Yukawa Alignment in Two-Higgs-Doublet Models

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1. Introduction

2. Aligned Two-Higgs-Doublet Model

3. Phenomenology

4. Conclusions

Outline

1 Introduction

2 Aligned Two-Higgs-Doublet Model

3 Phenomenology

4 Conclusions

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

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

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \Omega \begin{pmatrix} \phi_1 \\ e^{-i\theta}\phi_2 \end{pmatrix} \quad ; \quad \Omega \equiv \frac{1}{v}\begin{bmatrix} v_1 & v_2 \\ v_2 & -v_1 \end{bmatrix}$$

Higgs basis

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

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

Benefits of having more than one Higgs doublet

- 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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$$\mathscr{L}_Y = -\overline{Q}'_L(\Gamma_1\phi_1 + \Gamma_2\phi_2)d'_R - \overline{Q}'_L(\Delta_1\tilde{\phi}_1 + \Delta_2\tilde{\phi}_2)u'_R - \overline{L}'_L(\Pi_1\tilde{\phi}_1 + \Pi_2\tilde{\phi}_2)l'_R + h.c.$$

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

- $M'_f \longrightarrow M_f$ diagonal
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How to avoid FCNC:

- Yukawa couplings: $g_{ij} \propto \sqrt{m_i m_j} \longleftarrow$ particular Yukawa textures (type III)
- Heavy enough $M_{Hbosons} \longrightarrow$ suppressed FCNC ('phenomenologically-non-relevant' 2HDM)
- Impossing discrete $\mathcal{Z}_2$ symmetry

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

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

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

- ϕ_2 to **all-fermions** (type I)
- ϕ_1 to d and l and ϕ_2 to u (type II)
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NO-FCNC but also NO new potential CP violating sources

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Alignment in flavor space of the Yukawa couplings of the doublets

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

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

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+(x)\left\{\bar{u}(x)\left[\zeta_d V_{CKM} M_d \mathcal{P}_R - \zeta_u M_u V_{CKM}\mathcal{P}_L\right] d(x) + \zeta_l \bar{\nu}(x) M_l \mathcal{P}_R l(x)\right\} - \frac{1}{v}\sum_{\phi=H,h,A} \phi(x) \sum_{f=u,d,l} y_f^{\phi}\, \bar{f}(x)\, M_f \mathcal{P}_R\, f(x) \quad + \quad h.c.$$

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

- Fermionic couplings $\propto$ mass matrices
- Neutral Yukawas diagonal in flavor
- FC source: V_{CKM} in the quark sector only
- ζ_f: complex numbers $\rightarrow$ new sources of CP violation without tree-level FCNC
- ζ_f: universality and scalar-basis independence ...

Aligned Two-Higgs-Doublet Model

Alignment in flavor space of the Yukawa couplings of the doublets

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

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$$\begin{aligned}\mathcal{L}_Y = \; & - \frac{\sqrt{2}}{v} H^+(x) \left\{ \bar{u}(x) \left[\zeta_d V_{CKM} M_d \mathscr{P}_R - \zeta_u M_u V_{CKM} \mathscr{P}_L\right] d(x) + \zeta_l \bar{\nu}(x) M_l \mathscr{P}_R l(x) \right\} \\ & - \frac{1}{v} \sum_{\phi = H,h,A} \phi(x) \sum_{f=u,d,l} y_f^{\phi}\, \bar{f}(x)\, M_f \mathscr{P}_R\, f(x) \qquad + \qquad h.c.\end{aligned}$$

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

- Fermionic couplings $\propto$ mass matrices
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Type II	$(0, \infty, 0)$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$(\infty, \infty, 0)$	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$(0, \infty, \infty)$	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	$\tan\beta$	0	0	0

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Note on ζ_l

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

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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
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Outline

1 Introduction

2 Aligned Two-Higgs-Doublet Model

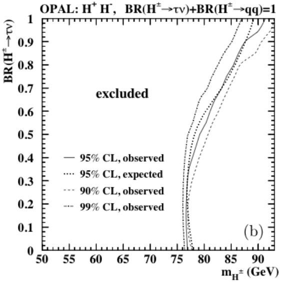
3 Phenomenology

4 Conclusions

Phenomenology in A2HDM

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

OPAL Collaboration, arXiv:0812.0267 [hep-ex]



M_H (GeV)	>79.6	>79.2	>91.2
B_{τ}	0	0.5	1

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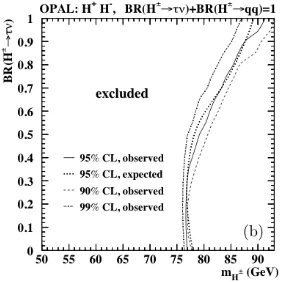

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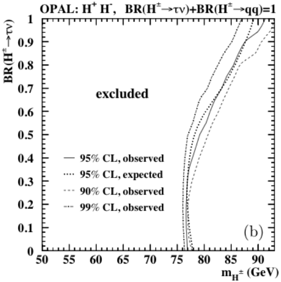

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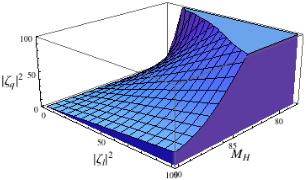
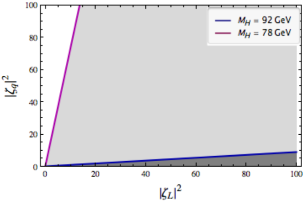
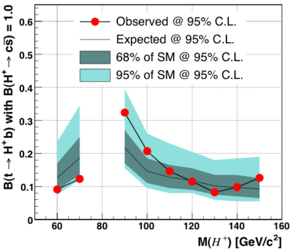




CDF Collaboration, arXiv:0907.1269 [hep-ex]



$|\zeta_u| < 0.5\,|\zeta_l| + 1$

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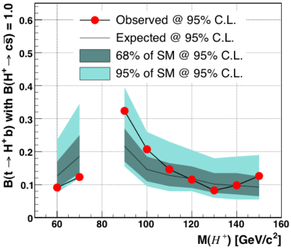

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Phenomenology in A2HDM

$t \to H^+ b,\ H^+ \to c\bar{s}$

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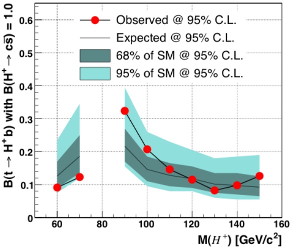
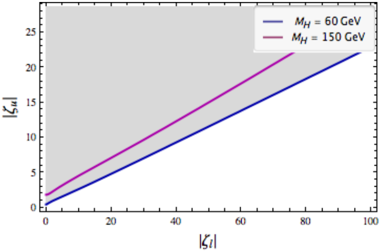


$B(t \to H^+ b) \cdot [1 - B_\tau] < f(M_H)$



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

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

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

For $f_B = 216 \pm 22$ (PDG 2008):

$$|1 - \Delta_{ub}| = 1.05 \pm 0.14$$

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

$B \to X_s \gamma$

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

$$C_i^{0,eff} = C_{i,SM}^{0,eff} + |\zeta_u|^2 \, C_{i,YY}^{0,eff} - (\zeta_d \zeta_u^*) \, C_{i,XY}^{0,eff}$$

$B_{exp} = (3.52 \pm 0.23) 10^{-4}$ (HFAG, arXiv:0808.1297)

$M_H = 150$ GeV, $\zeta_{u,d}$ reals

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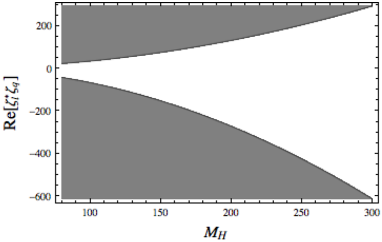

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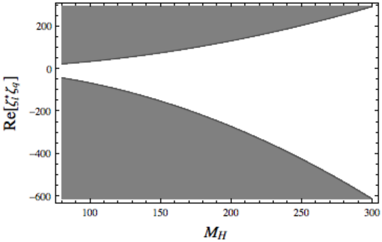

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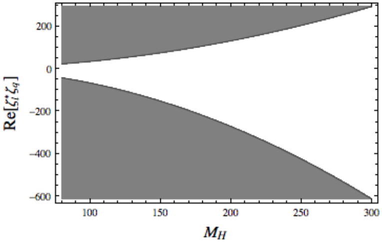

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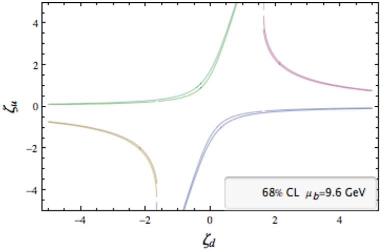

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Outline

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

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- parametrizes the phenomenology with **only three parameters**: ζ_u, ζ_d and ζ_l
  - $\mathcal{Z}_2$-2HDMs are included in this approach

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Thanks !

Explicit y_f^ϕ

General $\mathscr{R}$

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

CP-symmetric potential:

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