

# 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:1006.0470 [hep-ph]

# Standard Model

$$\bar{Q}'_L \equiv (\bar{u}'_L, \bar{d}'_L) \quad , \quad \tilde{\Phi} \equiv i\tau_2 \Phi^*$$

One Higgs Doublet  $\Phi = \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix}$  ,  $\langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$

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

 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



  $\left\{ \begin{array}{l} \text{GIM Mechanism (Unitarity)} \\ \text{Yukawas proportional to masses} \end{array} \right.$

**No Flavour-Changing Neutral Currents**

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

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

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

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

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

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

# 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

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{Q}'_L (M'_d \Phi_1 + Y'_d \Phi_2) d'_R + \bar{Q}'_L (M'_u \tilde{\Phi}_1 + Y'_u \tilde{\Phi}_2) u'_R \right.$$
$$\left. + \bar{L}'_L (M'_l \Phi_1 + Y'_l \Phi_2) l'_R + \text{h.c.} \right\}$$

$M'_f$  and  $Y'_f$  unrelated  **FCNCs**

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

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

# 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)

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



**CP conserved in the scalar sector**

# Aligned 2HDM

(Pich - Tuzón '09)

Require alignment in Flavour Space of Yukawa couplings:

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



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

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

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

- Fermionic couplings proportional to fermion masses.
- Neutral Yukawas are diagonal in flavour

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

- $V_{\text{CKM}}$  is the only source of flavour-changing phenomena
- All leptonic couplings are diagonal in flavour
- Only three new (universal) couplings  $s_f$ .
- The usual  $\mathbb{Z}_2$  models are recovered in the limits  $\xi_f \rightarrow 0, \infty$

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

- $s_f$  are arbitrary complex numbers

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

## A2HDM: General phenomenological setting without tree-level FCNCs

$$\begin{aligned}\mathcal{L}_Y = & -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[ \varsigma_d V_{\text{CKM}} M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V_{\text{CKM}} \mathcal{P}_L \right] d + \varsigma_I (\bar{\nu} M_I \mathcal{P}_R I) \right\} \\ & -\frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0} \varphi_i^0 (\bar{f} M_f \mathcal{P}_R f) + \text{h.c.}\end{aligned}$$

$\mathbb{Z}_2$  models:

Model	$\varsigma_d$	$\varsigma_u$	$\varsigma_I$
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

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

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

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

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

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

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

## 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)

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

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

# Phenomenological Constraints

Jung-Pich-Tuzón

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



$$|\varsigma_I|/M_{H^\pm} < 0.43 \text{ GeV}^{-1} \quad (95\% \text{ CL})$$

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

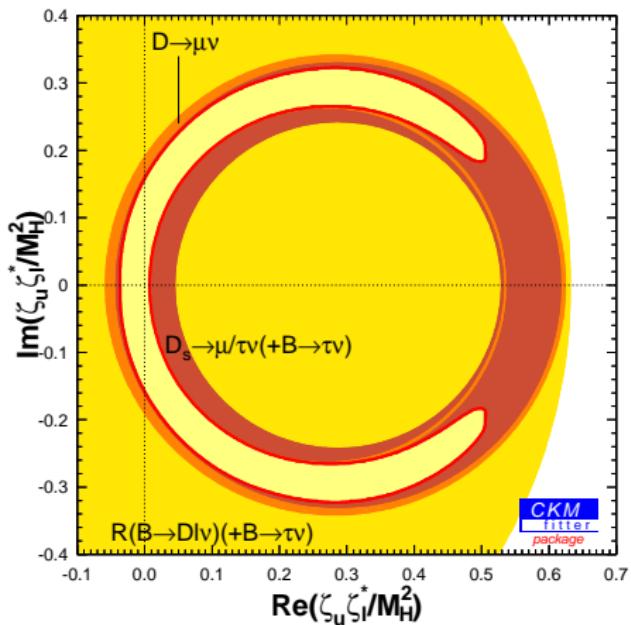
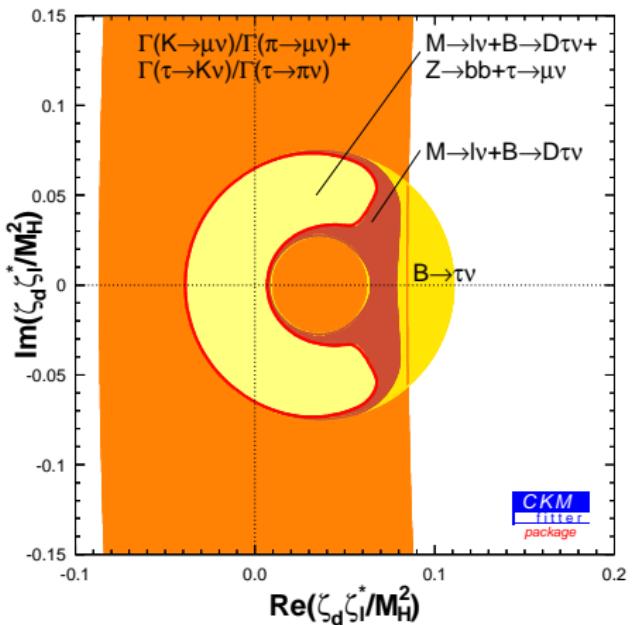
$$\Delta_{ij} = \frac{m_P^2}{M_{H^\pm}^2} \varsigma_I^* \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

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

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

# Global fit to $P \rightarrow l\nu_l$ , $\tau \rightarrow P\nu_\tau$ , $P \rightarrow P'\bar{l}\nu_l$ (95% CL)

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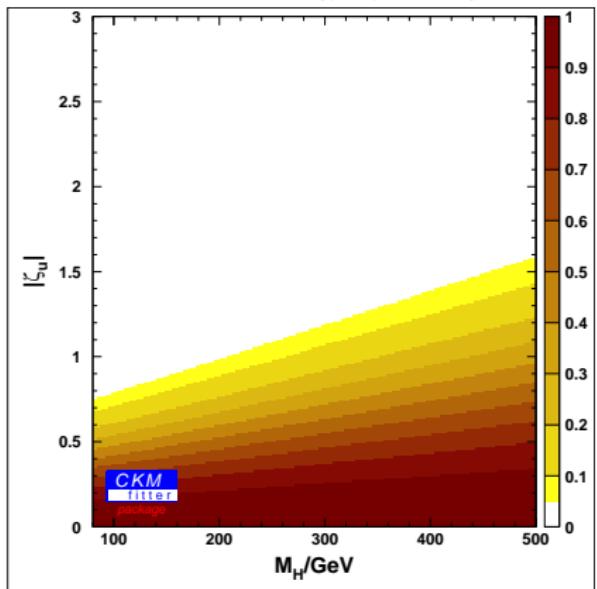


( $\text{GeV}^{-2}$  units)

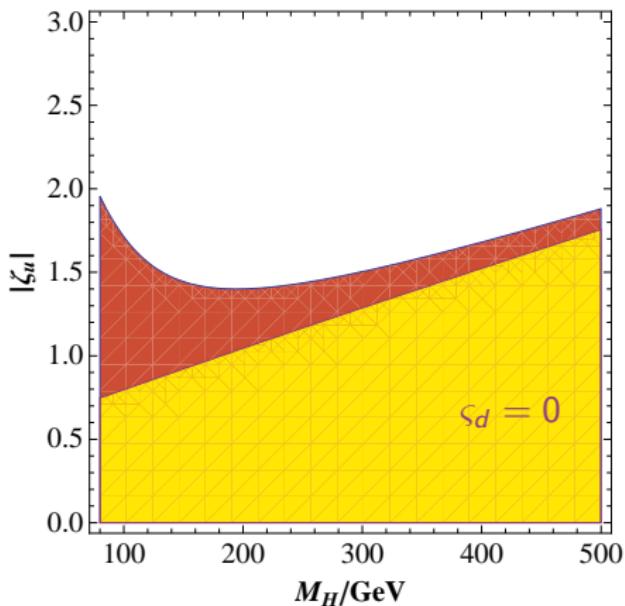
# Constraints from $Z \rightarrow b\bar{b}$ and $\Delta M_{B_s}$ (95% CL)

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$Z \rightarrow b\bar{b}$  ( $|\zeta_d| < 50$ )



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



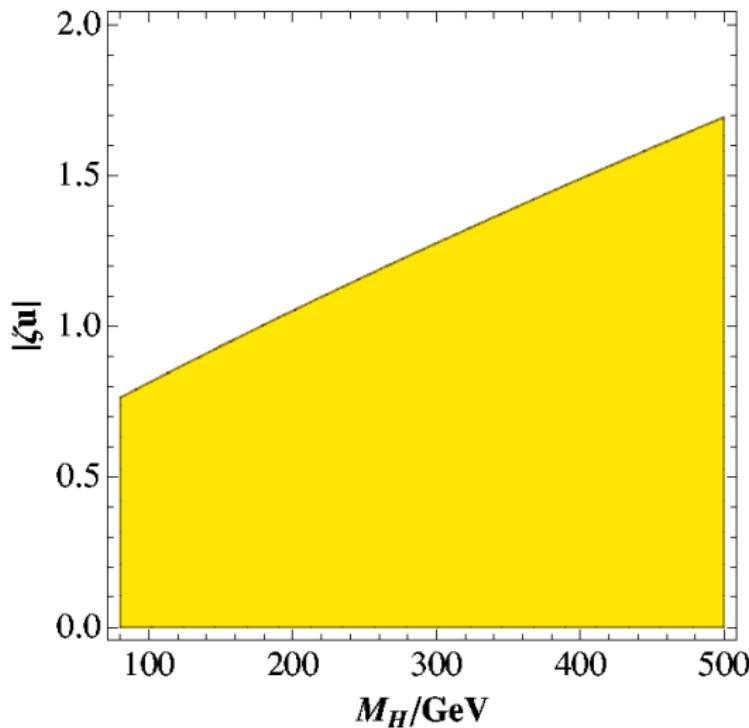
$$|\zeta_u|/M_{H^\pm} < 0.010 \text{ GeV}^{-1}$$



$$|\zeta_u \zeta_l^*|/M_{H^\pm}^2 < 0.0041 \text{ GeV}^{-2}$$

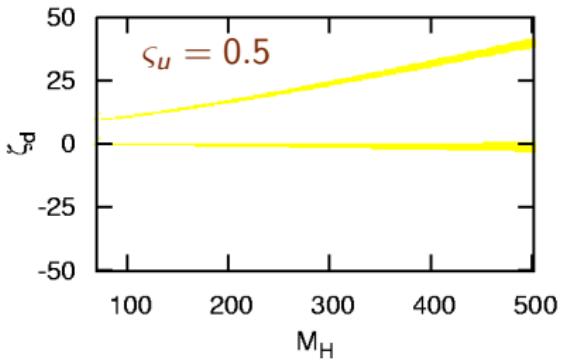
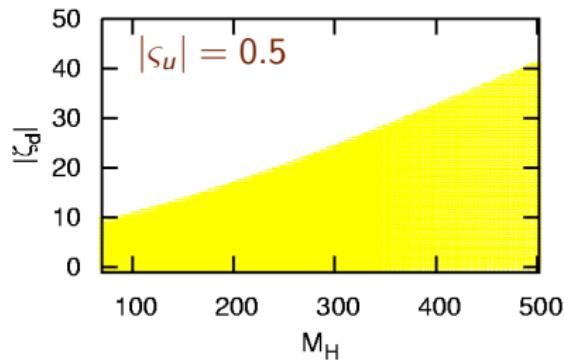
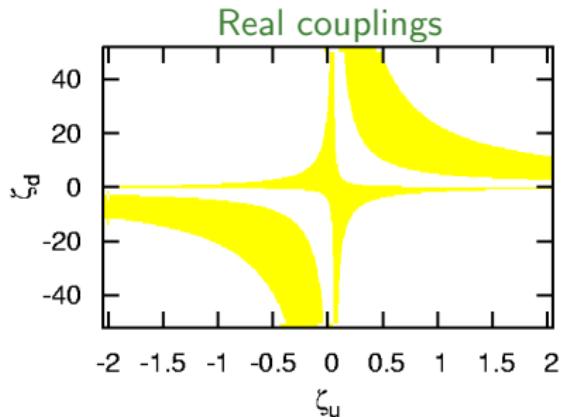
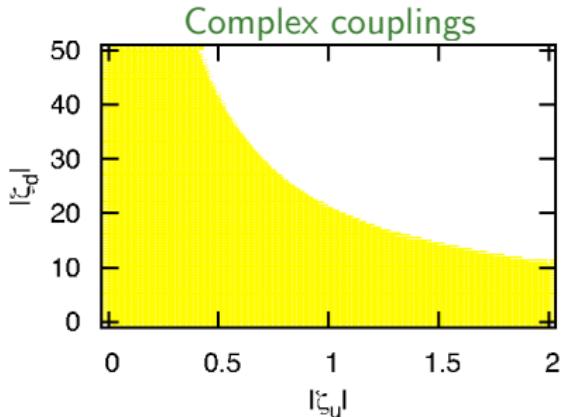
# Constraints from $\epsilon_K$ (95% CL)

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

Jung-Pich-Tuzón



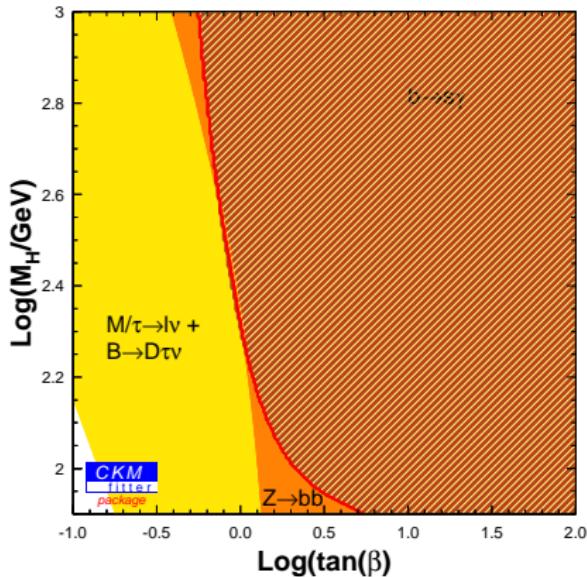
$$C_i^{\text{eff}}(\mu_W) = C_{i,SM} + |\zeta_u|^2 C_{i,uu} - (\zeta_u^* \zeta_d) C_{i,ud}$$

# Global Constraints on $\mathcal{Z}_2$ Models

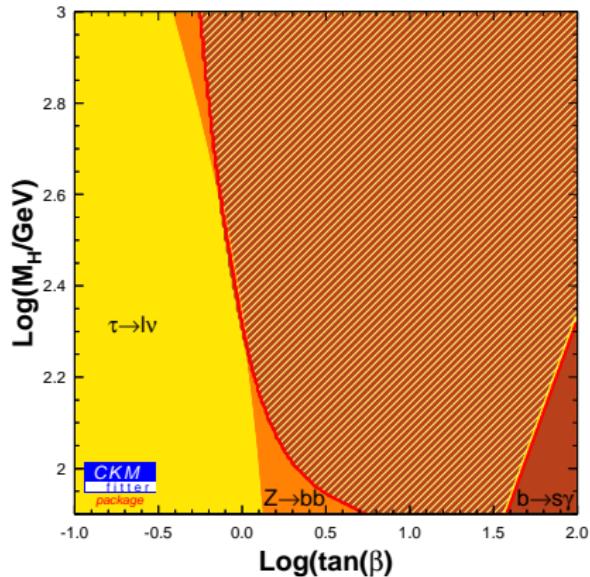
(95% CL)

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Type I



Type X



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

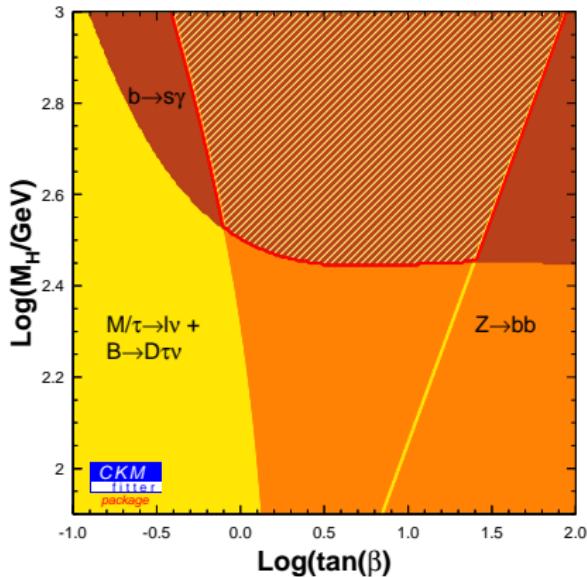
$$\varsigma_u = \varsigma_d = -\varsigma_l^{-1} = \cot \beta$$

# Global Constraints on $\mathcal{Z}_2$ Models

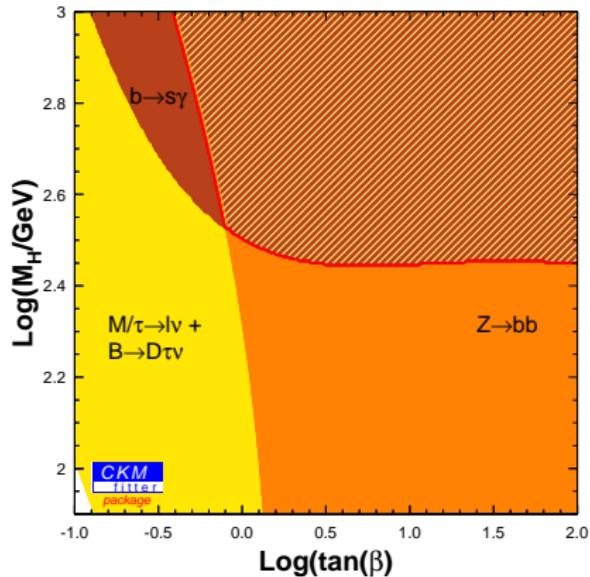
(95% CL)

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Type II



Type Y

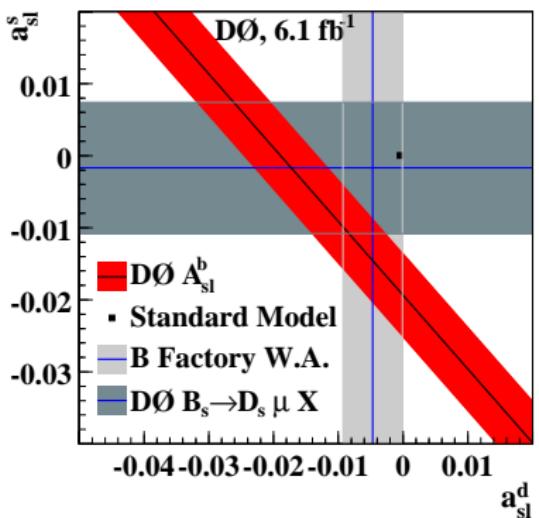


$$\varsigma_u = -\varsigma_d^{-1} = -\varsigma_l^{-1} = \cot \beta$$

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

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

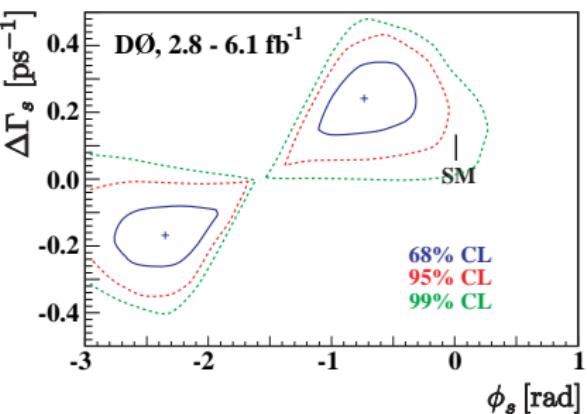
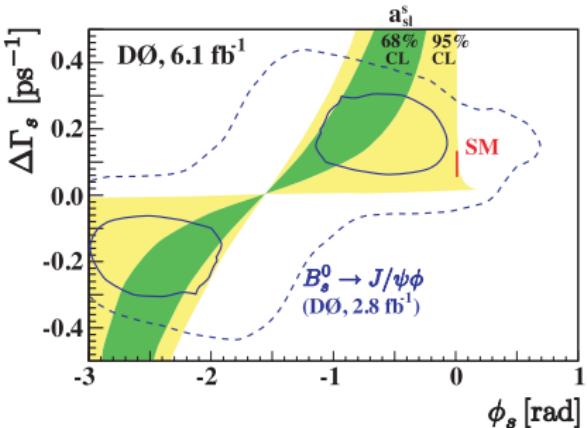
$B^0$  Mixing



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

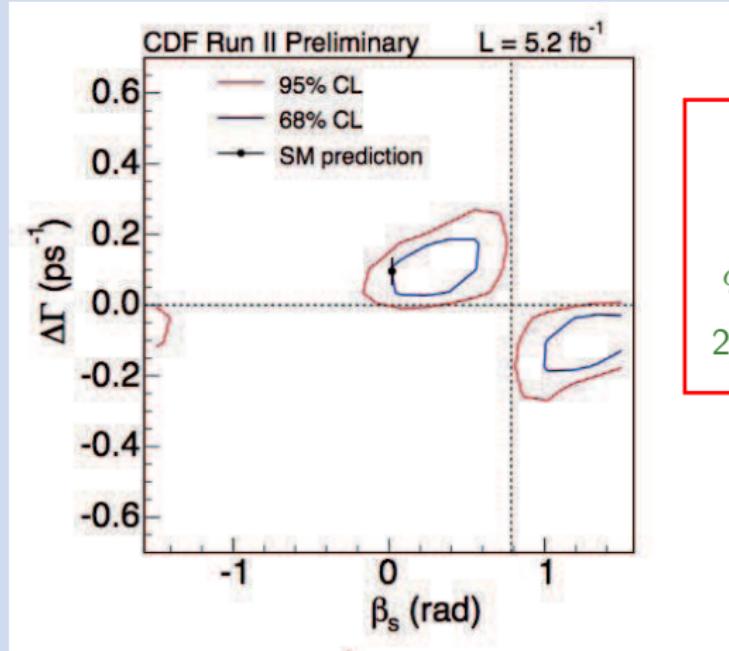
$$a_{sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \rightarrow \mu^+ X) - \Gamma(B_q^0 \rightarrow \mu^- X)}{\Gamma(\bar{B}_q^0 \rightarrow \mu^+ X) + \Gamma(B_q^0 \rightarrow \mu^- X)}$$

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



# New CDF measurement of $\beta_s$

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$$B_s^0 \rightarrow J/\psi \phi$$

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

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

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

P-value for SM point: 44%  
( $0.8\sigma$  deviation)

# Caveat

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

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

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

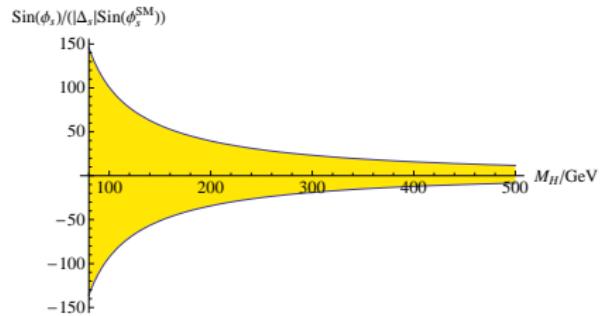
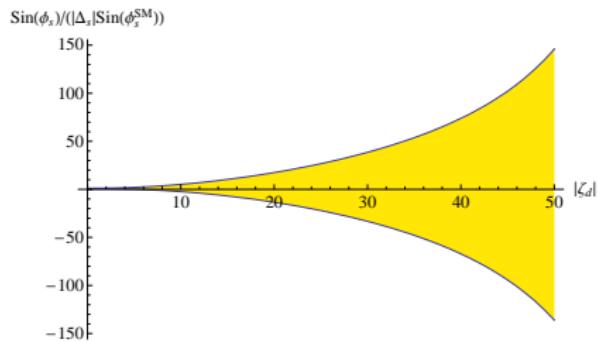
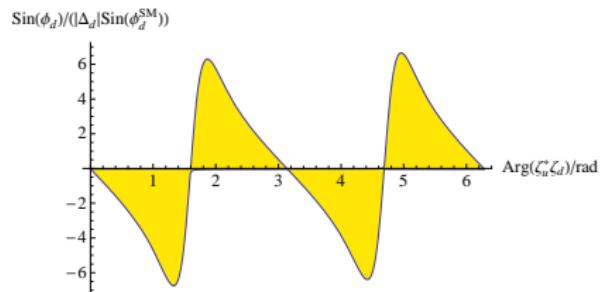
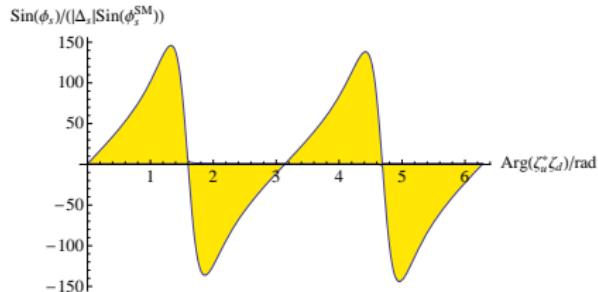
Measured D0 central value incompatible with  $\Delta\Gamma_s = \Delta\Gamma_s^{\text{SM}}$

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

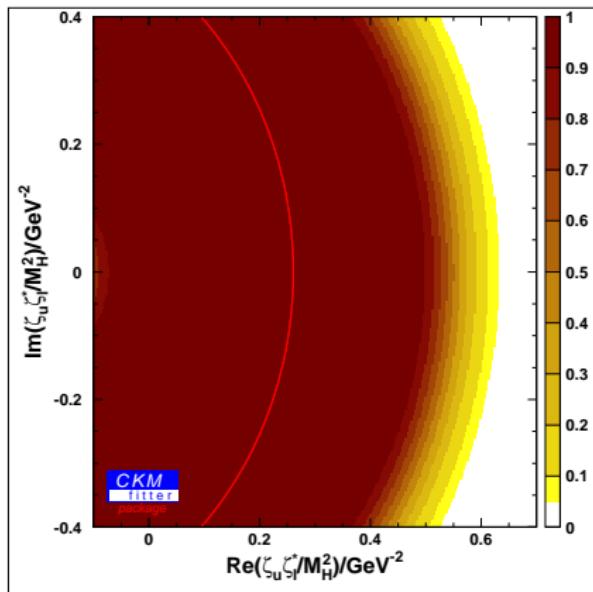
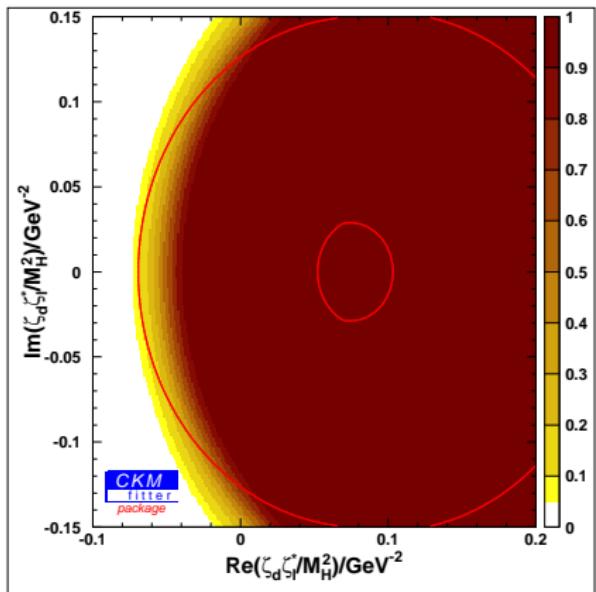
# SUMMARY

- 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  $S_f$
- Could accommodate a large  $B_s^0$  mixing phase  $\phi_s$
- **Many questions:** dipole moments, one-loop FCNC phenomena ...

# Backup Slides

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

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

Parameter	Value	Comment
$f_{B_s}$	$(0.242 \pm 0.003 \pm 0.022) \text{ GeV}$	
$f_{B_s}/f_{B_d}$	$1.232 \pm 0.016 \pm 0.033$	
$f_{D_s}$	$(0.2417 \pm 0.0012 \pm 0.0053) \text{ GeV}$	
$f_{D_s}/f_{D_d}$	$1.171 \pm 0.005 \pm 0.02$	
$f_K/f_\pi$	$1.192 \pm 0.002 \pm 0.013$	
$f_{B_s} \sqrt{\hat{B}_{B_s^0}}$	$(0.266 \pm 0.007 \pm 0.032) \text{ GeV}$	
$f_{B_d} \sqrt{\hat{B}_{B_d^0}} / (f_{B_s} \sqrt{\hat{B}_{B_s^0}})$	$1.258 \pm 0.025 \pm 0.043$	
$\hat{B}_K$	$0.732 \pm 0.006 \pm 0.043$	
$ V_{ud} $	$0.97425 \pm 0.00022$	
$\lambda$	$0.2255 \pm 0.0010$	$(1 -  V_{ud} ^2)^{1/2}$
$ V_{ub} $	$(3.8 \pm 0.1 \pm 0.4) \cdot 10^{-3}$	$b \rightarrow u/\nu$ (excl. + incl.)
$A$	$0.80 \pm 0.01 \pm 0.01$	$b \rightarrow c/\nu$ (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
$\rho^2 _{B \rightarrow D l \nu}$	$1.18 \pm 0.04 \pm 0.04$	
$\Delta _{B \rightarrow D l \nu}$	$0.46 \pm 0.02$	
$f_+^{K\pi}(0)$	$0.965 \pm 0.010$	

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

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

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

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

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

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{bmatrix} \cos(\alpha - \beta) & \sin(\alpha - \beta) \\ -\sin(\alpha - \beta) & \cos(\alpha - \beta) \end{bmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}$$