Flavour Constraints on the Aligned Two-Higgs-Doublet Model

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- A. Pich, P. Tuzón, Phys. Rev. D80 (2009) 091702
- M. Jung, A. Pich, P. Tuzón, arXiv:1006.xxxx [hep-ph]

Planck 2010, CERN, 31 May – 4 June 2010

Standard Model

One Higgs Doublet Φ **:** $\quad \langle 0|\Phi|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad , \quad \tilde{\Phi} \equiv i\tau_2\,\Phi^*$

$$\mathcal{L}_Y = -\bar{Q}'_{iL}\,\Gamma_{ij}\,\Phi\,d'_{jR} - \bar{Q}'_{iL}\,\Delta_{ij}\tilde{\Phi}\,u'_{jR} - \bar{L}'_{iL}\,\Pi_{ij}\Phi\,l'_{jR} + \text{h.c.}$$

↓ **SSB**

$$M'_d = \frac{v}{\sqrt{2}}\,\Gamma \quad , \quad M'_u = \frac{v}{\sqrt{2}}\,\Delta \quad , \quad M'_l = \frac{v}{\sqrt{2}}\,\Pi$$

Diagonalization → { **GIM Mechanism** (Unitarity)
Yukawas proportional to masses }

No Flavour-Changing Neutral Currents

Two Higgs Doublets: $\phi_a \quad (a = 1, 2)$

$$\langle 0 | \phi_a^T(x) | 0 \rangle = \frac{1}{\sqrt{2}} \left(0 \, , v_a \, e^{i\theta_a} \right) \qquad , \qquad \theta_1 = 0 \qquad , \qquad \theta \equiv \theta_2 - \theta_1$$

Higgs basis: $\quad v \equiv \sqrt{v_1^2 + v_2^2} \quad , \quad \tan\beta \equiv v_2 / v_1$

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \begin{pmatrix} \phi_1 \\ e^{-i\theta} \phi_2 \end{pmatrix}$$

$$\rightarrow \quad \Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}} \left(v + S_1 + i G^0 \right) \end{bmatrix} \quad , \quad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}} \left(S_2 + i S_3 \right) \end{bmatrix}$$

Mass eigenstates: $H^\pm \; , \; \varphi_i^0(x) \equiv \{ h(x), H(x), A(x) \} = \mathcal{R}_{ij} \, S_j(x)$

Yukawa Interactions in 2HDMs

$$\mathcal{L}_Y = -\bar{Q}_L' (\Gamma_1 \phi_1 + \Gamma_2 \phi_2)\, d_R' - \bar{Q}_L' (\Delta_1 \tilde{\phi}_1 + \Delta_2 \tilde{\phi}_2)\, u_R' - \bar{L}_L' (\Pi_1 \phi_1 + \Pi_2 \phi_2)\, l_R' + \text{h.c.}$$

↓ **SSB**

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{Q}_L' (M_d' \Phi_1 + Y_d' \Phi_2)\, d_R' + \bar{Q}_L' (M_u' \tilde{\Phi}_1 + Y_u' \tilde{\Phi}_2)\, u_R' + \bar{L}_L' (M_l' \Phi_1 + Y_l' \Phi_2)\, l_R' + \text{h.c.} \right\}$$

M_f' and Y_f' unrelated → **FCNCs**

$$\sqrt{2}\, M_d' = v_1 \Gamma_1 + v_2 \Gamma_2 e^{i\theta} \quad , \quad \sqrt{2}\, M_u' = v_1 \Delta_1 + v_2 \Delta_2 e^{-i\theta}$$

$$\sqrt{2}\, Y_d' = v_1 \Gamma_2 e^{i\theta} - v_2 \Gamma_1 \quad , \quad \sqrt{2}\, Y_u' = v_1 \Delta_2 e^{-i\theta} - v_2 \Delta_1$$

Avoiding FCNCs

- Very large scalar masses ➡ THDM irrelevant at low energies
- Very small scalar couplings
- Type III model: $(Y_f)_{ij} \propto \sqrt{m_i m_j}$ Yukawa textures
  (Cheng - Sher '87)
- Discrete $\mathcal{Z}_2$ symmetries: only one $\phi_a(x)$ couples to a given $f_R(x)$
  (Glashow - Weinberg '77)

$\mathcal{Z}_2$: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$, $Q_L \to Q_L$, $L_L \to L_L$, $f_R \to \pm f_R$

➡ **CP conserved in the scalar sector**

Aligned 2HDM

(Pich - Tuzón '09)

Require alignment in Flavour Space of Yukawa couplings:

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

$$\Downarrow$$

$$Y_{d,l} = \varsigma_{d,l} \, M_{d,l} \, , \qquad Y_u = \varsigma_u^* \, M_u \, , \qquad \varsigma_f \equiv \frac{\xi_f - \tan\beta}{1 + \xi_f \tan\beta}$$

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \, H^+ \left\{ \bar{u} \left[\varsigma_d \, V_{\mathrm{CKM}} M_d \mathcal{P}_R - \varsigma_u \, M_u^\dagger V_{\mathrm{CKM}} \mathcal{P}_L \right] d \; + \; \varsigma_l \; \left(\bar{\nu} \, M_l \, \mathcal{P}_R \, l \right) \right\}$$
$$-\frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0} \; \varphi_i^0 \; \left(\bar{f} \, M_f \, \mathcal{P}_R \, f \right) \quad + \quad \mathrm{h.c.}$$

- Fermionic couplings proportional to fermion masses.

- Neutral Yukawas are diagonal in flavour

$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\,\mathcal{R}_{i3})\,\varsigma_{d,l} \qquad , \qquad y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i\,\mathcal{R}_{i3})\,\varsigma_u^*$$

- V_{CKM} is the only source of flavour-changing phenomena

- All leptonic couplings are diagonal in flavour

- Only three new (universal) couplings ς_f.

- The usual $\mathcal{Z}_2$ models are recovered in the limits $\xi_f \to 0, \infty$

  The *inert* doublet model corresponds to $\varsigma_f = 0 \quad (\xi_f = \tan\beta)$

- ς_f are arbitrary complex numbers

➡ **New sources of CP violation without tree-level FCNCs**

A2HDM: General phenomenological setting without tree-level FCNCs

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[\varsigma_d \, V_{\rm CKM} M_d \mathcal{P}_R - \varsigma_u \, M_u^\dagger V_{\rm CKM} \mathcal{P}_L \right] d \; + \; \varsigma_l \; (\bar{\nu} \, M_l \, \mathcal{P}_R \, l) \right\}$$

$$- \frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0} \, \varphi_i^0 \; \left(\bar{f} \, M_f \, \mathcal{P}_R \, f \right) \quad + \quad \text{h.c.}$$

$\mathcal{Z}_2$ models:

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

Quantum Corrections

$\mathcal{L}_{\rm A2HDM}$ invariant under the phase transformation: $[\alpha_i^\nu = \alpha_i^l]$

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

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

- **Leptonic FCNCs absent to all orders in perturbation theory**
- **Loop-induced FCNCs local terms take the form:**

$$\bar{u}_L V_{\rm CKM} (M_d M_d^\dagger)^n V_{\rm CKM}^\dagger (M_u M_u^\dagger)^m M_u u_R$$

$$\bar{d}_L V_{\rm CKM}^\dagger (M_u M_u^\dagger)^n V_{\rm CKM} (M_d M_d^\dagger)^m M_d d_R$$

MFV structure (D'Ambrosio et al, Chivukula-Georgi, Hall-Randall, Buras et al, Cirigliano et al)

FCNCs at one Loop

General 2HDM 1-loop Renormalization Group Eqs. known (Cvetic et al, Ferreira et al)

↓ (Jung-Pich-Tuzón)

$$\mathcal{L}_{\rm FCNC} = -\frac{\log(\mu/\mu_0)}{4\pi^2 v^3}\,(1+\varsigma_u^*\varsigma_d)\,\sum_i \varphi_i^0(x)$$
$$\times \Big\{(\mathcal{R}_{i2}+i\,\mathcal{R}_{i3})\,(\varsigma_d-\varsigma_u)\,\left[\bar d_L\, V^\dagger_{\rm CKM} M_u M_u^\dagger\, V_{\rm CKM} M_d\, d_R\right]$$
$$-\,(\mathcal{R}_{i2}-i\,\mathcal{R}_{i3})\,(\varsigma_d^*-\varsigma_u^*)\,\left[\bar u_L\, V_{\rm CKM} M_d M_d^\dagger\, V^\dagger_{\rm CKM} M_u\, u_R\right]\Big\}$$
$$+\ \ {\rm h.c.}$$

- Vanish in all $\mathcal{Z}_2$ models as it should
- Suppressed by $m_q m_{q'}^2/(4\pi^2 v^3)$ and $V_{\rm CKM}^{qq'}$ → $\bar s_L b_R$, $\bar c_L t_R$

Phenomenological Constraints

- $\tau \to \mu / e$: $\quad |g_\mu / g_e|^2 = 1.0036 \pm 0.0029$

$$\longrightarrow \quad \boxed{|\varsigma_l| / M_{H^\pm} < 0.43 \ \mathrm{GeV}^{-1} \quad (95\% \ \mathrm{CL})}$$

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

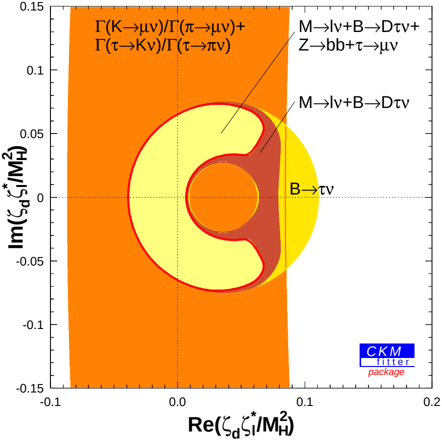
$$\Delta_{ij} = \frac{m_P^2}{M_{H^\pm}^2} \, \varsigma_l^* \, \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

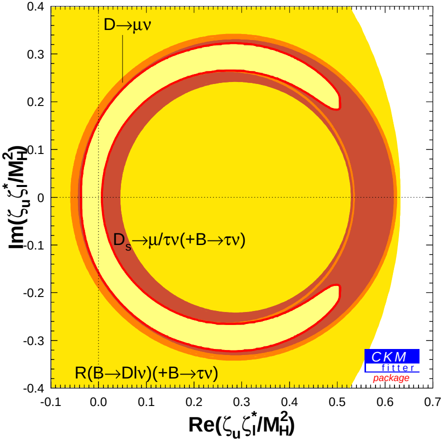
- $\Gamma(P \to P' l^- \bar{\nu}_l) \longrightarrow$ Scalar form factor: $\quad \tilde{f}_0(t) = f_0(t) \, (1 + \delta_{ij} \, t)$

$$\delta_{ij} \equiv - \frac{\varsigma_l^*}{M_{H^\pm}^2} \, \frac{m_i \varsigma_u - m_j \varsigma_d}{m_i - m_j}$$

Global fit to $P \to l\nu_l$, $\tau \to P\nu_\tau$, $P \to P' l\nu_l$ (95% CL)

Jung-Pich-Tuzón





(GeV^{-2} units)

Constraints from $Z \to b\bar{b}$ and ΔM_{B_s} (95% CL)

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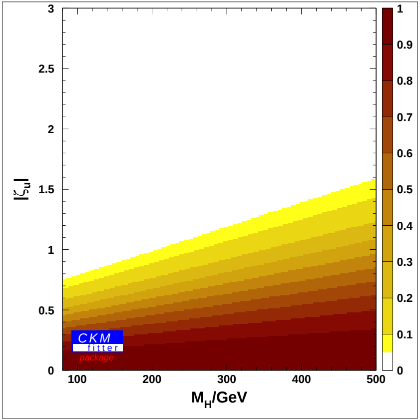
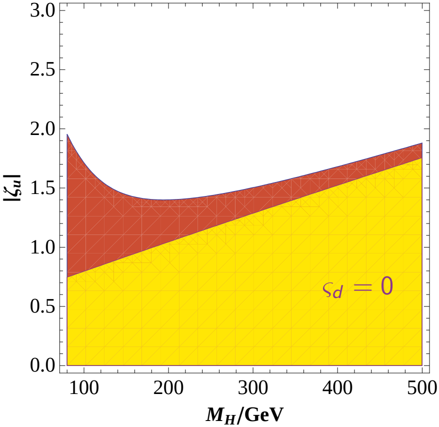
$Z \to b\bar{b} \quad (|\varsigma_d| < 50)$



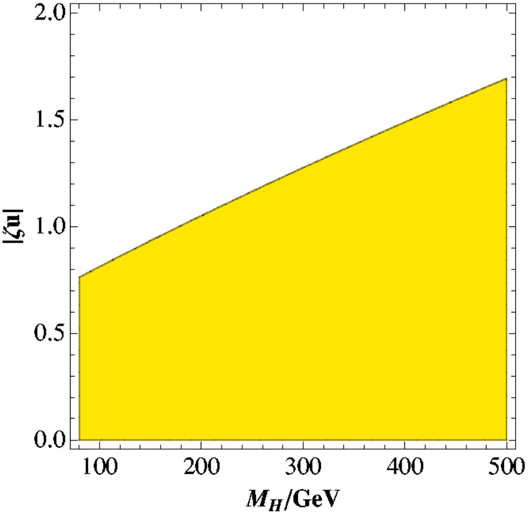
$\Delta M_{B_s} \quad (|\varsigma_d| < 50)$



$$|\varsigma_u|/M_{H^\pm} < 0.010 \ \text{GeV}^{-1} \quad \xrightarrow{\tau} \quad |\varsigma_u \varsigma_l^*|/M_{H^\pm}^2 < 0.0041 \ \text{GeV}^{-2}$$

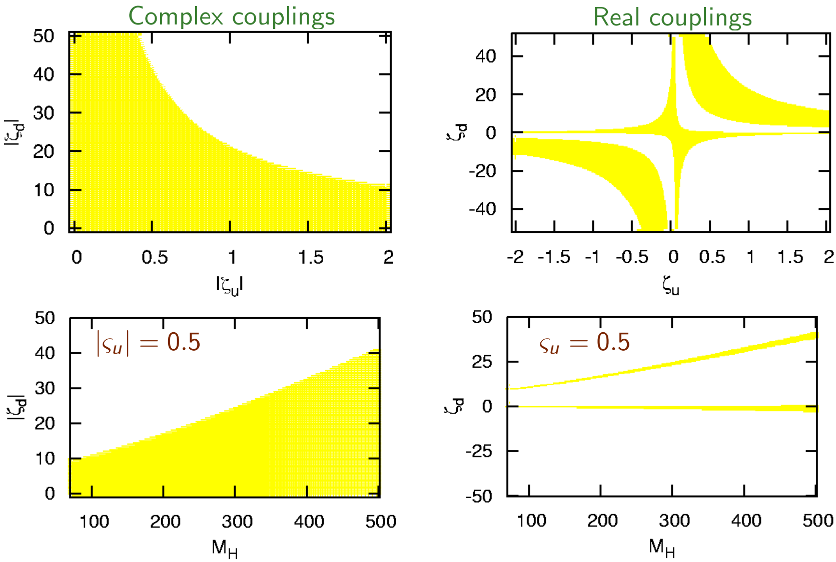
Constraints from ϵ_K (95% CL)

Jung-Pich-Tuzón



Constraints from $b \to s\gamma$ (95% CL)

Jung-Pich-Tuzón

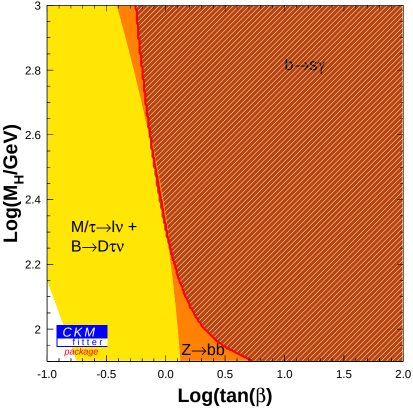


$$C_i^{\text{eff}}(\mu_W) = C_{i,SM} + |\varsigma_u|^2 \; C_{i,uu} - (\varsigma_u^* \varsigma_d \;\;) \; C_{i,ud}$$

Global Constraints on $\mathcal{Z}_2$ Models (95% CL)

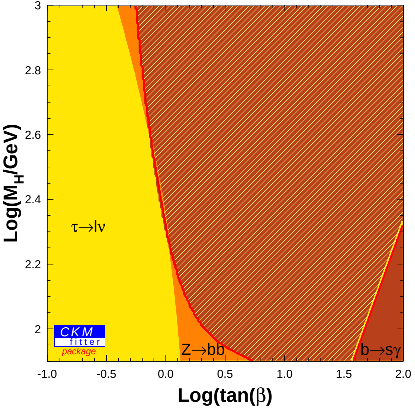
Jung-Pich-Tuzón

Type I



$$\varsigma_u = \varsigma_d = \varsigma_l = \cot\beta$$

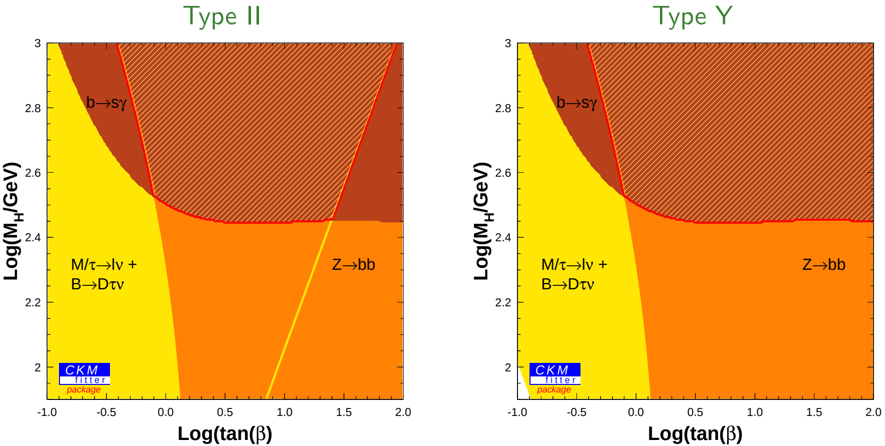
Type X



$$\varsigma_u = \varsigma_d = -\varsigma_l^{-1} = \cot\beta$$

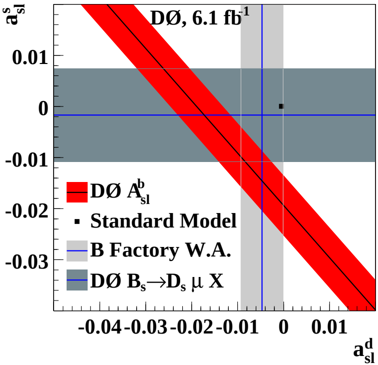
Global Constraints on $\mathcal{Z}_2$ Models (95% CL)

Jung-Pich-Tuzón



$$\varsigma_u = -\varsigma_d^{-1} = -\varsigma_l^{-1} = \cot\beta \qquad\qquad \varsigma_u = -\varsigma_d^{-1} = \varsigma_l = \cot\beta$$

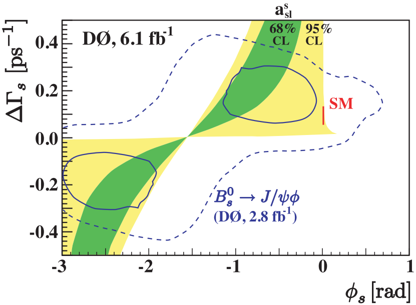
D0: $\mu^\pm\mu^\pm$ Asymmetry

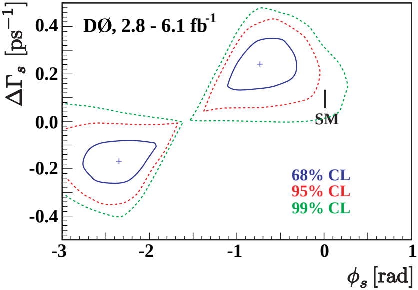


$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

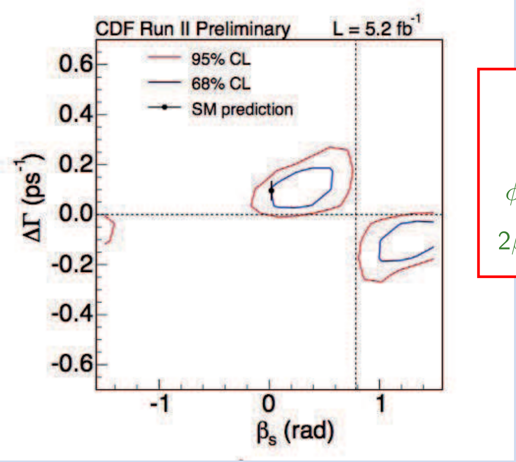
$$a_{sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}$$

$$= \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$





New CDF measurement of β_s



$B_s^0 \to J/\psi\, \phi$

$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}$

$2\beta_s = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}$

Coverage adjusted 2D likelihood contours for β_s and $\Delta\Gamma$

P-value for SM point: 44%
(0.8σ deviation)

Caveat

$$a_{sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

$$A_{sl}^b\Big|_{D0} + a_{sl}^d\Big|_{HFAG} \quad \longrightarrow \quad a_{sl}^s = -0.0146 \pm 0.0075$$

$$a_{sl}^s + \Delta M_s^{\mathrm{exp}} + \Delta\Gamma_s^{\mathrm{SM}} \quad \longrightarrow \quad \sin\phi_s = -2.7 \pm 1.4 \pm 1.6$$

Measured D0 central value incompatible with $\Delta\Gamma_s = \Delta\Gamma_s^{\mathrm{SM}}$

SM: $\phi_s = 0.24^\circ \pm 0.08^\circ$, $\phi_d = -5.2^\circ\,{}^{+1.5^\circ}_{-2.1^\circ}$ (Lenz-Nierste)

B_s^0–$\bar{B}_s^0$ Mixing Phase within the A2HDM

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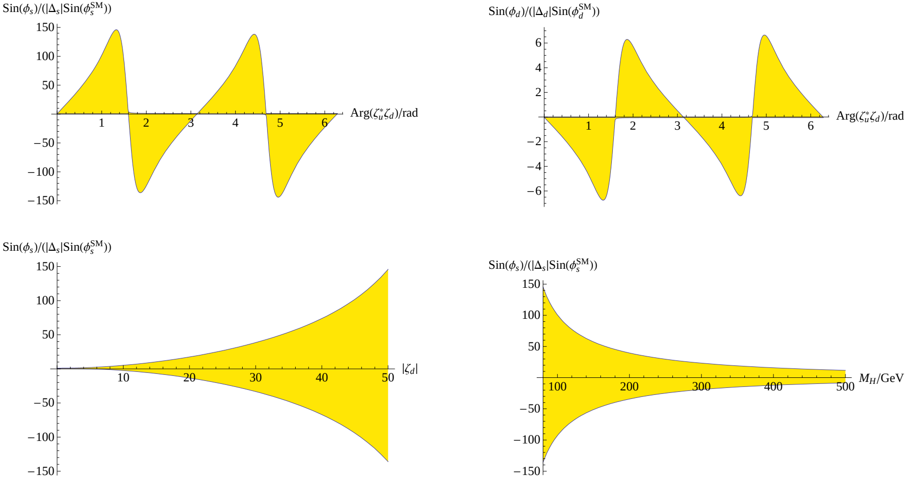

$$\phi \equiv \arg\left(-M_{12}/\Gamma_{12}\right) \qquad , \qquad \Delta \equiv M_{12}/M_{12}^{\mathrm{SM}}$$

SUMMARY

- The **Aligned THDM** provides a **general phenomenological setting**

  Includes all $\mathcal{Z}_2$ models

- **Tree-level FCNCs absent** by construction

- **Leptonic FCNCs forbidden to all orders**

- **Loop-induced quark FCNCs very constrained (MFV like)**

- **New sources of CP violation through** ς_f

- **Could accommodate a large B_s^0 mixing phase** ϕ_s

- **Many questions:** dipole moments, one-loop FCNC phenomena ...

Backup Slides

$$\Phi_1 = \left[\begin{array}{c} G^+ \\ \frac{1}{\sqrt{2}} \left(v + S_1 + i G^0 \right) \end{array} \right] \quad , \quad \Phi_2 = \left[\begin{array}{c} H^+ \\ \frac{1}{\sqrt{2}} \left(S_2 + i S_3 \right) \end{array} \right]$$

Goldstones: $G^\pm \, , \; G^0$

Mass eigenstates: $H^\pm \quad , \quad \varphi_i^0(x) = \{h(x), H(x), A(x)\}$

$$\varphi_i^0(x) = \{h(x), H(x), A(x)\} \; = \; \mathcal{R}_{ij} \; S_j(x)$$

CP-conserving scalar potential: $A(x) = S_3(x)$

$$\left(\begin{array}{c} H \\ h \end{array} \right) = \left[\begin{array}{cc} \cos(\alpha - \beta) & \sin(\alpha - \beta) \\ -\sin(\alpha - \beta) & \cos(\alpha - \beta) \end{array} \right] \left(\begin{array}{c} S_1 \\ S_2 \end{array} \right)$$

Constraints from $B \to D\tau\nu_\tau$ (95% CL)

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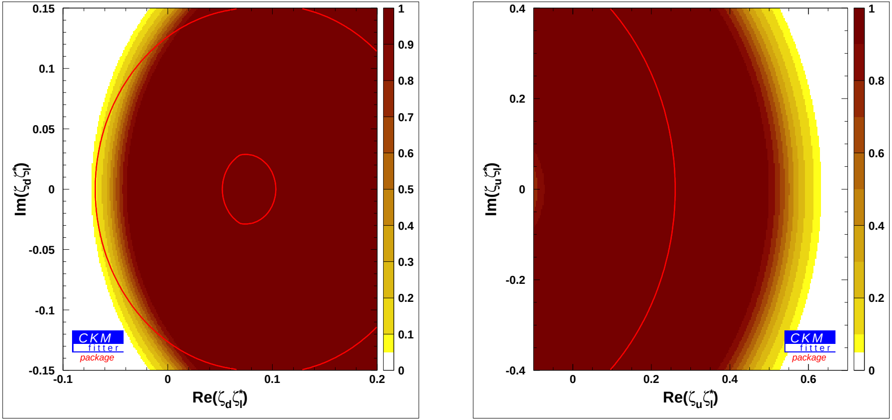

Units of $M_{H^\pm}^{-2}$. Colours indicate $1 - CL$. $D \to \mu\nu$ and $B \to \tau\nu$ used to constrain the combination not shown. The red lines show the constraint for $\varsigma_l^* \varsigma_{u,d}/M_H^2 \to 0$.

Parameter	Value	Comment
f_{B_s}	$(0.242 \pm 0.003 \pm 0.022)$ GeV	
f_{B_s}/f_{B_d}	$1.232 \pm 0.016 \pm 0.033$	
f_{D_s}	$(0.2417 \pm 0.0012 \pm 0.0053)$ GeV	
f_{D_s}/f_{D_d}	$1.171 \pm 0.005 \pm 0.02$	
f_K/f_π	$1.192 \pm 0.002 \pm 0.013$	
$f_{B_s}\sqrt{\hat{B}_{B_s^0}}$	$(0.266 \pm 0.007 \pm 0.032)$ GeV	
$f_{B_d}\sqrt{\hat{B}_{B_s^0}}/(f_{B_s}\sqrt{\hat{B}_{B_s^0}})$	$1.258 \pm 0.025 \pm 0.043$	
$\hat{B}_K$	$0.732 \pm 0.006 \pm 0.043$	
$\lvert V_{ud}\rvert$	0.97425 ± 0.00022	
λ	0.2255 ± 0.0010	$\left(1 - \lvert V_{ud}\rvert^2\right)^{1/2}$
$\lvert V_{ub}\rvert$	$(3.8 \pm 0.1 \pm 0.4) \cdot 10^{-3}$	$b \to u l \nu$ (excl. + incl.)
A	$0.80 \pm 0.01 \pm 0.01$	$b \to c l \nu$ (excl. + incl.)
$\bar{\rho}$	$0.15 \pm 0.02 \pm 0.05$	Our fit
$\bar{\eta}$	$0.38 \pm 0.01 \pm 0.06$	Our fit
$\rho^2\rvert_{B\to Dl\nu}$	$1.18 \pm 0.04 \pm 0.04$	
$\Delta\rvert_{B\to Dl\nu}$	0.46 ± 0.02	
$f_+^{K\pi}(0)$	0.965 ± 0.010	