# Yukawa Alignment in Two-Higgs-Doublet Models

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Aligned Two-Higgs-Doublet Model

Phenomenology

Conclusions

## Outline

Introduction

- 2 Aligned Two-Higgs-Doublet Model
- Phenomenology

Conclusions

The doublets and the benefits

Two Higgs doublets  $\phi_a$  (a=1,2) with  $Y=\frac{1}{2}$  whose neutral components acquire VEV's:

$$<0|\phi_a^T(x)|0>=\frac{1}{\sqrt{2}}\big(0,v_ae^{i\theta_a}\big) \qquad v=\sqrt{v_1^2+v_2^2} \qquad \text{Choice: } \theta_1=0\,, \theta\equiv\theta_2-\theta_1$$

$$\left(\begin{array}{c} \Phi_1 \\ -\Phi_2 \end{array}\right) \equiv \Omega \left(\begin{array}{c} \phi_1 \\ e^{-i\theta}\phi_2 \end{array}\right) \qquad ; \qquad \Omega \equiv \frac{1}{v} \left[\begin{array}{cc} v_1 & v_2 \\ v_2 & -v_1 \end{array}\right]$$

Higgs basis

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + S_1 + iG^0) \end{bmatrix} \qquad ; \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}} (S_2 + iS_3) \end{bmatrix}$$

 $S_1, S_2, S_3 \xrightarrow{\mathcal{R}} H, h, A$ 

- Present or required in many new-physics scenarios (SUSY)
- Potential new sources of CP symmetry breaking (also Spontaneous CP violation, Axion phenomenology, dark matter candidates...)

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$$\mathcal{L} = \mathcal{L}^{SM} + \overbrace{T_H + V_H}^{\mathcal{L}_H} + \mathcal{L}_Y$$

$$\mathcal{L}_{Y} = -\overline{Q}'_{L}(\Gamma_{1}\phi_{1}) \qquad )d'_{R} - \overline{Q}'_{L}(\Delta_{1}\widetilde{\phi}_{1}) \qquad )u'_{R} - \overline{L}'_{L}(\Pi_{1}\widetilde{\phi}_{1}) \qquad )l'_{R} + h.c.$$

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Fermion-mass-eigenstate basis  $\mathcal{L}_{Y}[f' \to f]$  (f = u, d, l):

- $M'_f \longrightarrow M_f$  diagonal
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- Yukawa couplings:  $g_{ij} \propto \sqrt{m_i m_j} \leftarrow$  particular Yukawa textures (type III)
- $\bullet$  Heavy enough  $M_{Hbosons} \longrightarrow$  suppressed FCNC ('phenomenologically-non-relevant' 2HDM)
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- $\phi_2$  to all-fermions (type I)
- $\phi_1$  to **d** and **l** and  $\phi_2$  to **u** (type II)
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- ullet Heavy enough  $M_{Hbosons}$   $\longrightarrow$  suppressed FCNC ('phenomenologically-non-relevant' 2HDM)
- ullet Impossing discrete  $\mathcal{Z}_2$  symmetry

$$\phi_1 \rightarrow \phi_1 \,,\, \phi_2 \rightarrow -\phi_2 \,,\, Q_L \rightarrow Q_L \,,\, L_L \rightarrow L_L$$

Only one scalar doublet is coupling to a given right-handed fermion field

## Different implementations of $\mathcal{Z}_2$ symmetry

- $\phi_2$  to all-fermions (type I)
- ullet  $\phi_1$  to  $oldsymbol{d}$  and  $oldsymbol{I}$  and  $\phi_2$  to  $oldsymbol{u}$  (type II)
- ullet  $\phi_1$  to **leptons** and  $\phi_2$  to **quarks** (leptophilic or type X)
- $\phi_1$  to **d** and  $\phi_2$  to **u** and **I** (type Y)

### Since $\mathcal{Z}_2$ is scalar-basis dependent:

•  $\Phi_1$  to all-fermions required! (inert or dark model)  $\rightarrow$  natural frame for Dark Matter

Avoiding FCNC

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## Outline

Introduction

- 2 Aligned Two-Higgs-Doublet Model
- 3 Phenomenology
- 4 Conclusions

Alignment in flavor space of the Yukawa couplings of the doublets

$$\Gamma_2 = \xi_d \mathrm{e}^{-i\theta} \Gamma_1 \qquad \Delta_2 = \xi_u^* \mathrm{e}^{i\theta} \Delta_1 \qquad \Pi_2 = \xi_I \mathrm{e}^{-i\theta} \Pi_1$$

$$Y_{d,l} = \zeta_{d,l} M_{d,l} \qquad Y_u = \zeta_u M_u \qquad ; \qquad \zeta_f \equiv \frac{\xi_f - \tan \beta}{1 + \xi_f \tan \beta} \qquad \left( \tan \beta = \frac{v_2}{v_1} \right)$$

$$\mathcal{L}_{Y} = -\frac{\sqrt{2}}{v}H^{+}(\mathbf{x})\left\{\overline{u}(x)\left[\zeta_{d}V_{CKM}M_{d}\mathcal{P}_{R} - \zeta_{u}M_{u}V_{CKM}\mathcal{P}_{L}\right]d(x) + \zeta_{I}\overline{v}(x)M_{I}\mathcal{P}_{R}I(x)\right\}$$

$$-\frac{1}{v}\sum_{\phi=H,h,A}\phi(\mathbf{x})\sum_{f=u,d,I}y_{f}^{\phi}\overline{f}(x)M_{f}\mathcal{P}_{R}f(x) + h.c.$$

$$\mathcal{P}_{R,L} \equiv \frac{1}{5}(1+x)\frac{1}{2}(1+x$$

 $\mathscr{P}_{R,L} \equiv \frac{1}{2} (1 \pm \gamma_5)$ 

- Fermionic couplings ox mass matrices
- Neutral Yukawas diagonal in flavor
- FC source: V<sub>CKM</sub> in the quark sector only
- $\circ$   $\zeta_f$ : complex numbers  $\to$  new sources of CP violation without tree-level FCNC
- ζε: universality and scalar-basis independence

$$\Gamma_2 = \xi_d e^{-i\theta} \Gamma_1 \qquad \Delta_2 = \xi_u^* e^{i\theta} \Delta_1 \qquad \Pi_2 = \xi_I e^{-i\theta} \Pi_1$$

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Recovering usual  $\mathcal{Z}_2$  models, warning and noting

Model	$(\xi_d, \xi_u, \xi_l)$	$\zeta_d$	ζυ	ζΙ
Type I	$(\infty, \infty, \infty)$	$\cot \beta$	$\cot \beta$	$\cot \beta$
Type II	$(0,\infty,0)$	$-\tan \beta$	$\cot \beta$	$-\tan \beta$
Type X	$(\infty, \infty, 0)$	$\cot \beta$	$\cot \beta$	−tanβ
Type Y	$(0,\infty,\infty)$	$-\tan \beta$	$\cot \beta$	$\cot \beta$
Inert	aneta	0	0	0

Table 1

### Note on $\zeta_I$

Lepton sector: FCNC are identically zero to all orders in PT

ullet  $\mathcal{Z}_2$  symmetries unnecessary o Models X and Y less compelling

 $I_I$  any value (e.g.  $\zeta_I = 0$  leptophobic model)

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## Aligned Two-Higgs-Doublet Model

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A comment on Radiative Corrections

#### Alignment Yukawa couplings is not directly protected by any symmetry: radiative FCNC

### Nevertheless .

• 
$$f_i \rightarrow f_i e^{i\theta_{f_i}}$$
,  $V_{ij} \rightarrow e^{i\theta_{u_i}} V_{ij} e^{-\theta_{d_j}}$ 

- Loops cannot generate LFV
- FCNCs have a particular structure

$$u_i F_{ij} u_j$$
 ,  $d_i F_{ij} d_j$ 

$$F_{ij} \rightarrow e^{i\theta_{ij}} F_{ij} e^{-i\theta_{ij}}$$
 ,  $\widetilde{F}_{ij} \rightarrow e^{i\theta_{ij}} \widetilde{F}_{ij} e^{-i\theta_{ij}}$ 

• 
$$F = V M_d^n V^{\dagger}$$
,  $\widetilde{F} = V^{\dagger} M_d^n V$  with  $n \ge 1$ 



#### Nevertheless . . .

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$$f_i \rightarrow f_i e^{i\theta f_i}$$
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$$\begin{aligned} \overline{u}_{i}F_{ij}u_{j} &, \quad \overline{d}_{i}\widetilde{F}_{ij}d_{j} \\ F_{ij} \rightarrow e^{i\theta}u_{i}F_{ij}e^{-i\theta}u_{j} &, \quad \widetilde{F}_{ij} \rightarrow e^{i\theta}d_{i}\widetilde{F}_{ij}e^{-i\theta}d_{i} \\ F_{ij} &= \sum_{k}V_{ik}\ell(m_{k})V_{kj}^{\dagger} \\ \overline{F}_{ij} &= \sum_{k}V_{ik}^{\dagger}\widetilde{F}(m_{k})V_{kj} \end{aligned}$$

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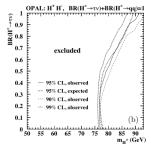
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$$H^{\pm} \rightarrow \tau^{\pm} \nu_{\tau}$$

OPAL Collaboration, arXiv:0812.0267 [hep-ex]



M <sub>H</sub> (GeV)	> 79.6	> 79.2	> 91.2
$B_{\tau}$	0	0.5	1

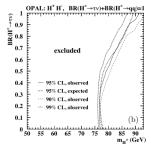
• 
$$H^{\pm} \rightarrow \tau^{\pm} \nu_{\tau}, q\overline{q}'$$

• 
$$B_{\tau} = 0$$
 (1)  $\longleftrightarrow \zeta_{I} = 0$  ( $\zeta_{u,d} = 0$ )

$$\begin{split} B(H^+ \to \tau^+ \nu_T) \approx \left\{ 1 + \frac{1.8 |\zeta_q|^2}{|\zeta_I|^2} \right\}^{-1} \\ |\zeta_q|^2 = |\zeta_u|^2 + \frac{m_S^2}{m_P^2} |\zeta_d|^2 \end{split}$$

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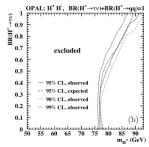
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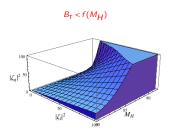


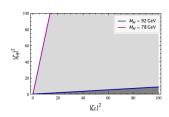
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$B_{\tau}$	0	0.5	1

- $H^{\pm} \rightarrow \tau^{\pm} \nu_{\tau}, q\overline{q}'$
- $B_{\tau} = 0$  (1)  $\longleftrightarrow \zeta_I = 0$  ( $\zeta_{u,d} = 0$ )

$$B(H^+ \to \tau^+ \nu_\tau) \approx \left\{ 1 + \frac{1.8 |\zeta_q|^2}{|\zeta_I|^2} \right\}^{-1}$$

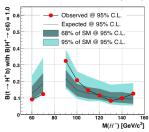
$$|\zeta_q|^2 = |\zeta_u|^2 + \frac{m_s^2}{m_c^2} |\zeta_d|^2$$





 $t \rightarrow H^+ b, H^+ \rightarrow c\overline{s}$ 

#### CDF Collaboration, arXiv:0907.1269 [hep-ex]



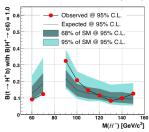
$$B(t \to H^+ b) \cdot B(H^+ \to c\overline{s})$$

$$B(t \to H^+ b) = \left\{ 1 + \left( \frac{m_t^2 - M_W^2}{m_t^2 - M_H^2} \right)^2 \left( 1 + 2 \frac{M_W^2}{m_t^2} \right) \frac{1 + \delta_{QCD}}{|\zeta_u|^2} \right\}^{-1}$$

$$|\zeta_U|<0.5\,|\zeta_I|+1$$

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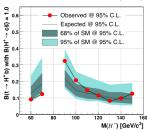


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 $|\zeta_{U}|<0.5\,|\zeta_{J}|+1$ 

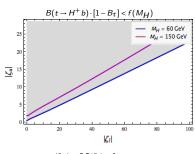
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$$|\zeta_{II}| < 0.5 \, |\zeta_I| + 1$$

$$B^{\pm} 
ightarrow au^{\pm} v_{\mathcal{T}}$$
 and  $D_{\mathcal{S}}^{\pm} 
ightarrow au^{\pm} v_{\mathcal{T}}$ 

$$\Gamma(P^- \to l^- \overline{v}_l) = \frac{G_F^2}{8\pi} \, |V_{ij}|^2 \, \frac{f_P^2}{f_P^2} \, \frac{m_l^2 \, (m_P^2 - m_l^2)^2}{m_P^3} \, |1 - \Delta_{ij}|^2$$

$$B^{\pm} \rightarrow \tau^{\pm} \nu_{\tau}$$

[M. Antonelli et al '09] 
$$f_B = 216 \pm 22$$
  
 $|1 - \Delta_{ub}| = 1.32 \pm 0.20$ 

$$\Delta_{ub} \approx \frac{m_B^2}{M_H^2} \zeta_I^* \zeta_Q \qquad \zeta_Q = \zeta_d + \frac{m_u}{m_b} \zeta_u$$

$$D_S^{\pm} \to \tau^{\pm} \nu_{\tau}$$

[E. Follana et al '09 and CLEO] 
$$f_{D_8} = 242 \pm 6$$
 
$$|1 - \Delta_{CS}| = 1.07 \pm 0.05$$

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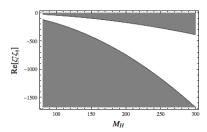
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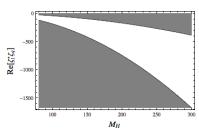
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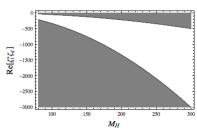
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# Phenomenology in A2HDM $B \rightarrow X_S \gamma$

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$$BR(\overline{B} \to X_s \gamma) \propto |C_7^{0,eff}(\mu_b)|^2 \longrightarrow C_{7,8,2}^{0,eff}(\mu_W)$$

$$C_{i}^{0,eff} = C_{i,SM}^{0,eff} + \frac{|\zeta_{u}|^{2}}{C_{i,YY}^{0,eff}} - \frac{(\zeta_{d}\zeta_{u}^{*})}{C_{i,XY}^{0,eff}}$$

$$B_{exp} = (3.52 \pm 0.23)10^{-4}$$
 (HFAG, arXiv:0808.1297)  
 $M_H = 150$  GeV,  $\zeta_{u,d}$  reals

Work in progress...

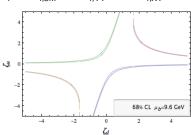
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- CP asymmetry

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## Outline

Introduction

- 2 Aligned Two-Higgs-Doublet Model
- Phenomenology
- Conclusions

- The alignment of Yukawa couplings gives a general approach of the 2THDM without tree level FCNC and ...
- parametrizes the phenomenology with only three parameters:  $\zeta_u$ ,  $\zeta_d$  and  $\zeta_I$   $\mathbb{Z}_{5^*}$ 2HDMs are included in this approach
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Thanks!

## Explicit $y_f^{\phi}$

## General $\mathcal R$

$$y_{d,l}^\phi = \mathcal{R}_{i1} + \left(\mathcal{R}_{i2} + i\mathcal{R}_{i3}\right)\zeta_{d,l} \qquad y_u^\phi = \mathcal{R}_{i1} + \left(\mathcal{R}_{i2} + -\mathcal{R}_{i3}\right)\zeta_u^*$$

#### CP-symmetric potential:

$$\begin{aligned} y_{d,l}^{H} &= \cos(\alpha - \beta) + \sin(\alpha - \beta)\zeta_{d,l} & y_{u}^{H} &= \cos(\alpha - \beta) + \sin(\alpha - \beta)\zeta_{u}^{*} \\ y_{d,l}^{h} &= -\sin(\alpha - \beta) + \cos(\alpha - \beta)\zeta_{d,l} & y_{u}^{h} &= s\sin(\alpha - \beta) + \sin(\alpha - \beta)\zeta_{u}^{*} \\ y_{d,l}^{A} &= i\zeta_{d,l} & y_{u}^{A} &= -i\zeta_{u}^{*} \end{aligned}$$