Yukawa Alignment in Two-Higgs-Doublet Models

Paula Tuzón Marco

IFIC, Universitat de València - CSIC

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Outline

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

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

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

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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- Heavy enough $M_{Hbosons} \longrightarrow$ suppressed FCNC ('phenomenologically-non-relevant' 2HDM)
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$$\phi_1 \to \phi_1 \, , \phi_2 \to -\phi_2 \, , Q_L \to Q_L \, , L_L \to L_L$$

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

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

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

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

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

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

- Fermionic couplings $\propto$ mass matrices
- Neutral Yukawas diagonal in flavor
- FC source: V_{CKM} in the quark sector only
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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

Table 1

Note on ζ_l

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

- $\mathcal{Z}_2$ symmetries unnecessary → Models X and Y less compelling

ζ_l any value (e.g. $\zeta_l = 0$ leptophobic model)

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

Nevertheless . . .

- $f_i \to f_i e^{i\theta_{f_i}}$, $V_{ij} \to e^{i\theta_{u_i}} V_{ij} e^{-\theta_{d_j}}$
  - Loops cannot generate LFV
  - FCNCs have a particular structure:

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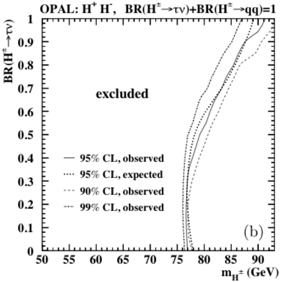
Outline

OPAL Collaboration, arXiv:0812.0267 [hep-ex]



M_H (GeV)	>79.6	>79.2	>91.2
B_τ	0	0.5	1

- $H^{\pm} \to \tau^{\pm} \nu_{\tau}, q\bar{q}'$
- $B_\tau = 0\ (1) \longleftrightarrow \zeta_l = 0\ (\zeta_{u,d} = 0)$

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

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Phenomenology in A2HDM

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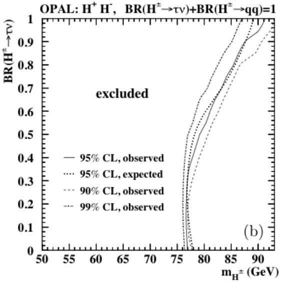

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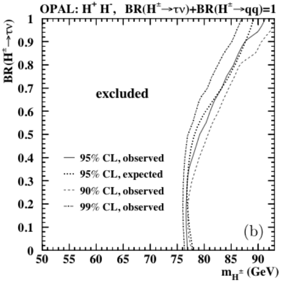

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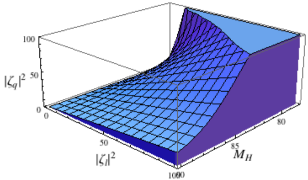
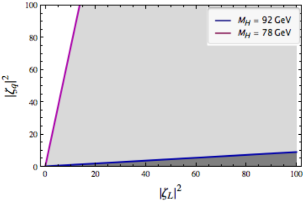
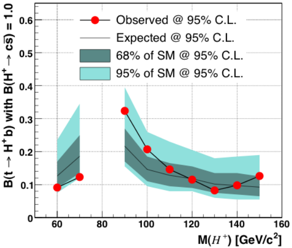




CDF Collaboration, arXiv:0907.1269 [hep-ex]



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

- $B(t \to H^+ b) \cdot \overbrace{B(H^+ \to c\bar{s})}^{1-B_\tau}$

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

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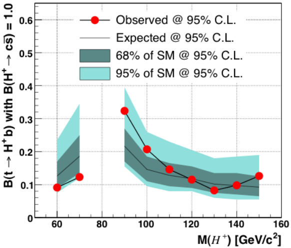

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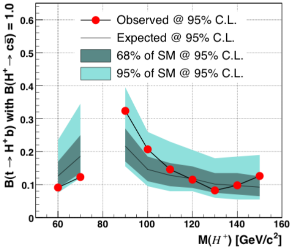
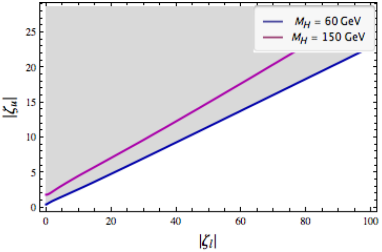


$B(t \to H^+ b)\cdot[1 - B_\tau] < f(M_H)$



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Phenomenology in A2HDM

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

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

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

[M. Antonelli *et al* '09] $f_B = 216 \pm 22$

$$|1 - \Delta_{ub}| = 1.32 \pm 0.20$$

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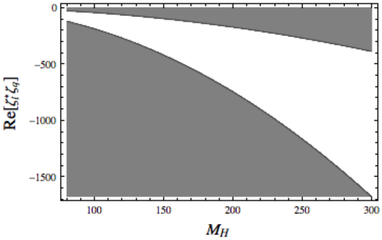

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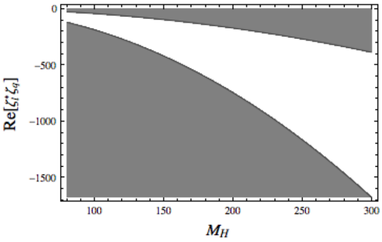

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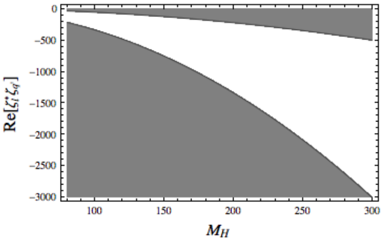

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$$BR(\overline{B} \to X_s \gamma) \propto |C_7^{0,eff}(\mu_b)|^2 \longrightarrow C_{7,8,2}^{0,eff}(\mu_W)$$

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

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

Work in progress...

- Not a (semi)leptonic process
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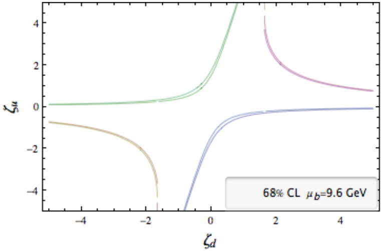

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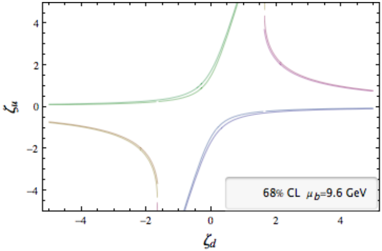

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Outline

Conclusions

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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:

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