension!

Also:

- May provide a simple framework (provided other ingredients, see e.g. [A. Angelescu, A. Djouadi, G. Moreau ([arXiv:1512.04921](#))] for understanding the  $\gamma\gamma$  excess seen by both ATLAS & CMS at  $\approx 750$  GeV at the beginning of Run-II @ 13 TeV [[ATLAS/CMS 13 TeV Results, 15 Dec. 2015](#)]).
- DM candidate?

# Why looking at 2HDM?

- Motivated extensions of the SM such as SUSY having an extended scalar sector.
- Ex. in SUSY: two Higgs superfields couple separately to up and down-type fermions. Needed to cancel anomalies due to higgsinos; holomorphicity of superpotential.
- Composite models can generate two doublets, with a coupling structure different from SUSY [Mrazek et al. ([arXiv:1105.5403](#))].
- It's one simple SM extension!

Also:

- May provide a simple framework (provided other ingredients, see e.g. [A. Angelescu, A. Djouadi, G. Moreau ([arXiv:1512.04921](#))] for understanding the  $\gamma\gamma$  excess seen by both ATLAS & CMS at  $\approx 750$  GeV at the beginning of Run-II @ 13 TeV [[ATLAS/CMS 13 TeV Results, 15 Dec. 2015](#)]).
- DM candidate?

# 2HDM recap. (1/2)

*See Olcyr's talk*

Two Higgs doublets  $\Phi_{1,2}$ . Imposing  $\mathbb{Z}_2$  symmetry to forbid FCNC @ tree-level (or softly broken):  $\Phi_1 \rightarrow \Phi_1$ ;  $\Phi_2 \rightarrow -\Phi_2$ .

Choice a basis of doublets such that only one acquires a VEV (always possible).

$$\Phi_{1,2} \quad \rightarrow \quad H_1 = \begin{pmatrix} -iG^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG_z) \end{pmatrix}; \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + iA) \end{pmatrix}$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}-H} + |D_\mu H_1|^2 + |D_\mu H_2|^2 + \mathcal{L}_{\text{Yuk}}(H_1, H_2) - V(H_1, H_2)$$

**Yukawa terms** (sum over  $f = u, d, \ell$ , and  $\eta_f = 1$  or  $-t_\beta^2$  according to 2HDM type):

$$\mathcal{L}_{\text{Yuk}}(H_1, H_2) = -H_1^\dagger \overline{f_R} Y_f f_L - \frac{\eta_f}{t_\beta} H_2^\dagger \overline{f_R} Y_f f_L + \text{h.c.}$$

Scalar potential in the VEV basis (Usually called "Higgs basis" . . .):

$$\begin{aligned} V(H_1, H_2) = & Y_1 |H_1|^2 + Y_2 |H_2|^2 + (Y_3 H_1^\dagger H_2 + \text{h.c.}) + \frac{Z_1}{2} |H_1|^4 + \frac{Z_2}{2} |H_2|^4 \\ & + Z_3 |H_1|^2 |H_2|^2 + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{ \frac{Z_5}{2} (H_1^\dagger H_2)^2 + (Z_6 |H_1|^2 + Z_7 |H_2|^2)(H_1^\dagger H_2) + \text{h.c.} \right\} \end{aligned}$$

## 2HDM recap. (2/2)

Diagonalize the mass matrix. Rewrite the neutral real eigenstates  $h_{1,2}$  in terms of the light  $h$  and heavy  $H_0$  mass eigenstates:

$$h_1 = s_{\beta-\alpha} h + c_{\beta-\alpha} H_0, \quad h_2 = c_{\beta-\alpha} h - s_{\beta-\alpha} H_0.$$

Couplings to fermions (Yukawa terms) in different ways ( $\Rightarrow$  4 types of 2HDM):

	Type-I	Type-II		$\ell$ -specific (Type-X)		Flipped (Type-Y)	
	$u, d, \ell$	$u$	$d, \ell$	$u, d$	$\ell$	$u, \ell$	$d$
$h$	$c_\alpha/s_\beta$	$c_\alpha/s_\beta$	$-s_\alpha/c_\beta$	$c_\alpha/s_\beta$	$-s_\alpha/c_\beta$	$c_\alpha/s_\beta$	$-s_\alpha/c_\beta$
$H_0$	$s_\alpha/s_\beta$	$s_\alpha/s_\beta$	$c_\alpha/c_\beta$	$s_\alpha/s_\beta$	$c_\alpha/c_\beta$	$s_\alpha/s_\beta$	$c_\alpha/c_\beta$
$A$	$\pm \cot \beta$	$\cot \beta$	$+t_\beta$	$\pm \cot \beta$	$+t_\beta$	$\pm \cot \beta$	$+t_\beta$

Couplings to vector bosons are  $\propto s_{\beta-\alpha}$  for  $h$ ;  $\propto c_{\beta-\alpha}$  for  $H_0$  and none for  $A$ .

Two limits:

- Alignment limit:  $c_{\beta-\alpha} \ll 1$ , i.e.  $h$  lives in  $H_1$  and corresponds to the SM Higgs boson, while the other eigenstates can be near in energy;
- Decoupling limit:  $Y_2 \gg v^2$ , so that  $m_{H_0, H^\pm, A} \gg m_h$ .

## 2HDM recap. (2/2)

Diagonalize the mass matrix. Rewrite the neutral real eigenstates  $h_{1,2}$  in terms of the light  $h$  and heavy  $H_0$  mass eigenstates:

$$h_1 = s_{\beta-\alpha} h + c_{\beta-\alpha} H_0, \quad h_2 = c_{\beta-\alpha} h - s_{\beta-\alpha} H_0.$$

Couplings to fermions (Yukawa terms) in different ways ( $\Rightarrow$  4 types of 2HDM):

	Type-I	Type-II		$\ell$ -specific (Type-X)		Flipped (Type-Y)	
	$u, d, \ell$	$u$	$d, \ell$	$u, d$	$\ell$	$u, \ell$	$d$
$h$	$c_\alpha/s_\beta$	$c_\alpha/s_\beta$	$-s_\alpha/c_\beta$	$c_\alpha/s_\beta$	$-s_\alpha/c_\beta$	$c_\alpha/s_\beta$	$-s_\alpha/c_\beta$
$H_0$	$s_\alpha/s_\beta$	$s_\alpha/s_\beta$	$c_\alpha/c_\beta$	$s_\alpha/s_\beta$	$c_\alpha/c_\beta$	$s_\alpha/s_\beta$	$c_\alpha/c_\beta$
$A$	$\pm \cot \beta$	$\cot \beta$	$+t_\beta$	$\pm \cot \beta$	$+t_\beta$	$\pm \cot \beta$	$+t_\beta$

Couplings to vector bosons are  $\propto s_{\beta-\alpha}$  for  $h$ ;  $\propto c_{\beta-\alpha}$  for  $H_0$  and none for  $A$ .

Two limits:

- Alignment limit:  $c_{\beta-\alpha} \ll 1$ , i.e.  $h$  lives in  $H_1$  and corresponds to the SM Higgs boson, while the other eigenstates can be near in energy;
- Decoupling limit:  $Y_2 \gg v^2$ , so that  $m_{H_0, H^\pm, A} \gg m_h$ .

# Overview

1 Introduction: Motivation, EFT, 2HDM

2 Higgs EFT & The setup

3 Results & Comments

4 Conclusion

# SM Higgs EFT: Prerequisites

## General assumptions for SM Higgs EFT

- The operators are  $SU(3) \times SU(2) \times U(1)$  invariant.
- The 125 GeV Higgs boson  $h$  is part of the Higgs doublet  $H$  that transforms as  $(\mathbf{1}, \mathbf{2})_{1/2}$  representation of the Standard Model  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge group and acquires a VEV  $v$ .
- No violation of baryon and lepton numbers.

## And additionally for this work...

- No Flavour-Changing operators.
- We keep operators with at most 2 derivatives.
- We express the final results in the “Higgs basis” from LHC Higgs XSec WG2 [[LHCHXSWG-INT-2015-001](#)].

# SM Higgs EFT: Prerequisites

## General assumptions for SM Higgs EFT

- The operators are  $SU(3) \times SU(2) \times U(1)$  invariant.
- The 125 GeV Higgs boson  $h$  is part of the Higgs doublet  $H$  that transforms as  $(\mathbf{1}, \mathbf{2})_{1/2}$  representation of the Standard Model  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge group and acquires a VEV  $v$ .
- No violation of baryon and lepton numbers.

## And additionally for this work...

- No Flavour-Changing operators.
- We keep operators with at most 2 derivatives.
- We express the final results in the “Higgs basis” from LHC Higgs XSec WG2 [[LHCHXSWG-INT-2015-001](#)].

# Procedure – $d = 6$ @ tree-level in decoupling limit

Suppose **decoupling limit**  $\Rightarrow H_0, H^\pm, A$  are heavy: integrate them out.

Equivalent [Barbieri et al. (arXiv:hep-ph/0405040)] to integrate out the (gauge-eigenstate)  $H_2$  doublet (and  $Y_2$  plays the role of  $\Lambda_{\text{NP}}$ ).

Equation of motion for  $H_2$ , and use  $Y_3 = -\frac{Z_6 v^2}{2}$  “vacuum relation”:

$$Y_2 H_2 \equiv C = -\frac{\eta_f}{t_\beta} \bar{f}_R Y_f f_L - Z_6 \left( |H_1|^2 - \frac{v^2}{2} \right) H_1$$

Replace  $H_2$  in the Lagrangian:

$$\mathcal{L}_{\text{eff}}^{D=6} = \mathcal{L}_{\text{SM}-H} + |D_\mu H_1|^2 + \mathcal{L}_{\text{Yuk}}(H_1) - V(H_1) + \frac{|C|^2}{Y_2}$$

Induced shifts of the Yukawas, and the trilinear Higgs coupling (decoupling limit):

$$\begin{aligned} \mathcal{L}_{hff}^{D=6} &= -\frac{h}{v} \sum_{\substack{f=u,d,e \\ i \neq j}} \sqrt{m_{fi} m_{fj}} [[\delta y_f]_{ij} \bar{f}_{R,i} f_{L,j} + \text{h.c.}] & \mathcal{L}_{h^3}^{D=6} &= -\delta \lambda_3 v h^3 \\ [\delta y_{u,d,e}]_{ij} &= -\frac{\eta_{u,d,e}}{t_\beta} Z_6 \frac{v^2}{Y_2} \delta_{ij} \quad ; \quad \delta \lambda_3 = -\frac{3Z_6^2}{2} \frac{v^2}{Y_2}. \end{aligned}$$

(plus other shifts elsewhere, not relevant for us). No corrections to  $hVV$  couplings at tree-level  $\Rightarrow$  go 1-loop.

# One-loop $d = 6$ EFT in decoupling limit

We focus on  $h\gamma\gamma$  and  $hZ\gamma$  at 1-loop: in the SM from a fermion loop and bosonic loops, with the addition of charged scalar loops from the 2HDM.

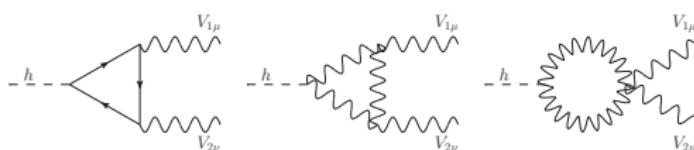


Figure: SM loops with possible 2HDM rescalings  
( $\sim 1$  in decoupling/alignment limit)

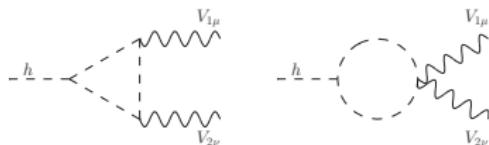


Figure: 2HDM loops with charged Higgs

Leading contributions:

$$c_{\gamma\gamma} \approx \frac{1}{48\pi^2} \frac{Z_3 v^2}{Y_2 + Z_3 v^2/2} + \mathcal{O}\left(\frac{v^4}{Y_2^2}\right)$$

$$c_{Z\gamma} \approx \frac{1}{96\pi^2} \frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} \frac{Z_3 v^2}{Y_2 + Z_3 v^2/2}$$

In decoupling limit:

$$c_{\gamma\gamma} = \frac{Z_3 v^2}{48\pi^2 Y_2}$$

$$c_{Z\gamma} = \frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} \frac{Z_3 v^2}{96\pi^2 Y_2}$$

# Case of alignment limit without decoupling...

- Here  $Y_2$  **not very large** (equivalently,  $m_{H_0, H^\pm, A}$  are not all  $\gg m_h$ ).  
 ⇒ The previous EFT derivation is expected to fail, in particular in scattering processes where a  $H_0, H^\pm, A$  is exchanged.
- However we still have:  $c_{\beta-\alpha} \ll 1$  so we may somewhat perform an expansion in  $c_{\beta-\alpha}$  instead of in  $1/Y_2$ , using:

$$c_{\beta-\alpha} \approx \frac{Z_6 v^2}{Y_2 + \frac{v^2}{2}(Z_{345} - 2Z_1)}$$

- Replace  $Y_2$  by  $\widetilde{Y}_2 = Y_2 + \frac{v^2}{2}(Z_{345} - 2Z_1)$  in the Yukawas & trilinear; use the original  $c_{\gamma\gamma}$  and  $c_{Z\gamma}$ :

$$[\delta y_{u,d,e}]_{ij} = -\frac{\eta_{u,d,e}}{t_\beta} Z_6 \frac{v^2}{\widetilde{Y}_2} \delta_{ij} \quad ; \quad \delta\lambda_3 = -\frac{3Z_6^2}{2} \frac{v^2}{\widetilde{Y}_2} \quad ;$$

$$c_{\gamma\gamma} \approx \frac{1}{48\pi^2} \frac{Z_3 v^2}{Y_2 + Z_3 v^2/2} + \mathcal{O}\left(\frac{v^4}{Y_2^2}\right) \quad ; \quad c_{Z\gamma} \approx \frac{1}{96\pi^2} \frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} \frac{Z_3 v^2}{Y_2 + Z_3 v^2/2} .$$

# Overview

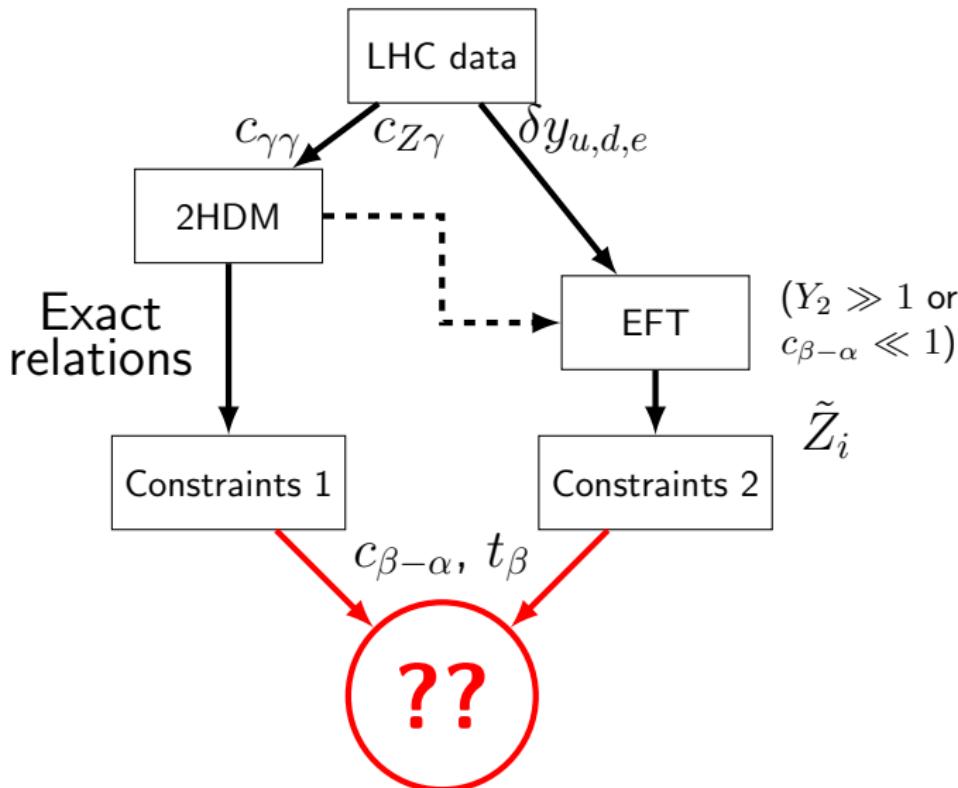
1 Introduction: Motivation, EFT, 2HDM

2 Higgs EFT & The setup

3 Results & Comments

4 Conclusion

# Procedure



# LHC data

Channel	$\mu_{\text{ATLAS}}$	$\mu_{\text{CMS}}$	Production	Ref.
$\gamma\gamma$	$1.30^{+2.62}_{-1.75}$	$2.7^{+2.4}_{-1.7}$	tth	[ATLAS (1507.04548)], [CMS (1412.8662)]
$Z\gamma$	$2.7^{+4.5}_{-4.3}$	$-0.2^{+4.9}_{-4.9}$	total	[ATLAS (1507.04548)], [CMS (1307.5515)]
$\tau\tau$	$1.5^{+1.1}_{-1.1}$	$1.2^{+1.6}_{-1.5}$	tth	[ATLAS (1503.05066)], [CMS (1502.02485)]
$\mu\mu$	$-0.7^{+3.7}_{-3.7}$	$0.8^{+3.5}_{-3.4}$	total	[ATLAS (1507.04548)], [CMS (1410.6679)]
multi- $\ell$	$2.1^{+1.4}_{-1.2}$	$3.8^{+1.4}_{-1.4}$	tth	[ATLAS (1506.05988)], [CMS (1408.1682)]

**Table:** The LHC Higgs results used in the analysis in addition to the combined ATLAS+CMS 2D likelihoods in [ATLAS+CMS (ATLAS-CONF-2015-044)].

# Data fit to 2HDM, and EFT

$$\begin{pmatrix} c_{\gamma\gamma} \\ c_{Z\gamma} \\ \delta y_u \\ \delta y_d \\ \delta y_e \end{pmatrix} = \begin{pmatrix} 0.001 \pm 0.010 \\ -0.002 \pm 0.095 \\ 0.028 \pm 0.13 \\ -0.15 \pm 0.17 \\ -0.05 \pm 0.15 \end{pmatrix}, \quad \rho = \begin{pmatrix} 1 & 0.06 & -0.32 & -0.61 & -0.38 \\ . & 1 & -0.03 & -0.06 & -0.04 \\ . & . & 1 & 0.75 & 0.33 \\ . & . & . & 1 & 0.51 \\ . & . & . & . & 1 \end{pmatrix}.$$

For EFT: define:  $\tilde{Z}_i = Z_i v^2 / \Lambda^2$  with  $\Lambda^2 = Y_2 \dots$ . The  $\delta y_{u,d,e}$  are correlated.  
 Recast the fit into:

- For **Type-I**:

$$\frac{\tilde{Z}_6}{t_\beta} = -0.04 \pm 0.11, \quad \tilde{Z}_3 = -3.9 \pm 4.0.$$

- For **Type-II**:

$$\begin{pmatrix} \tilde{Z}_6/t_\beta \\ \tilde{Z}_6 t_\beta \\ \tilde{Z}_3 \end{pmatrix} = \begin{pmatrix} -0.07 \pm 0.11 \\ -0.09 \pm 0.14 \\ -0.4 \pm 4.7 \end{pmatrix},$$

- For **Type-X** and **Type-Y**: similar to Type-II.

# Data fit to 2HDM and EFT/2HDM comparison (1/2)

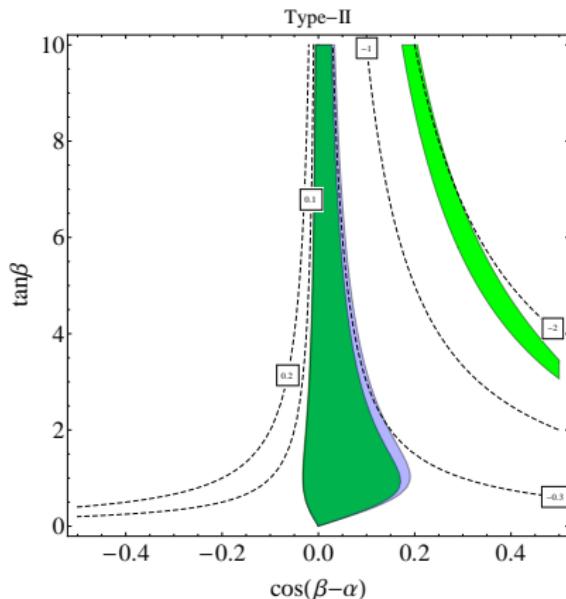
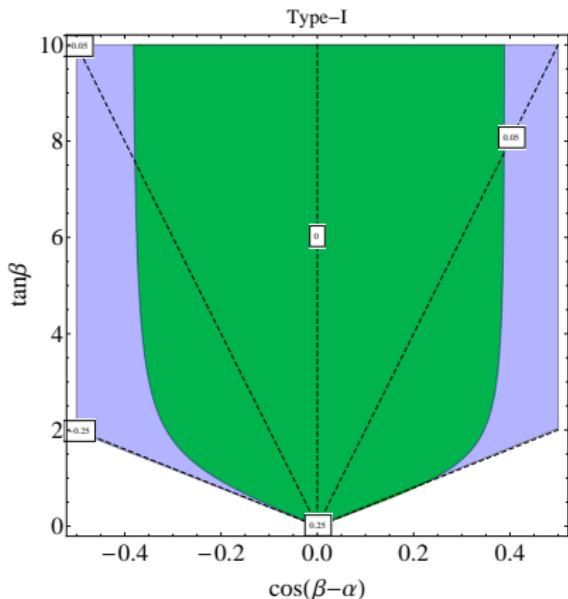


Figure: Allowed 95% CL region in the  $c_{\beta-\alpha}$ - $t_\beta$  plane in the linearized dimension-6 EFT corresponding to type-I (left) and type-II (right) 2HDM (blue). This is compared to the coupling fit directly in the 2HDM (green) where all non-linear terms in the likelihood are kept. Also shown are contours of constant  $\delta y_d$ .

# Data fit to 2HDM and EFT/2HDM comparison (2/2)

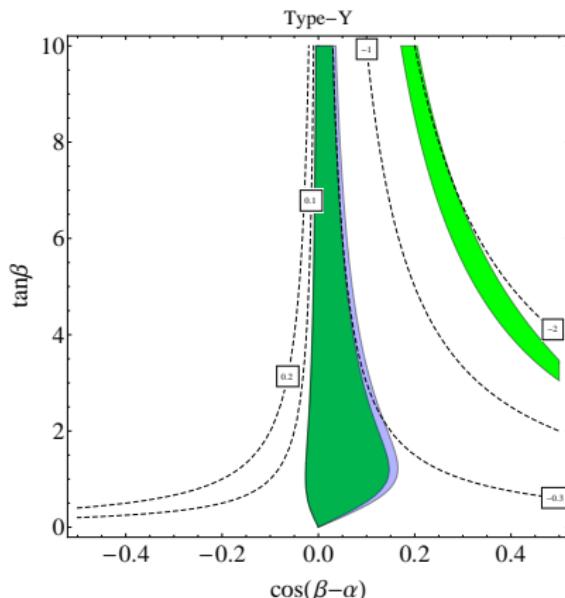
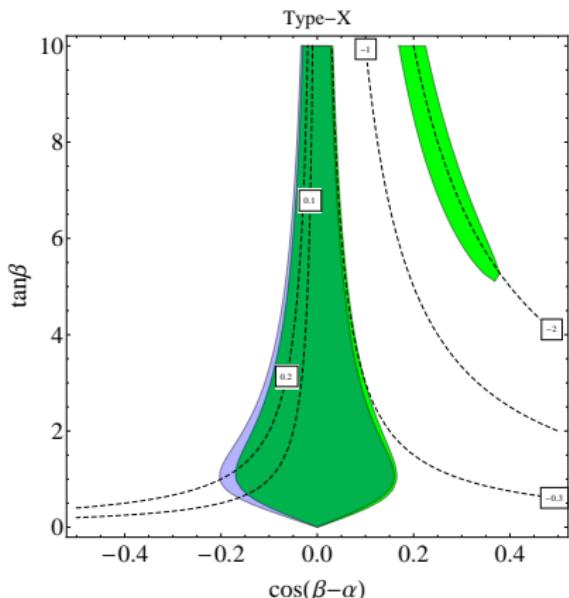


Figure: Allowed 95% CL region in the  $c_{\beta-\alpha}$ - $\tan\beta$  plane in the linearized dimension-6 EFT corresponding to type-X (left) and type-Y (right) 2HDM (blue). This is compared to the coupling fit directly in the 2HDM (green) where all non-linear terms in the likelihood are kept. Also shown are contours of constant  $\delta y_e$  (for type-X) and  $\delta y_d$  (for type-Y).

# Going further? $d = 8$ EFT

- Equation of motion for  $H_2$ :

$$\begin{aligned} 0 = & D^\mu D_\mu H_2 + Y_2 H_2 + Z_3 |H_1|^2 H_2 + Z_4 H_1 (H_1^\dagger H_2) + Z_5 H_1 (H_2^\dagger H_1) \\ & + \frac{\eta_f}{t_\beta} \bar{f}_R Y_f f_L + Y_3 H_1 + Z_6 |H_1|^2 H_1 \\ & + Z_7 (H_1^\dagger H_2) H_2 + Z_7^* (H_2^\dagger H_1) H_2 + Z_7 |H_2|^2 H_1 + Z_2 |H_2|^2 H_2 . \end{aligned}$$

- EFT at tree-level  $\Rightarrow$  solve for  $H_2$  supposing the following ansatz:

$$H_2 = H_2^{(0)} + \frac{1}{Y_2} H_2^{(1)} + \frac{1}{Y_2^2} H_2^{(2)} + \mathcal{O}\left(\frac{1}{Y_2^3}\right).$$

- We get:  $H_2^{(0)} = 0$  and:

$$H_2 = \frac{1}{Y_2} C + \frac{1}{Y_2^2} \left[ -D^\mu D_\mu C - Z_3 |H_1|^2 C - \left( Z_4 (H_1^\dagger C) + Z_5 (C^\dagger H_1) \right) H_1 \right],$$

where:

$$C = -\frac{\eta_f}{t_\beta} \bar{f}_R Y_f f_L - (Y_3 + Z_6 |H_1|^2) H_1 \quad ; \quad Y_3 = -\frac{Z_6}{2} v^2 .$$

# $d = 8$ Lagrangian @ tree-level

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{D \leq 8} = & \mathcal{L}_{\text{SM}-H} + |D_\mu H_1|^2 + \mathcal{L}_{\text{Yuk}}(H_1) - V(H_1) \\ & + \frac{1}{Y_2} |C|^2 + \frac{1}{Y_2^2} \left[ |D_\mu C|^2 - Z_3 |H_1|^2 |C|^2 - Z_4 (C^\dagger H_1)(H_1^\dagger C) \right] \\ & - \frac{Z_5}{2Y_2^2} \left\{ (H_1^\dagger C)^2 + \text{h.c.} \right\}\end{aligned}$$

where:

$$C = -\frac{\eta_f}{t_\beta} \bar{f}_R Y_f f_L - (Y_3 + Z_6 |H_1|^2) H_1 \quad ;$$

$$\mathcal{L}_{\text{Yuk}}(H_1) = -H_1^\dagger \bar{f}_R Y_f f_L + \text{h.c.} \quad ; \quad V(H_1) = Y_1 |H_1|^2 + \frac{Z_1}{2} |H_1|^4.$$

$\mathcal{L}_{\text{SM}-H}$ : SM Lagrangian without Higgs part.

Terms in red: dimension-6 operators.

Terms in blue: dimension-8 operators.

# New effects? (1/2) – WIP

Additional Yukawa, etc... contributions; no direct  $h - V - V$  modifications,  
**BUT...**

a modification of the Higgs kinetic term:

$$\frac{|D_\mu C|^2}{Y_2^2} \rightarrow \frac{v^2}{2} \frac{Z_6^2 v^4}{Y_2^2} (\partial_\mu \frac{h}{v})^2,$$

add it to the SM term  $\frac{v^2}{2} (\partial_\mu \frac{h}{v})^2$  (from  $|D_\mu H_1|^2$ ). To recover the canonical normalization of the Higgs kinetic term, redefine the Higgs field:

$$h \rightarrow \frac{h}{\sqrt{1 + \frac{Z_6^2 v^4}{Y_2^2}}} \approx h \left(1 - \frac{Z_6^2 v^4}{2 Y_2^2}\right).$$

This redefinition generates  $h - V - V$  shifts!

# New effects? (2/2) – WIP

At the end of the day:

- Yukawa contributions (always):

$$[\delta y_f]_{ij} = -\frac{\eta_f}{t_\beta} Z_6 \frac{v^2}{Y_2} \delta_{ij} + \frac{\eta_f}{t_\beta} \frac{Z_{345} Z_6}{2} \frac{v^4}{Y_2^2} \delta_{ij} - \frac{Z_6^2 v^4}{2 Y_2^2} \delta_{ij}.$$

- Trilinear Higgs coupling:

$$\delta \lambda_3 = -\frac{3 Z_6^2}{2} \frac{v^2}{Y_2} + \frac{5 Z_{345} Z_6^2}{4} \frac{v^4}{Y_2^2} - \frac{3 Z_6^2 v^4}{2 Y_2^2}.$$

- $h - V - V$ : only from  $d = 8$ :

$$\Delta \mathcal{L}_{hVV} = -\frac{Z_6^2 v^4}{2 Y_2^2} \frac{h}{v} [2 m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu].$$

This is Work In Progress!

# Overview

1 Introduction: Motivation, EFT, 2HDM

2 Higgs EFT & The setup

3 Results & Comments

4 Conclusion

# Conclusion (1/2)

- We have studied a simple example of EFT matching with the 2HDM.
- In the “decoupling limit” where  $m_{H_0, H^\pm, A} \gg m_h$ , EFT should work (as expected since we are in the correct conditions of usage).
- However EFT needs adaptation in the “alignment limit” (possibly without decoupling) where the Higgses may be almost degenerated in mass. In that case the expansion would better be done in  $c_{\beta-\alpha}$ .
- The EFT at  $d = 6$  tree + 1-loop doesn't capture all of the parameter space of the 2HDM...

## Conclusion (2/2)

The EFT at  $d = 6$  tree + 1-loop doesn't capture all of the parameter space of the 2HDM:

- Wrong-sign Yukawa region is not described: this indeed corresponds to a  $\mathcal{O}(1)$  deviation from the SM.
- No  $h \rightarrow VV$  modifications at tree level (there are, at loop level).  
⇒ Go to  $d = 8$ . Higgs kinetic term redefinition engenders  $h \rightarrow VV$  at tree-level.

What else?

- $d = 8$  is Work In Progress!
- We worked so far in CP-conserving 2HDM. What happens in the general CP-violating 2HDM? (in particular for  $h/A$  mixings).

*Thank you!*