Aligned two-Higgs-doublet model: Flavour constraints and CP violation

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Outline

1. Introduction
2. Aligned Two-Higgs-Doublet Model
3. Phenomenology
   - Tree-level decays
   - Loop-induced processes
4. CP violation
5. 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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The doublets and the benefits

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

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FCNC !

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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_H bosons $\longrightarrow$ 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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Since $\mathcal{Z}_2$ is scalar-basis dependent:

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Alignment in flavor space of the Yukawa couplings of the doublets [Pich and Tuzón'09]

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

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

- Fermionic couplings $\propto$ mass matrices
- Neutral Yukawas diagonal in flavor
- FC source: V_{CKM} in the quark sector only
- ς_f: complex numbers → new sources of CP violation without tree-level FCNC
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$$Y_{d,l} = \varsigma_{d,l} M_{d,l} \qquad Y_u = \varsigma_u M_u \qquad ; \qquad \varsigma_f \equiv \frac{\xi_f - \tan\beta}{1+\xi_f \tan\beta} \qquad \left(\tan\beta = \frac{v_2}{v_1}\right)$$

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

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

- Fermionic couplings $\propto$ mass matrices
- Neutral Yukawas diagonal in flavor
- FC source: V_{CKM} in the quark sector only
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- ς_f: universality and scalar-basis independence and ...

Aligned Two-Higgs-Doublet Model

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- $\mathcal{Z}_2$-type models are recovered

Model	(ξ_d, ξ_u, ξ_l)	ς_d	ς_u	ς_l
Type I	(∞,∞,∞)	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$(0,\infty,0)$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$(\infty,\infty,0)$	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$(0,\infty,\infty)$	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	$\tan\beta$	0	0	0

Table 1

- $\mathcal{Z}_2$-type models are recovered

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

Nevertheless ...

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$$f_L^i(x) \to e^{i\alpha_i^{f,L}} f_L^i(x) \quad , \quad f_R^i(x) \to e^{i\alpha_i^{f,R}} f_R^i(x)$$

$$V_{CKM}^{ij} \to e^{i\alpha_i^{u,L}} V_{CKM}^{ij} e^{-i\alpha_j^{d,L}} \quad , \quad M_{f,ij} \to e^{i\alpha_i^{f,L}} M_{f,ij} e^{-i\alpha_j^{f,R}}$$

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MFV structure [D'Ambrosio et al, Chivukula-Georgi, Hall-Randall, Buras et al, Cirigliano et al]

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General 2HDM 1-loop RGEs [Cvetic et al, Ferreira et al] → *aligned* case [Jung, Pich and Tuzón]

$$\begin{aligned}\mathcal{L}_{FCNC} &= -\frac{\log(\mu/\mu_0)}{4\pi^2 v^3}(1+\varsigma_u^*\varsigma_d)\sum_i \varphi_i^0(x) \\ &\times \Big\{(\mathcal{R}_{i2}+i\mathcal{R}_{i3})(\varsigma_d-\varsigma_u)\left[\bar{d}_L\, V^\dagger\, M_u M_u^\dagger\, V\, Md\, d_R\right] \\ &\quad -(\mathcal{R}_{i2}-i\mathcal{R}_{i3})(\varsigma_d^*-\varsigma_u^*)\left[\bar{u}_L\, V\, M_d M_d^\dagger\, V^\dagger\, Mu\, u_R\right]\Big\} \\ &\quad + h.c.\end{aligned}$$

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Outline

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- $\tau \to \mu/e$

$$|g_\mu/g_e|^2 = 1.0036 \pm 0.0029$$
$$\Downarrow$$
$$|\varsigma_l|/M_{H^\pm} < 0.40 \text{ GeV}^{-1} \text{ (95\% CL)}$$

- $P^- \to l^- \overline{\nu}_l$

$$\Gamma = \frac{m_P}{8\pi}\left(1 - \frac{m_l^2}{m_P^2}\right)^2 \left|G_F\, m_l\, f_P\, V^{ij}\right|^2 |1 - \Delta_{ij}|^2 \quad , \quad \Delta_{ij} = \frac{m_P^2}{M_{H^\pm}^2}\varsigma_l^* \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

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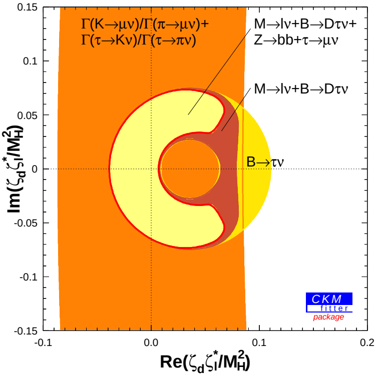
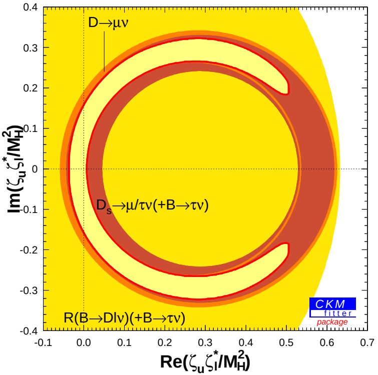
Global fit: $P \to l\nu_l$, $\tau \to P\nu_\tau$ and $P \to P' l\nu_l$





[GeV^{-2} units]

Outline

Observables

ΔM_{B_s}

ϵ_K $\Longrightarrow$ ς_u ς_d

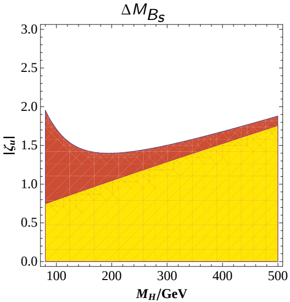
$Z \to b\overline{b}$

$\overline{B} \to X_s \gamma$

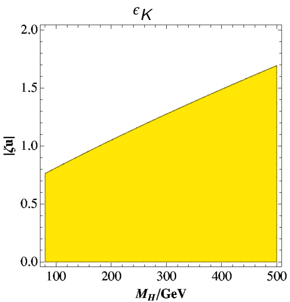
Assumptions

Charged scalar → dominant new physics corrections

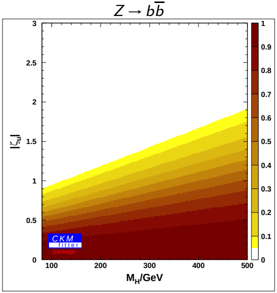
Subleading effects to the SM



ΔM_{B_s}
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$|\zeta_u|$
100
200
300
400
500
M_H/GeV



ϵ_K
2.0
1.5
1.0
0.5
0.0
$|\zeta_u|$
100
200
300
400
500
M_H/GeV



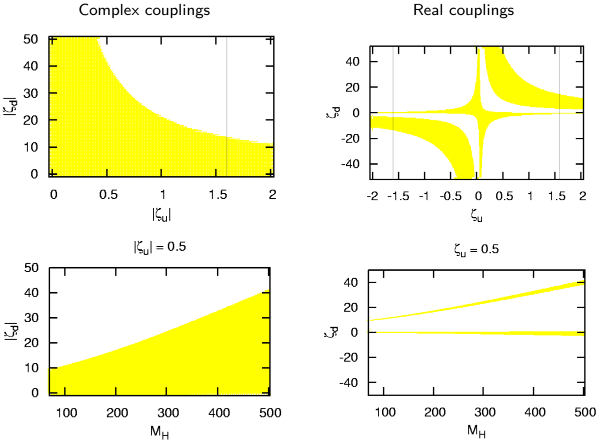
$Z \to b\bar{b}$
3
2.5
2
1.5
1
0.5
0
$|\zeta_u|$
100
200
300
400
500
M_H/GeV
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
CKM
fitter
package

Phenomenological Constraints

Loop-induced processes (95% CL) [Jung, Pich and Tuzón]

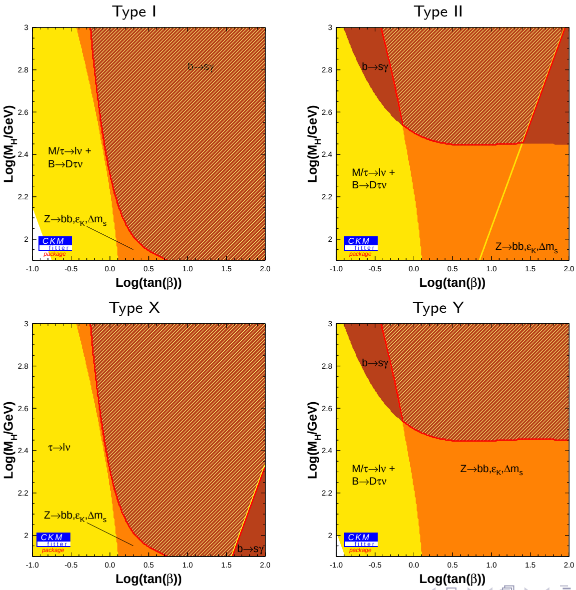
$\overline{B} \to X_s \gamma$

$$C_i^{eff}(\mu_0) = C_{i,SM} + |\varsigma_u|^2 C_{i,uu} - (\varsigma_u^* \varsigma_d) C_{i,ud}$$



Phenomenological Constraints

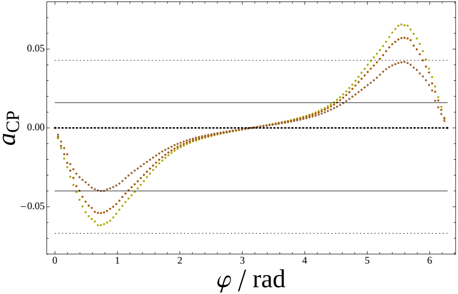
$tan(\beta) - M_{H^\pm}$ in $\mathcal{Z}_2$ *models* (95% CL) [Jung, Pich and Tuzón]



Outline

- $\overline{B} \to X_s \gamma \quad \Longrightarrow \quad a_{CP} = \frac{Br - \overline{Br}}{Br + \overline{Br}}$

Maximal and minimal a_{CP} at NLO



- $B_s^0 - \overline{B}_s^0 \quad \Longrightarrow \quad a_{sl}^q = \frac{\Gamma(\overline{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$

A_{sl}^b [D0] $+ a_{sl}^d$ [HFAG] $\longrightarrow$ $a_{sl}^s = -0.0146 \pm 0.0075$ and $\Delta M_s^{exp} + \Delta\Gamma_s^{SM} \Longrightarrow \sin\phi_s = -2.7 \pm 1.4 \pm 1.6$!!

SM: $\phi_s = 0.24 \pm 0.08$, $\phi_d = -5.2^{+1.5}_{-2.1}$ [Lenz and Nierste]

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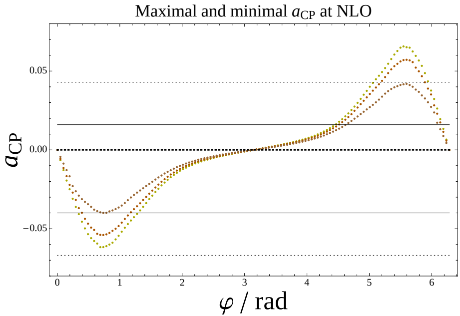

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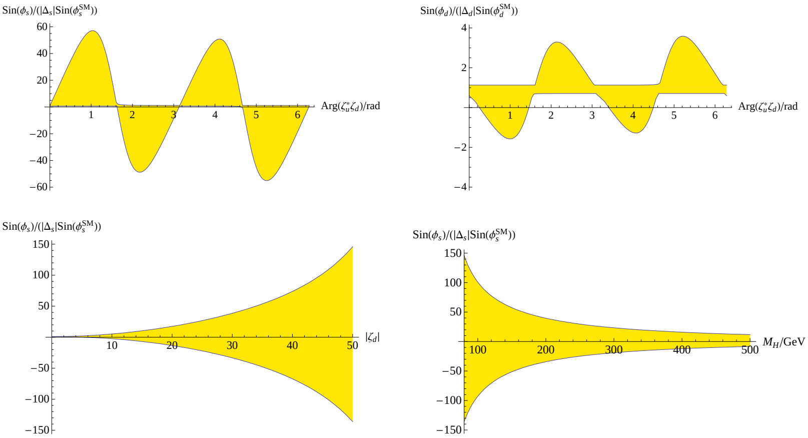
$\phi \equiv arg(-M_{12}/\Gamma_{12})$, $\Delta \equiv M_{12}/M_{12}^{SM}$



Outline

Conclusions

Aligned two-Higgs-doublet model (ATHDM):

Radiative FCNCs

- Absent in the lepton sector to all orders
- Very constrained in the quark sector (MFV like)

Advantages

- **New CP violating sources in Yukawa** terms with **NO FCNC** at tree level
- **Only three** parameters ⇒ $\varsigma_{u,d,l}$

  Basis independent and universal (flavour blind) →

  Complex → New CP violating sources

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Danke !

Explicit y_f^{ϕ}

General $\mathscr{R}$

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

CP-symmetric potential:

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