

# 3. Two Higgs Doublets

- FCNCs
- Flavour alignment
- Flavour bounds
- LHC constraints
- EDMs
- Rare decays



# Flavour Dynamics:

$N_G = 3$  Fermion Families

$$\Phi = \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \quad \rightarrow \quad \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}, \quad \tilde{\Phi} \equiv i \tau_2 \Phi^* = \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} \quad \rightarrow \quad \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix}$$

$$\mathcal{L}_Y = - \sum_{jk} \left\{ (\bar{u}'_j, \bar{d}'_j)_L \left[ c_{jk}^{(d)} \Phi d'_{kR} + c_{jk}^{(u)} \tilde{\Phi} u'_{kR} \right] - (\bar{\nu}'_j, \bar{\ell}'_j)_L c_{jk}^{(\ell)} \Phi \ell'_{kR} \right\} + \text{h.c.}$$

 SSB

$$\mathcal{L}_Y = - \left( 1 + \frac{H}{v} \right) \{ \bar{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + u'_L \cdot \mathbf{M}'_u \cdot u'_R + \ell'_L \cdot \mathbf{M}'_\ell \cdot \ell'_R + \text{h.c.} \}$$

Non-Diagonal Complex Mass Matrices:

$$(M'_f)_{jk} = c_{jk}^{(f)} \frac{v}{2}$$

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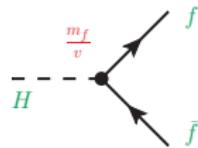
↓ SSB

$$\mathcal{L}_Y = - \left( 1 + \frac{H}{v} \right) \{ \bar{d}'_L \cdot M'_d \cdot d'_R + u'_L \cdot M'_u \cdot u'_R + \ell'_L \cdot M'_e \cdot \ell'_R + \text{h.c.} \}$$

Non-Diagonal Complex Mass Matrices:

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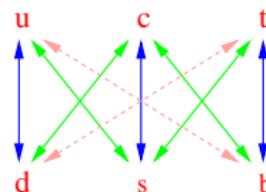
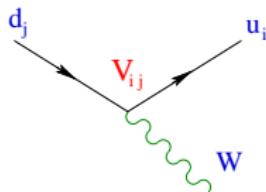
Diagonalization  $\rightarrow$   $\begin{cases} \text{GIM Mechanism} \\ g_{Hff} = m_f/v \end{cases}$



No Flavour-Changing Neutral Currents

# Flavour-Changing Charged Currents:

$$\mathcal{L}_{\text{cc}} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \left[ \sum_{ij} \bar{u}_i \gamma^\mu (1 - \gamma_5) V_{ij} d_j + \sum_\ell \bar{\nu}_\ell \gamma^\mu (1 - \gamma_5) \ell \right] + \text{h.c.}$$

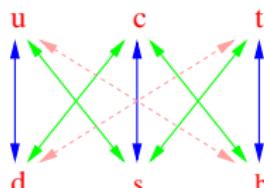
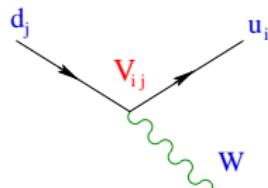


$$\bar{u}'_L d'_L = \bar{u}_L \cdot \mathbf{V} \cdot d_L$$

$$\bar{\nu}_{\ell j} \equiv \bar{\nu}_i V_{ij}^{(\ell)}$$

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$$\bar{u}'_L d'_L = \bar{u}_L \cdot \mathbf{V} \cdot d_L$$

$$\bar{\nu}_{\ell j} \equiv \bar{\nu}_i V_{ij}^{(\ell)}$$

# Flavour-Conserving Neutral Currents:

$$\bar{f}'_{L,R} f'_{L,R} = \bar{f}_{L,R} f_{L,R}$$

$$\mathcal{L}_{\text{nc}} = -\frac{2}{2 \sin \theta_W \cos \theta_W} Z_\mu \sum_f \bar{f} \gamma^\mu (v_f - a_f \gamma_5) f$$

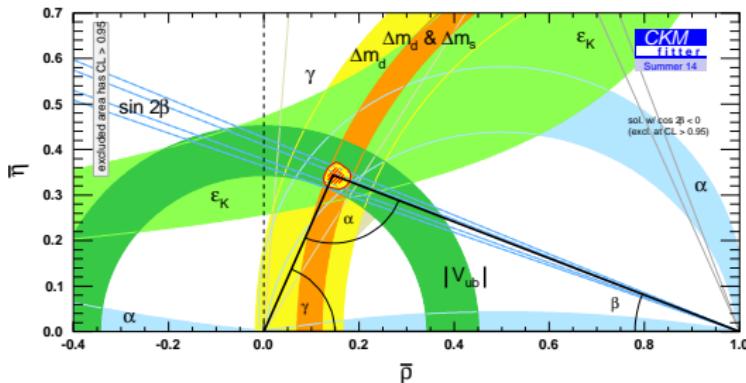


NO

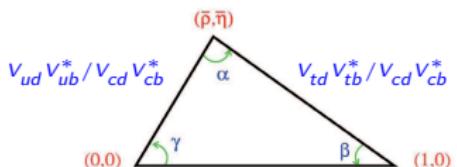
$$\text{Br}(K_S \rightarrow \mu^+ \mu^-) < 9 \times 10^{-9}$$

(LHCb, 90% CL)

# Quark Mixing



$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$



$$\mathbf{V} = \begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

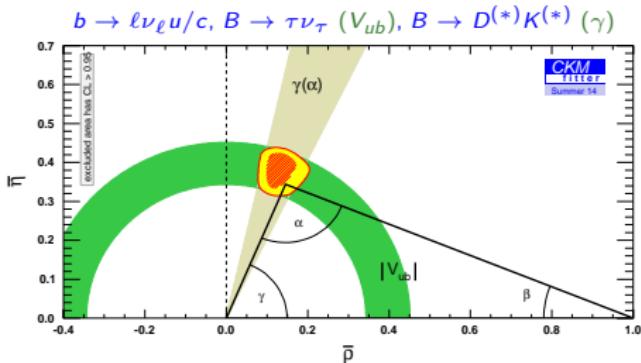
$\bar{\eta} \equiv \eta \left(1 - \frac{1}{2} \lambda^2\right) = 0.352 \pm 0.014$ 

**UT<sub>fit</sub>**

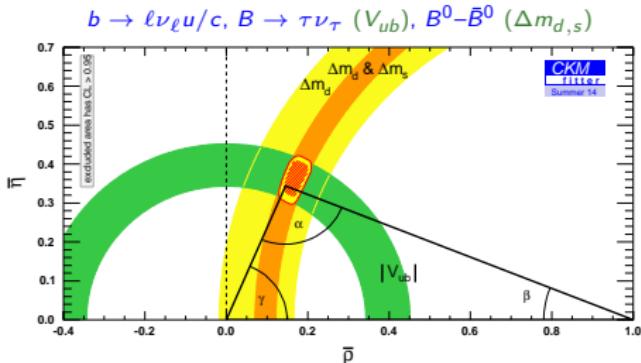
 $\bar{\rho} \equiv \rho \left(1 - \frac{1}{2} \lambda^2\right) = 0.132 \pm 0.023$ 
 $A = 0.821 \pm 0.012 \quad ; \quad \lambda = 0.2253 \pm 0.0007$

## Successful CKM Mechanism

## Tree-level determinations

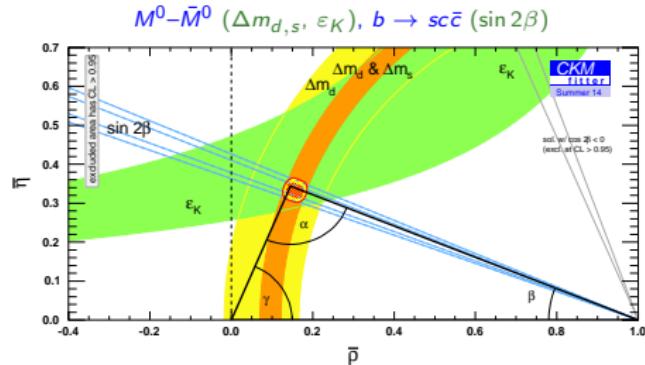


## CP conserving

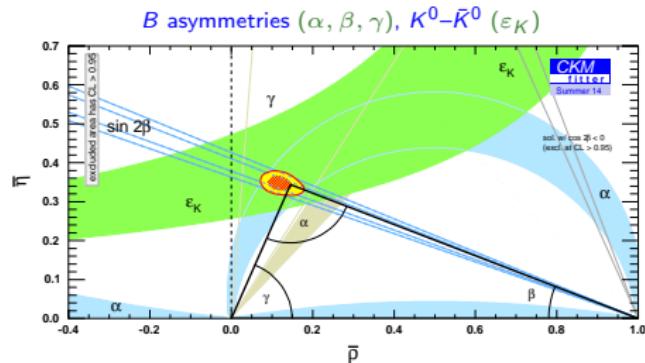


A. Pich

## Loop processes

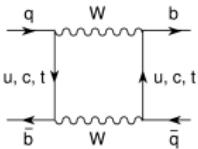
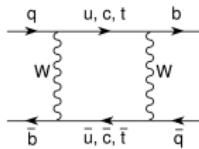


## CP violating



Higgs Physics

# Bounds on New Flavour Physics



$$L_{\text{eff}} = L_{\text{SM}} + \sum_{D>4} \sum_k \frac{c_k^{(D)}}{\Lambda_{\text{NP}}^{D-4}} O_k^{(D)}$$

Isidori, 1302.0661

Operator	Bounds on $\Lambda$ in TeV ( $c_{\text{NP}} = 1$ )		Bounds on $c_{\text{NP}}$ ( $\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	$9.8 \times 10^2$	$1.6 \times 10^4$	$9.0 \times 10^{-7}$	$3.4 \times 10^{-9}$	$\Delta m_K; \epsilon_K$
$(\bar{s}_L d_L)(\bar{s}_L d_R)$	$1.8 \times 10^4$	$3.2 \times 10^5$	$6.9 \times 10^{-9}$	$2.6 \times 10^{-11}$	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	$1.2 \times 10^3$	$2.9 \times 10^3$	$5.6 \times 10^{-7}$	$1.0 \times 10^{-7}$	$\Delta m_D;  q/p , \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	$6.2 \times 10^3$	$1.5 \times 10^4$	$5.7 \times 10^{-8}$	$1.1 \times 10^{-8}$	$\Delta m_D;  q/p , \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	$6.6 \times 10^2$	$9.3 \times 10^2$	$2.3 \times 10^{-6}$	$1.1 \times 10^{-6}$	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L d_L)(\bar{b}_L d_R)$	$2.5 \times 10^3$	$3.6 \times 10^3$	$3.9 \times 10^{-7}$	$1.9 \times 10^{-7}$	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	$1.4 \times 10^2$	$2.5 \times 10^2$	$5.0 \times 10^{-5}$	$1.7 \times 10^{-5}$	$\Delta m_{B_s}; S_{\psi \phi}$
$(\bar{b}_L s_L)(\bar{b}_L s_R)$	$4.8 \times 10^2$	$8.3 \times 10^2$	$8.8 \times 10^{-6}$	$2.9 \times 10^{-6}$	$\Delta m_{B_s}; S_{\psi \phi}$

- Generic flavour structure [ $c_{\text{NP}} \sim \mathcal{O}(1)$ ] ruled out at the TeV scale
- $\Lambda_{\text{NP}} \sim 1$  TeV requires  $c_{\text{NP}}$  to inherit the strong SM suppressions (GIM)

**Minimal Flavour Violation:** The up and down Yukawa matrices are the only source of quark-flavour symmetry breaking

D'Ambrosio et al, Buras et al

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

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

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

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

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

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

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

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

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

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos \tilde{\alpha} & \sin \tilde{\alpha} \\ -\sin \tilde{\alpha} & \cos \tilde{\alpha} \end{bmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix} \quad \text{CP-even}$$

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**Gauge couplings:**  $g_{\varphi_i^0 VV} = \mathcal{R}_{i1} g_{hVV}^{\text{SM}}$

$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 = (g_{hVV}^{\text{SM}})^2$$

# Yukawa Interactions in 2HDMs

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

 SSB

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

$M'_f$  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  $\rightarrow$  2HDM 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, Paschos '77

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



**CP conserved in the scalar sector**

# Aligned 2HDM

Pich-Tuzón, 0908.1554

**Yukawa alignment in Flavour Space:**  $Y_{d,I} = \varsigma_{d,I} M_{d,I}$  ,  $Y_u = \varsigma_u^* M_u$

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

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

$\varsigma_f \rightarrow$  New sources of CP violation without tree-level FCNCs

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$Z_2$  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

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

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

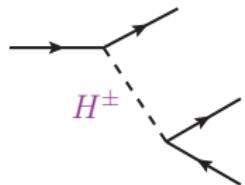
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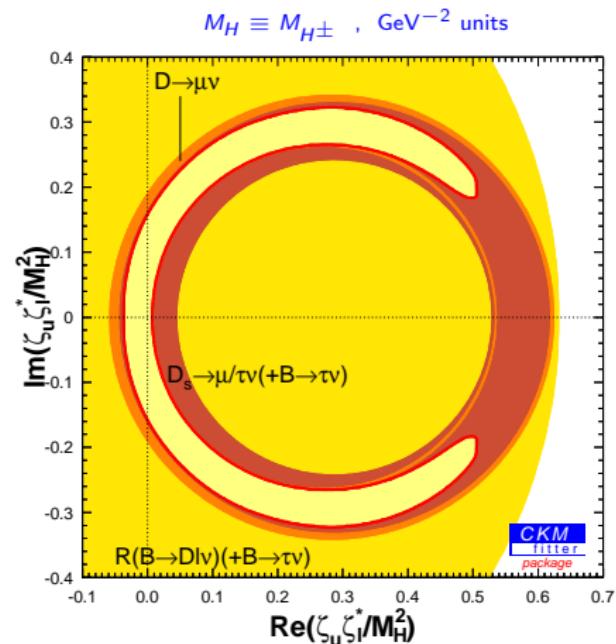
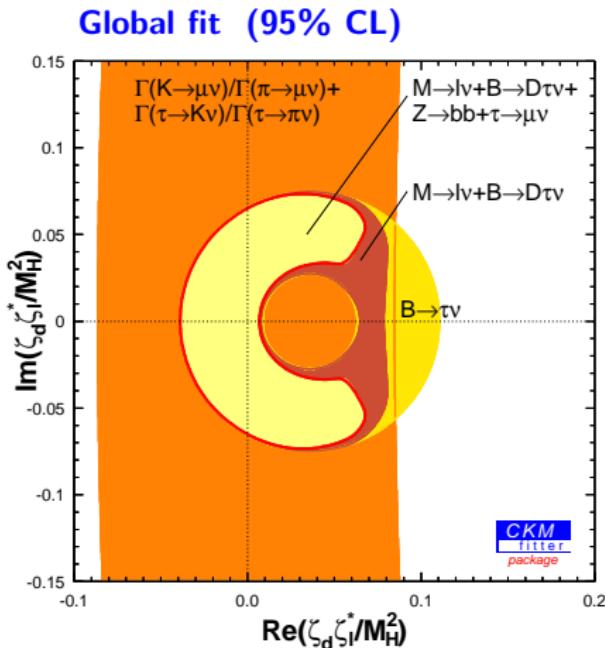
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Type Y	$-\tan \beta$	$\cot \beta$	$\cot \beta$
Inert	0	0	0

$$\begin{aligned} \Gamma_2 &= \xi_d e^{-i\theta} \Gamma_1 \\ \Delta_2 &= \xi_u^* e^{i\theta} \Delta_1 \\ \Pi_2 &= \xi_I e^{-i\theta} \Pi_1 \\ \varsigma_f &= \frac{\xi_f - \tan \beta}{1 + \xi_f \tan \beta} \end{aligned}$$

$$P \rightarrow \ell \nu_\ell, \tau \rightarrow P \nu_\tau, P \rightarrow P' \ell \nu_\ell$$

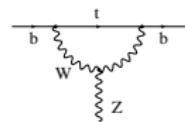
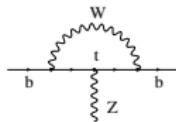
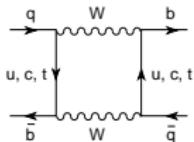
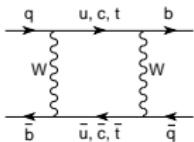


Jung-Pich-Tuzón, 1006.0470

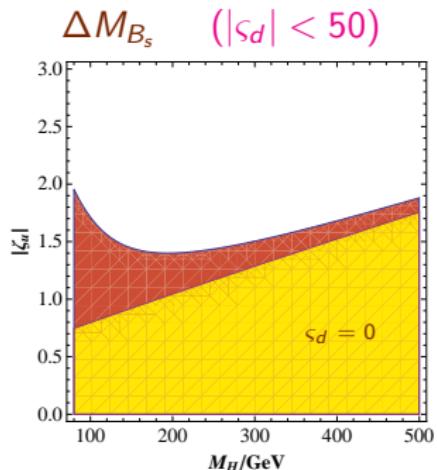


**Very weak constraints**

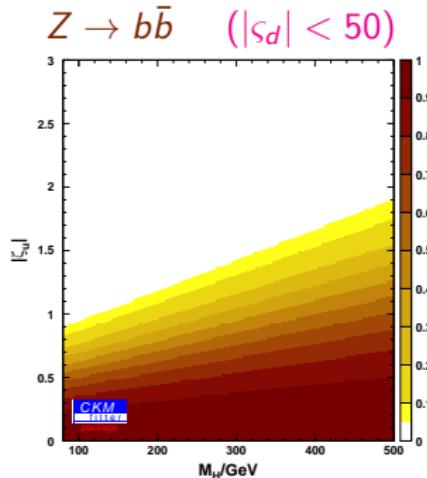
# 1-Loop Constraints on $H^\pm$ Couplings (95% CL)



**Virtual  $H^\pm / W^\pm$ . Top-dominated contributions**

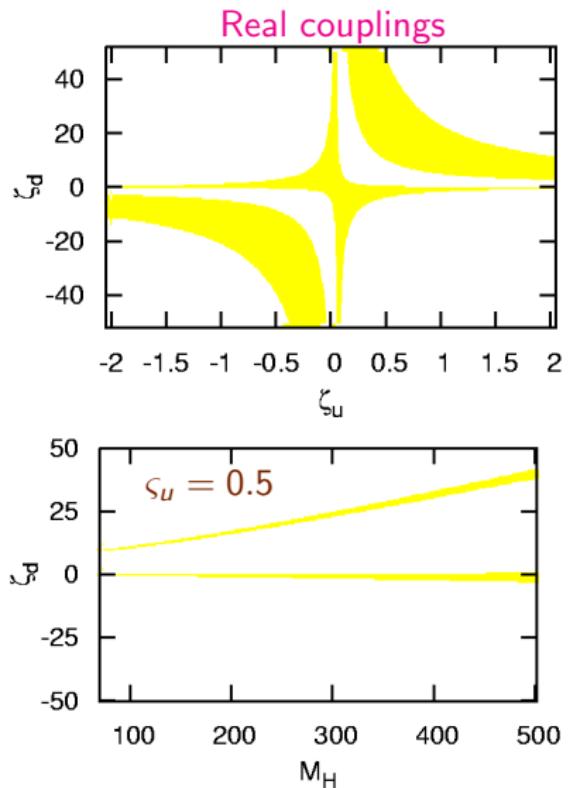
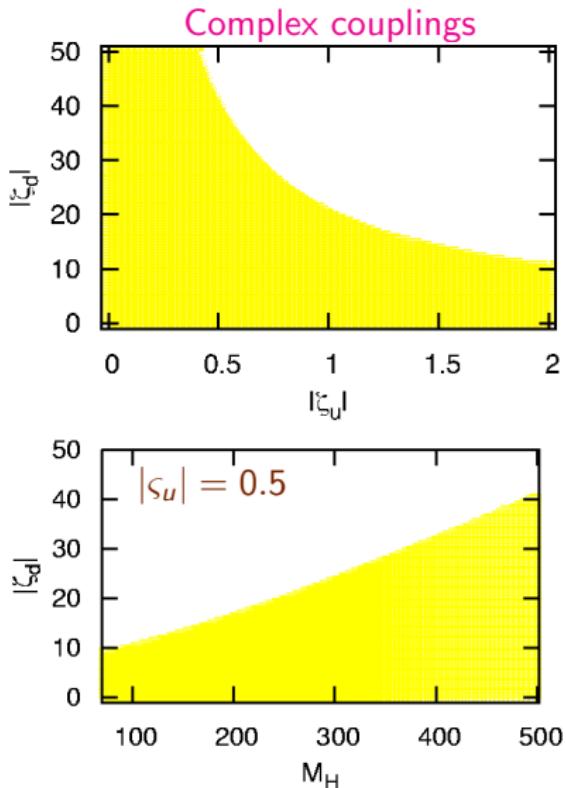


$$|\varsigma_u|/M_{H^\pm} < 0.011 \text{ GeV}^{-1}$$



Jung-Pich-Tuzón, 1006.0470

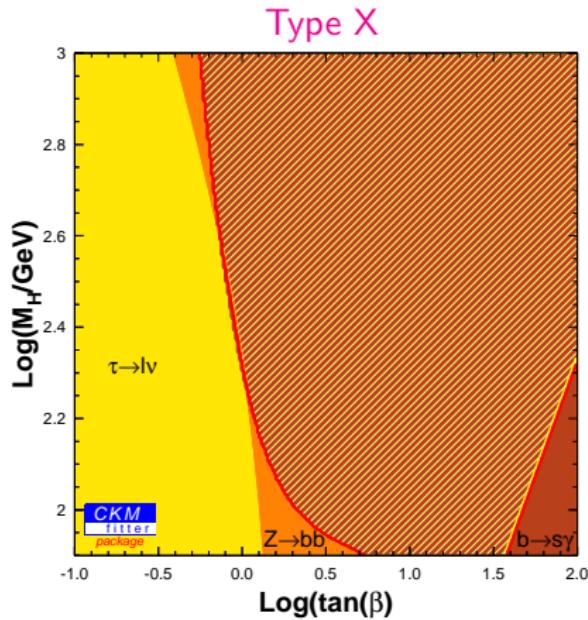
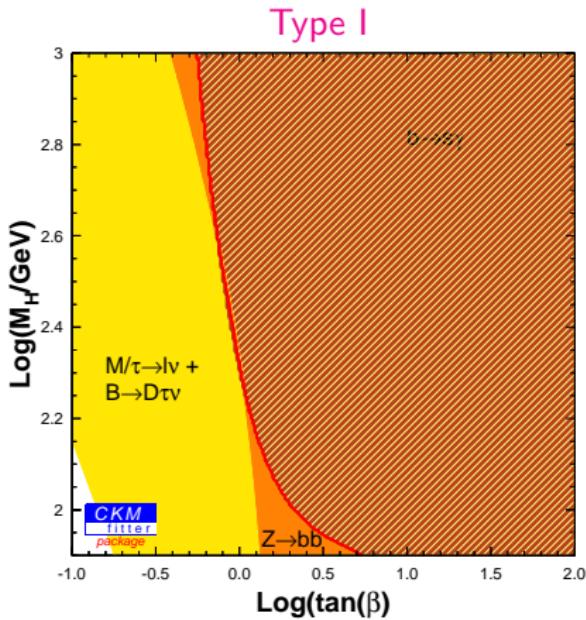
# Constraints from $b \rightarrow s\gamma$ (95% CL)



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

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

Jung-Pich-Tuzón, 1006.0470

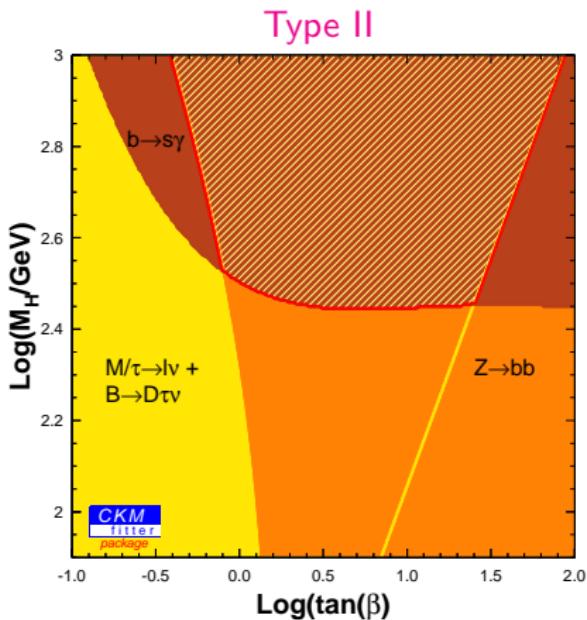


$$\varsigma_u = \varsigma_d = \varsigma_I = \cot \beta$$

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

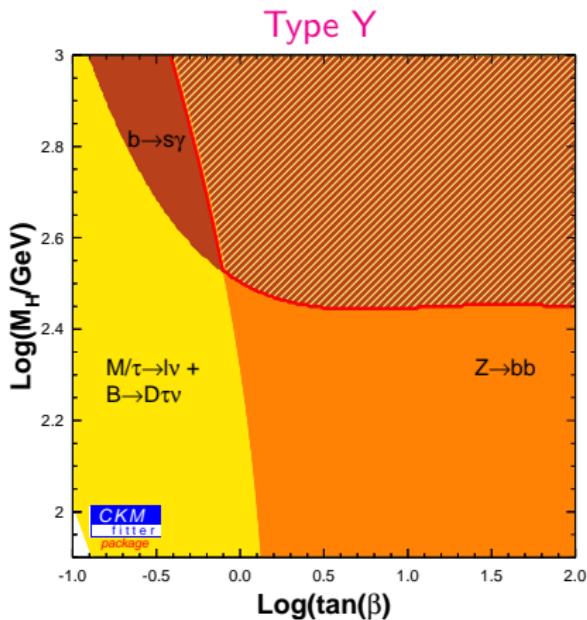
# Global Constraints on $\mathcal{Z}_2$ Models (95% CL)

Jung-Pich-Tuzón, 1006.0470



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

$M_{H^\pm} > 277 \text{ GeV}$



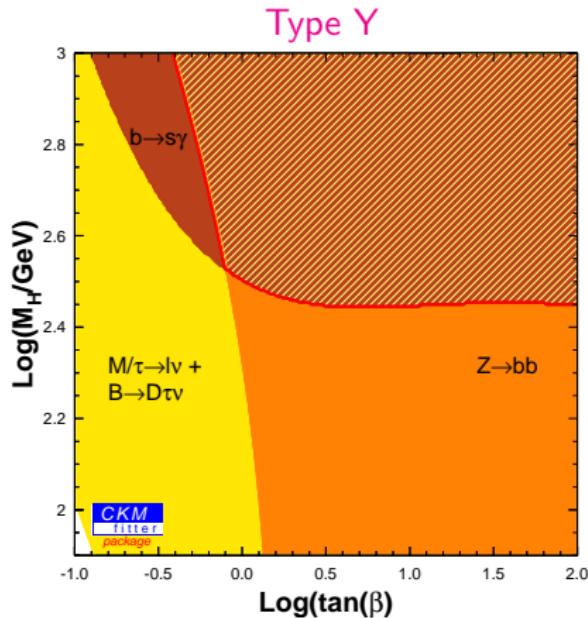
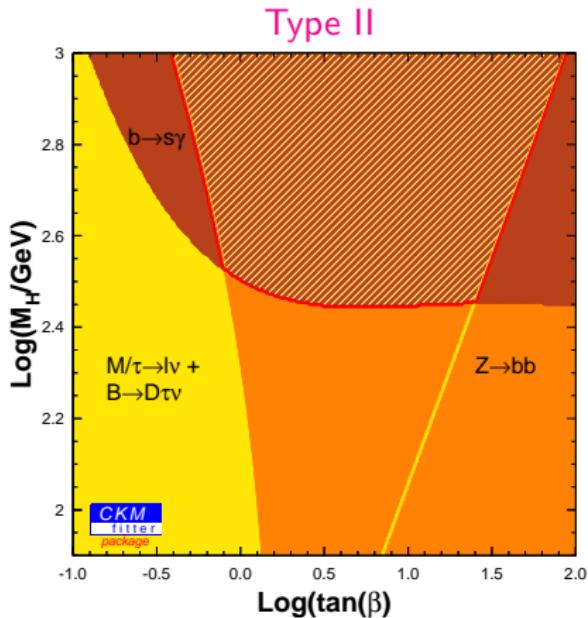
$$\varsigma_u = -\varsigma_d^{-1} = \varsigma_l = \cot \beta$$

In agreement with previous analyses

Aoki et al, Wahab et al, Deschamps et al, Flacher et al, Bona et al, Mahmoudi-Stal, Misiak et al ...

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

Jung-Pich-Tuzón, 1006.0470



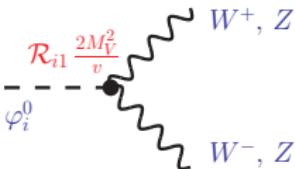
$$\varsigma_u = -\varsigma_d^{-1} = -\varsigma_l^{-1} = \cot \beta$$

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

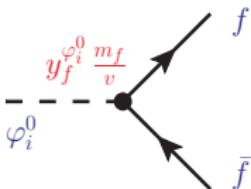
Updated bound (NNLO, new data):  $M_{H^\pm} > 480 \text{ GeV}$

Misiak et al., 1503.01789

# Scaling factors for Higgs Production & Decay



$$g_{\varphi_i^0 VV} = \mathcal{R}_{i1} g_{hVV}^{\text{SM}}$$



$$y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i \mathcal{R}_{i3}) \varsigma_u^*$$

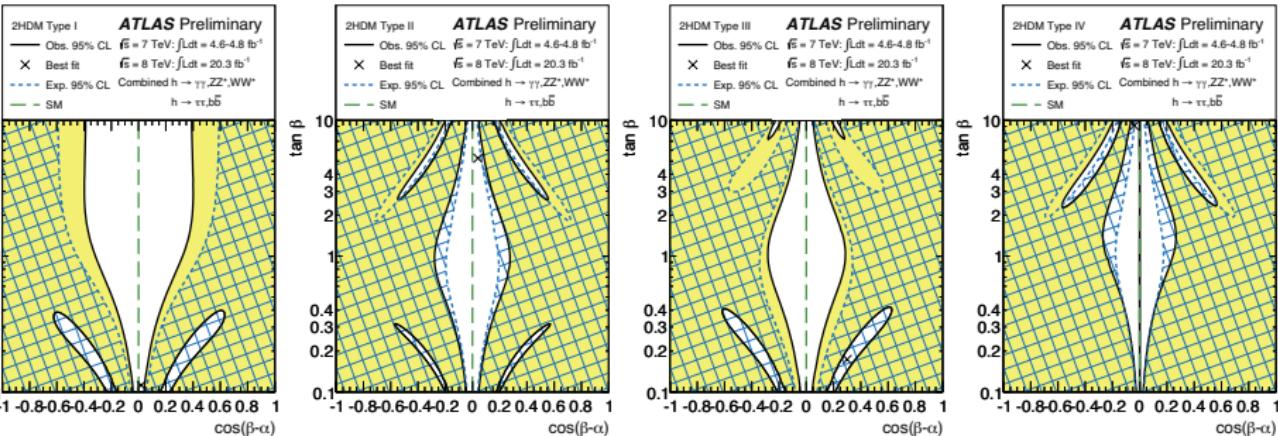
$$y_{d,I}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i \mathcal{R}_{i3}) \varsigma_{d,I}$$

- **CP Symmetry:**

$$g_{h_i VV} = \cos \tilde{\alpha} \ g_{hVV}^{\text{SM}} \quad , \quad g_{HVV} = -\sin \tilde{\alpha} \ g_{hVV}^{\text{SM}}$$

$$y_f^h = \cos \tilde{\alpha} + \varsigma_f \sin \tilde{\alpha} \quad , \quad y_f^H = -\sin \tilde{\alpha} + \varsigma_f \cos \tilde{\alpha} \quad , \quad y_u^A = -i \varsigma_u \quad , \quad y_{d,I}^A = i \varsigma_{d,I}$$

# LHC Fit within $\mathcal{Z}_2$ Models



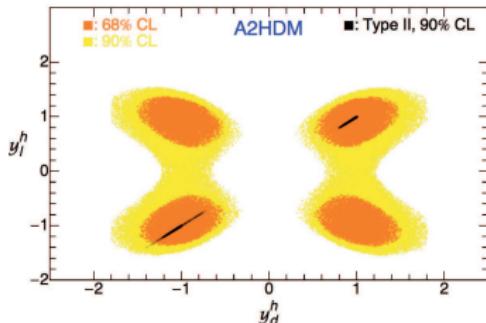
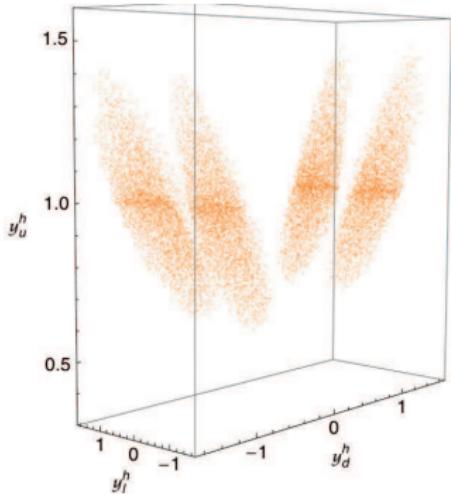
$$g_{Vvh}/g_{VVh}^{\text{SM}} = \cos \tilde{\alpha} \equiv \sin (\beta - \alpha)$$

$$y_f^h = \cos \tilde{\alpha} + s_f \sin \tilde{\alpha}$$

Model	$\zeta_d$	$\zeta_u$	$\zeta_l$
Type I	$\cot \beta$	$\cot \beta$	$\cot \beta$
Type II	$-\tan \beta$	$\cot \beta$	$-\tan \beta$
Type X (III)	$\cot \beta$	$\cot \beta$	$-\tan \beta$
Type Y (IV)	$-\tan \beta$	$\cot \beta$	$\cot \beta$
Inert	0	0	0

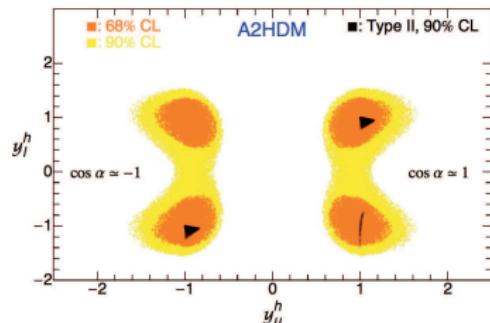
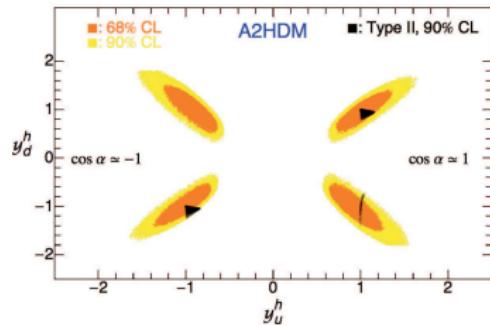
# A Light CP-even Higgs at 125 GeV

Celis-Illisie-Pich, 1302.4022, 1310.7941

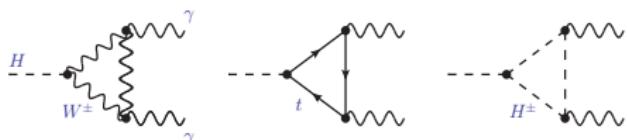
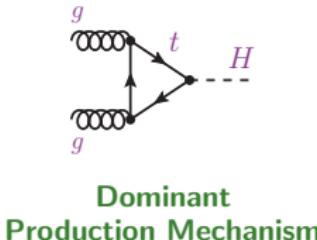


**CP conserved**

$$|\cos \tilde{\alpha}| > 0.80 \quad (90\% \text{ CL})$$



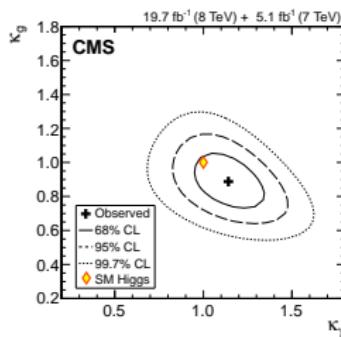
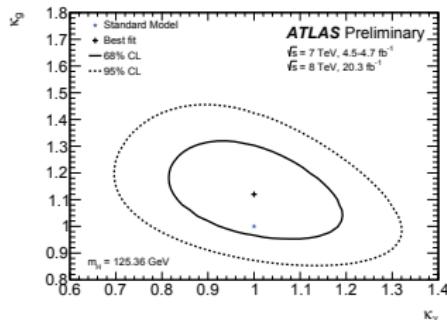
# Strong (indirect) evidence for Higgs coupling to t



$$\Gamma \propto | -8.4 \kappa_W + 1.8 \kappa_t + \mathcal{C}_{\text{NP}} |^2$$

**SM:**  $\kappa_W = \kappa_t = 1$  ,  $\mathcal{C}_{\text{NP}} = 0$

**Destructive interference**



$$\kappa_i \equiv g_i/g_i^{\text{SM}}$$

H → γγ	Signal Strength
ATLAS	$1.17 \pm 0.28$
CMS	$1.12 \pm 0.24$

# A Light CP-even Higgs at 125 GeV

Celis-Illisie-Pich, 1302.4022, 1310.7941

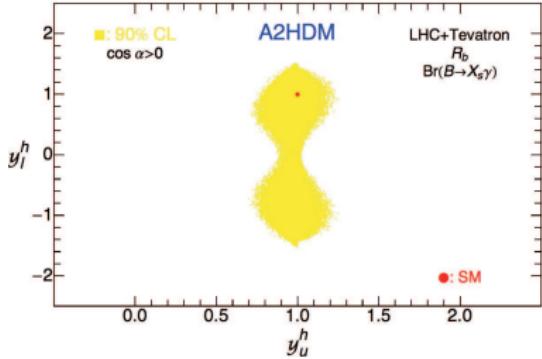
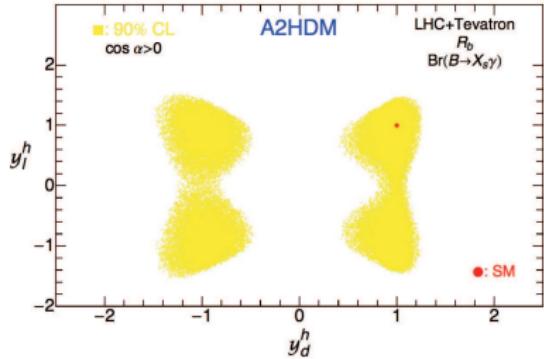
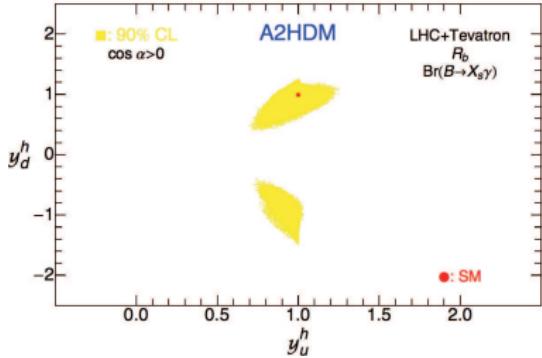
CP conserved

LHC + Tevatron +  $R_b$  +  $b \rightarrow s\gamma$

$$M_{H^\pm} \in [80, 500] \text{ GeV}$$

$$|\zeta_{d,I}| < 50$$

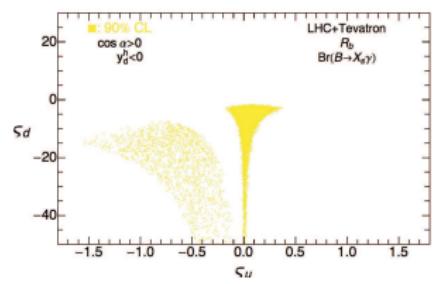
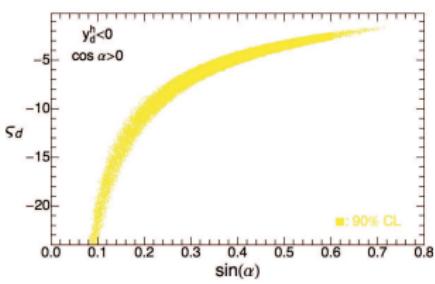
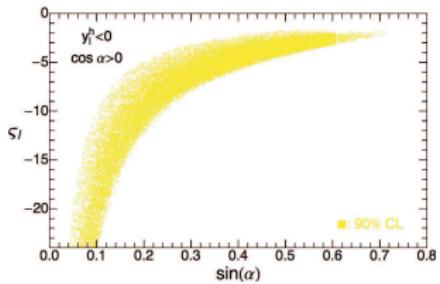
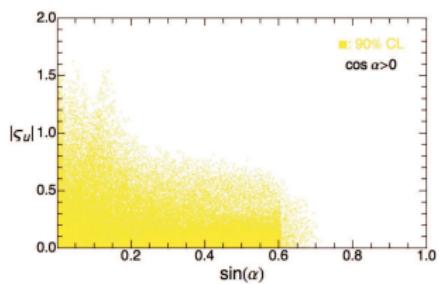
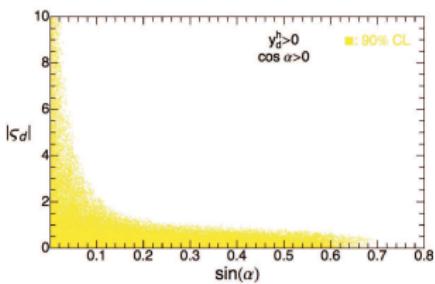
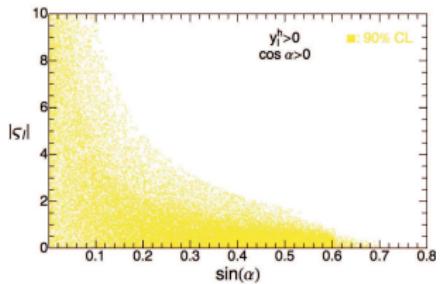
$H^\pm$  neglected in  $H \rightarrow 2\gamma$



# A Light CP-even Higgs at 125 GeV

Celis-Illisie-Pich, 1302.4022, 1310.7941

CP conserved



Strong constraints on the A2HDM parameters

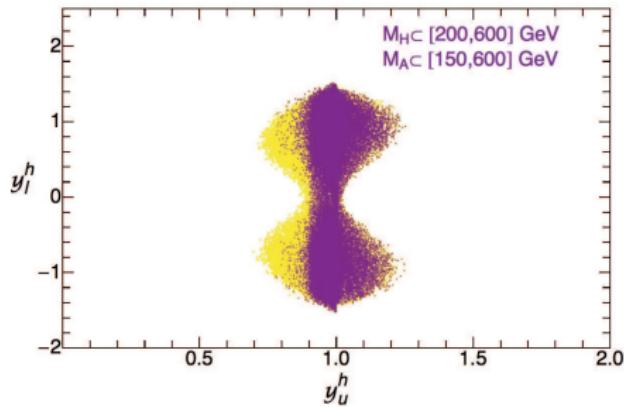
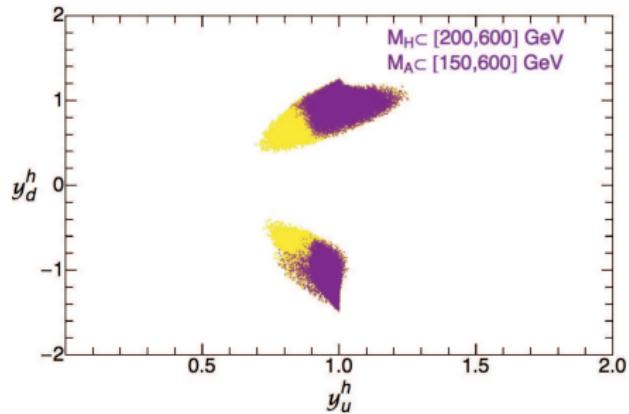
# Heavy Scalar Searches

**CP Symmetry:**

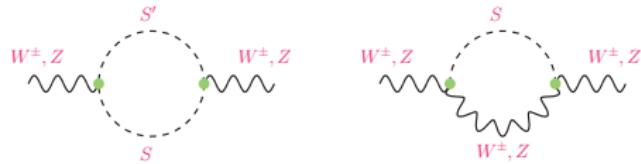
$$\kappa_V^h = \cos \tilde{\alpha} \quad , \quad \kappa_V^H = -\sin \tilde{\alpha} \quad , \quad \kappa_A^H = 0$$

$$y_f^h = \cos \tilde{\alpha} + \varsigma_f \sin \tilde{\alpha} \quad , \quad y_f^H = -\sin \tilde{\alpha} + \varsigma_f \cos \tilde{\alpha} \quad , \quad y_u^A = -i \varsigma_u \quad , \quad y_{d,I}^A = i \varsigma_{d,I}$$

→  $|\kappa_V^H|^2 = 1 - |\kappa_V^h|^2 \quad , \quad |y_f^H|^2 - |y_f^A|^2 = 1 - |y_f^h|^2 \quad , \quad \kappa_V^H y_f^H = 1 - \kappa_V^h y_f^h$

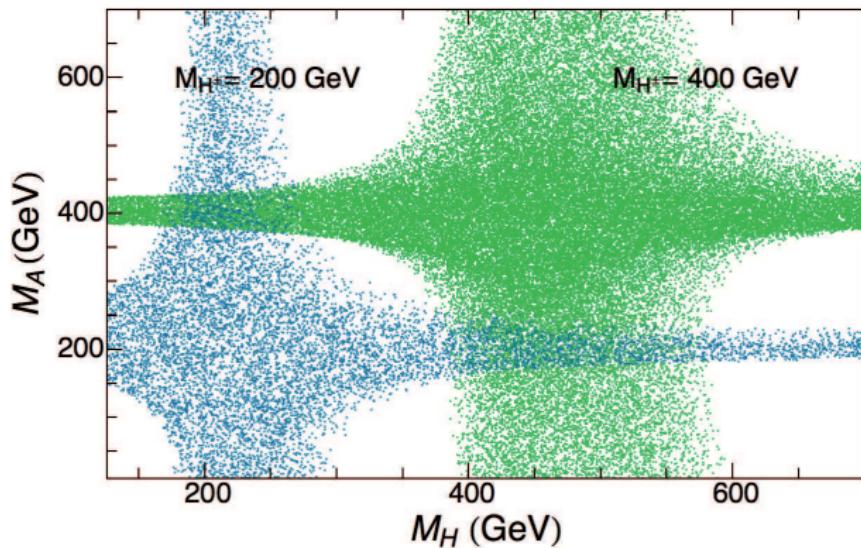


# Oblique Constraints (S, T, U)

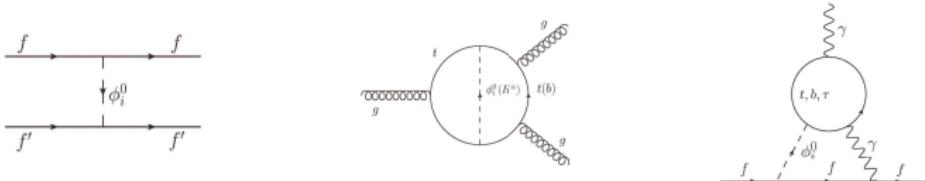


$$\cos \tilde{\alpha} \in [0.8, 1]$$

Celis-Ilisie-Pich, 1302.4022, 1310.7941



# Electric Dipole Moments



- Highly sensitive to flavour-blind CP-violating phases
- Stringent experimental bounds: neutron, Tl, Hg, YbF ...
- 1-loop  $H^\pm$  contributions very suppressed by light-quark masses
- Contributions from 4-fermion operators are small Buras et al
- Two-loop contributions dominate Weinberg, Dicus, Barr-Zee, Gunion-Wyler
- Strong cancelations among  $\phi_i^0$  contributions: Jung-Pich

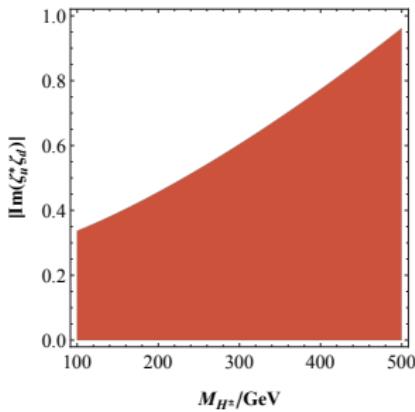
$$\sum_i \operatorname{Re}(y_f^{\phi_i^0}) \operatorname{Im}(y_{f'}^{\phi_i^0}) \propto \operatorname{Im}(\zeta_f^* \zeta_{f'})$$

Cancelation exact in the equal-mass and decoupling limits

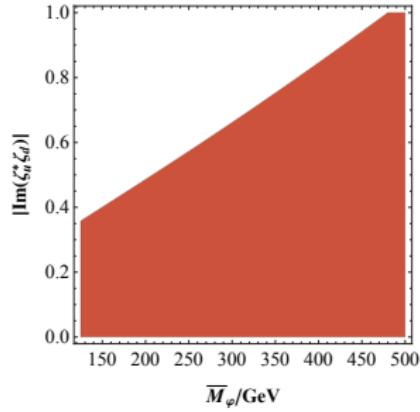
# Neutron EDM

Jung-Pich, 1308.6283

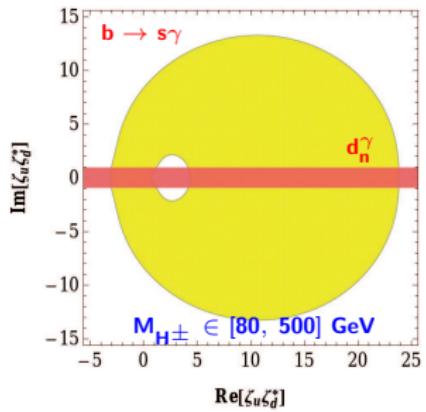
Charged contribution



Neutral contribution



Comparison with  $b \rightarrow s \gamma$

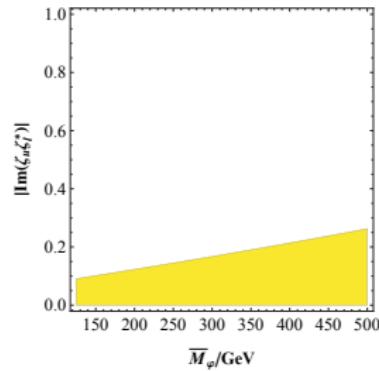
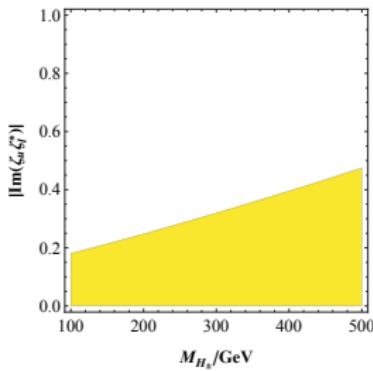


$\text{Im}(\zeta_u \zeta_d^*)$  strongly constrained, but not tiny

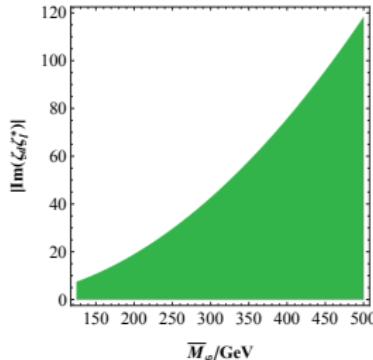
$$\overline{M}_\varphi = \langle M_{\varphi_i^0} \rangle \quad (\text{effective neutral mass})$$

# Electron EDM

Jung-Pich, 1308.6283



# Mercury EDM



# Quantum Corrections

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

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

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

- 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, Braeuninger-Ibarra-Simonetto

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

- $C(\mu) = C(\mu_0) - \log(\mu/\mu_0)$

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- $C(\mu) = C(\mu_0) - \log(\mu/\mu_0)$
- Vanish in all  $\mathcal{Z}_2$  models as it should

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- $C(\mu) = C(\mu_0) - \log(\mu/\mu_0)$
- Vanish in all  $\mathcal{Z}_2$  models as it should
- Suppressed by  $m_q m_{q'}^2 / (4\pi^2 v^3)$  and  $V_{\text{CKM}}^{qq'}$    $\bar{s}_L b_R, \bar{c}_L t_R$

# FCNCs at one Loop

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

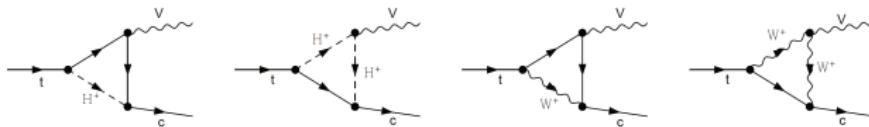


Jung-Pich-Tuzón, Braeuninger-Ibarra-Simonetto

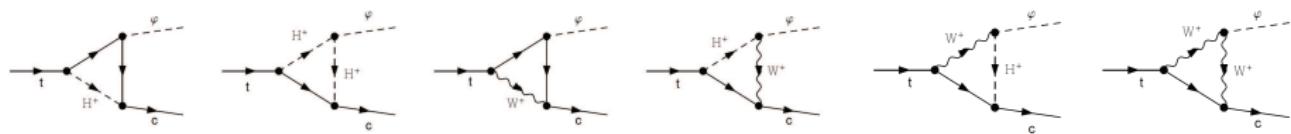
$$\begin{aligned}\mathcal{L}_{\text{FCNC}} = & \frac{C(\mu)}{4\pi^2 v^3} (1 + \varsigma_u^* \varsigma_d) \sum_i \varphi_i^0(x) \\ & \times \left\{ (\mathcal{R}_{i2} + i \mathcal{R}_{i3}) (\varsigma_d - \varsigma_u) \left[ \bar{d}_L V_{\text{CKM}}^\dagger M_u M_u^\dagger V_{\text{CKM}} M_d d_R \right]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

- $C(\mu) = C(\mu_0) - \log(\mu/\mu_0)$
- Vanish in all  $\mathcal{Z}_2$  models as it should
- Suppressed by  $m_q m_{q'}^2 / (4\pi^2 v^3)$  and  $V_{\text{CKM}}^{qq'}$   $\rightarrow$   $\bar{s}_L b_R, \bar{c}_L t_R$
- $\Delta M_{B_s^0} \rightarrow \frac{1}{4\pi^2} |C(M_W)(1 + \varsigma_u^* \varsigma_d)(\varsigma_d - \varsigma_u)| \lesssim \mathcal{O}(1)$

$t \rightarrow c V$       ( $V = \gamma, Z$ )



$t \rightarrow c \varphi_i^0$       ( $\varphi_i^0 = h, H, A$ )



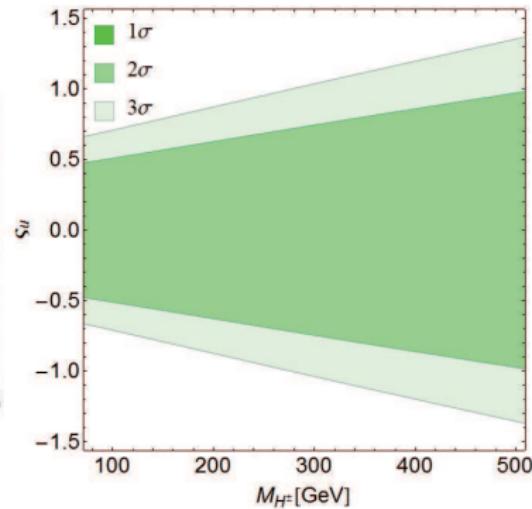
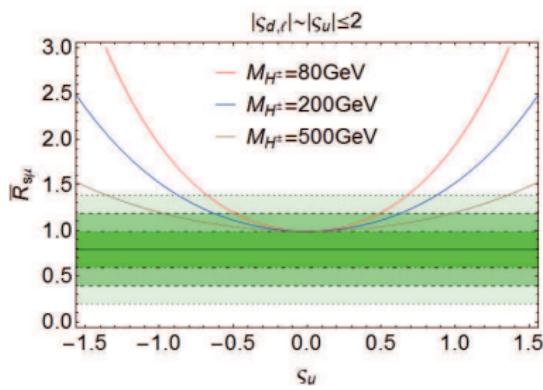
$M_{H^\pm}$ (GeV)	$\text{Br}(t \rightarrow c\gamma)$	$\text{Br}(t \rightarrow cZ)$	$\text{Br}(t \rightarrow ch)$
100	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-13}$	$\lesssim 6 \times 10^{-9}$
200	$\lesssim 10^{-10}$	$\lesssim 3 \times 10^{-11}$	$\lesssim 3 \times 10^{-8}$
300	$\lesssim 10^{-11}$	$\lesssim 5 \times 10^{-12}$	$\lesssim 2 \times 10^{-8}$
400	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-12}$	$\lesssim 5 \times 10^{-9}$
500	$\lesssim 10^{-12}$	$\lesssim 10^{-12}$	$\lesssim 2 \times 10^{-9}$
Exp. limit	$< 1.8 \times 10^{-3}$	$< 5 \times 10^{-4}$	$< 5.6 \times 10^{-3}$

$$B_{s,d}^0 \rightarrow \mu^+ \mu^-$$

Li-Lu-Pich, 1404.5865

**CMS & LHCb:**  $\overline{\mathcal{B}}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{exp.}} = (2.8 \pm 0.7) \times 10^{-9}$  [SM:  $(3.65 \pm 0.23) \times 10^{-9}$ ]

$$\overline{\mathcal{B}}(B_d^0 \rightarrow \mu^+ \mu^-)_{\text{exp.}} = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$
 [SM:  $(1.06 \pm 0.09) \times 10^{-10}$ ]



$$\bar{R}_{s\mu} \equiv \overline{\mathcal{B}}(B_s^0 \rightarrow \mu^+ \mu^-) / \overline{\mathcal{B}}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{SM}}$$

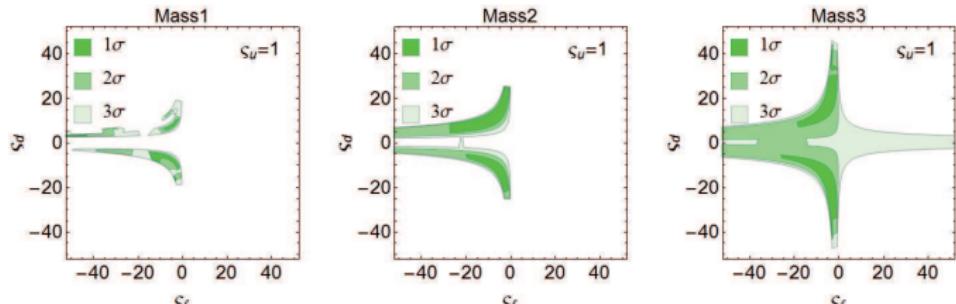
$$B_{s,d}^0 \rightarrow \mu^+ \mu^-$$

Mass1:

$$M_{H^\pm} = 80 \text{ GeV}$$

$$M_A = 80 \text{ GeV}$$

$$M_H = 130 \text{ GeV}$$

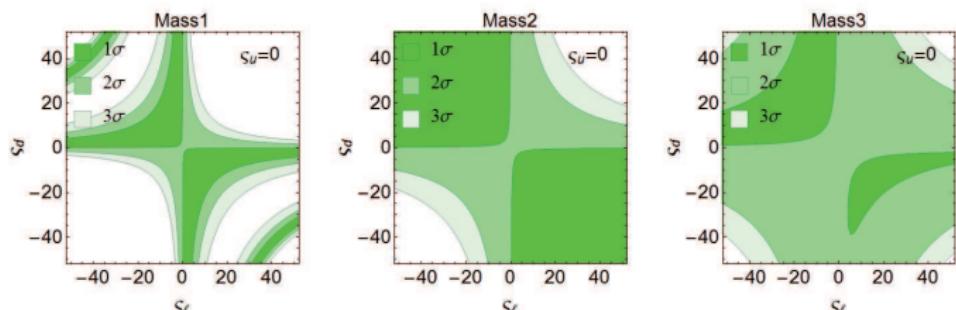


Mass2:

$$M_{H^\pm} = 200 \text{ GeV}$$

$$M_A = 200 \text{ GeV}$$

$$M_H = 200 \text{ GeV}$$

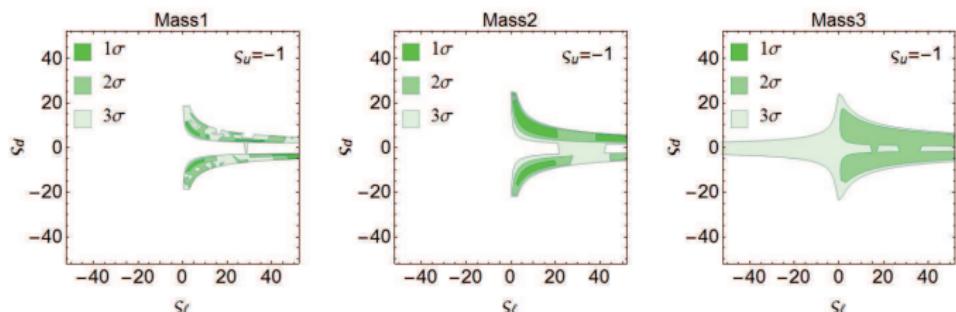


Mass3:

$$M_{H^\pm} = 500 \text{ GeV}$$

$$M_A = 500 \text{ GeV}$$

$$M_H = 500 \text{ GeV}$$



# 2HDM SUMMARY

- The **Aligned THDM** provides a **general phenomenological setting**  
Includes all  $\mathcal{Z}_2$  models
- Tree-level FCNCs **absent** by construction
- Loop-induced quark FCNCs **very constrained** (**MFV like**)
- New sources of CP violation through  $s_f$
- Satisfies flavour constraints with  $s_f \sim \mathcal{O}(1)$
- Sizeable flavour-blind phases allowed by EDMs
- Interesting collider phenomenology

**Neutral and charged scalars within LHC reach**

# Status & Outlook

- The **SM** appears to be the **right theory at the EW scale**
- The **H(125)** behaves as the SM scalar boson
- The **CKM** mechanism works very well
- Neutrinos do have **(tiny)** masses. **Lepton flavour is violated**
- Different **flavour structure** for quarks & leptons
- **New physics needed** to explain many pending questions:  
**Flavour, CP, baryogenesis, dark matter, cosmology...**

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- **How far is the Scale of New-Physics  $\Lambda_{\text{NP}}$ ?**
- **Which symmetry keeps  $M_H$  away from  $\Lambda_{\text{NP}}$ ?**  
Supersymmetry, scale/conformal symmetry...
- **Which kind of New Physics?**

# *Awaiting great discoveries @ LHC*



This, no doubt, Sancho, will be  
a most mighty and perilous  
adventure, in which it will be  
needful for me to put forth all  
my valour and resolution

Let your worship be  
calm, señor. Maybe it's  
all enchantment, like  
the phantoms last night

# Backup Slides



55. Cracow School of Theoretical Physics, Zakopane, Poland, 20-28 June 2015  
Particles and resonances of the Standard Model and beyond

# Minimal Flavour Violation in 2HDMs

**SU(N<sub>G</sub>)<sup>5</sup> Flavour Symmetry in the Gauge Sector (Q<sub>L</sub>, u<sub>R</sub>, d<sub>R</sub>, L<sub>L</sub>, l<sub>R</sub>)**

Chivukula-Georgi '87

## Spurion Formalism:

D'Ambrosio et al, Buras et al

- $\Gamma_1 \sim (N_G, 1, \bar{N}_G, 1, 1)$
- $\Delta_1 \sim (N_G, \bar{N}_G, 1, 1, 1)$
- $\Pi_1 \sim (1, 1, 1, N_G, \bar{N}_G)$



Aligned Yukawas  
are also invariant

## Allowed Operators:

$$\bar{Q}'_L (\Gamma_1 \Gamma_1^\dagger)^n (\Delta_1 \Delta_1^\dagger)^m \Delta_1 u'_R$$

$$\bar{Q}'_L (\Delta_1 \Delta_1^\dagger)^n (\Gamma_1 \Gamma_1^\dagger)^m \Gamma_1 d'_R$$

# Tree-level Constraints

Jung-Pich-Tuzón, 1006.0470

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



$$|\varsigma_I|/M_{H^\pm} < 0.40 \text{ GeV}^{-1} \quad (95\% \text{ CL})$$

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

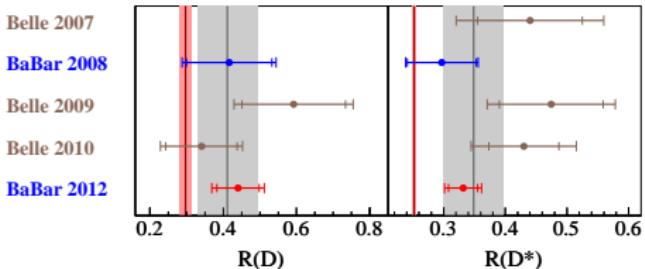
$$\Delta_{ij} = \frac{m_P^2}{M_{H^\pm}^2} \varsigma_I^* \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

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

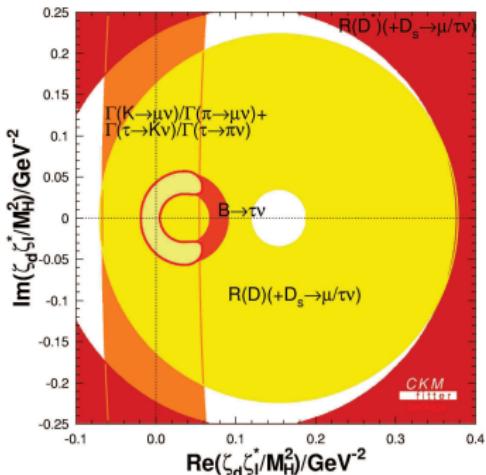
$$\delta_{ij} \equiv -\frac{\varsigma_I^*}{M_{H^\pm}^2} \frac{m_i \varsigma_u - m_j \varsigma_d}{m_i - m_j}$$

# $B \rightarrow D^{(*)}\tau\nu_\tau$ and $B \rightarrow \tau\nu_\tau$ decays

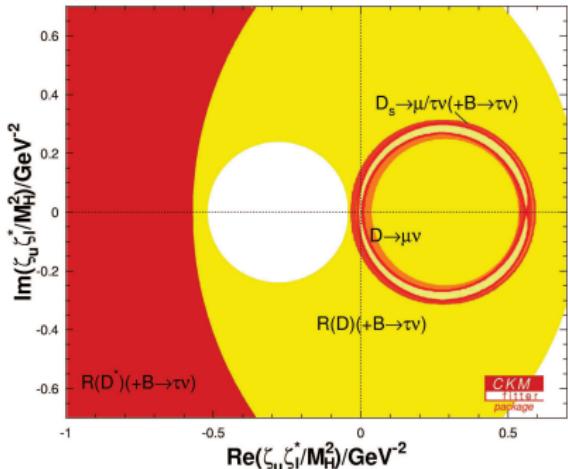
$$R(D^{(*)}) \equiv \frac{\text{Br}(\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau)}{\text{Br}(\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell)}$$



Celis-Jung-Li-Pich, 1210.8443



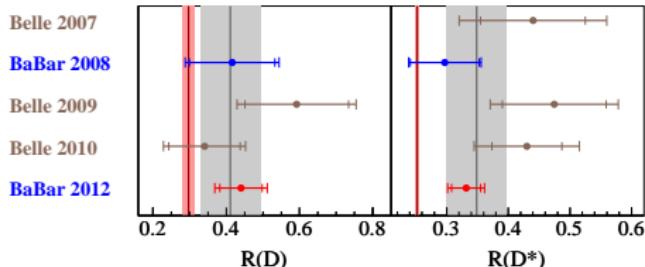
A. Pich



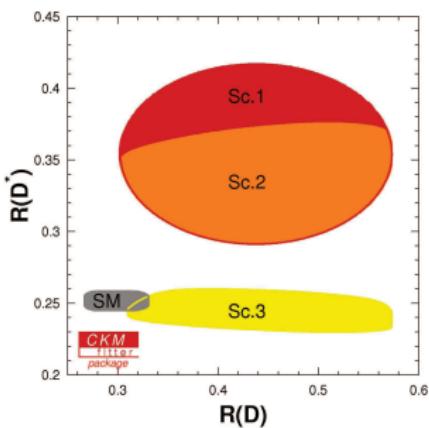
Higgs Physics

# $B \rightarrow D^{(*)}\tau\nu_\tau$ and $B \rightarrow \tau\nu_\tau$ decays

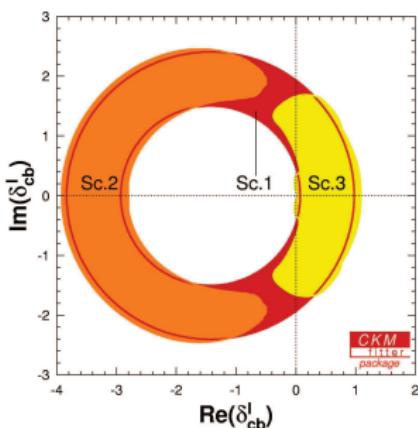
$$R(D^{(*)}) \equiv \frac{\text{Br}(\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau)}{\text{Br}(\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell)}$$



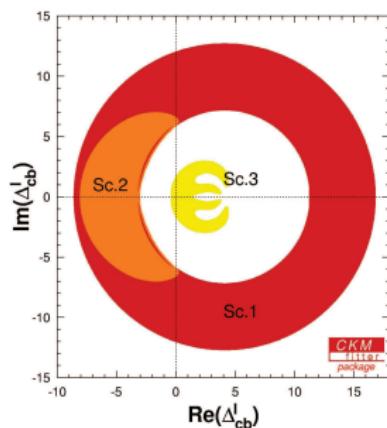
Celis-Jung-Li-Pich, 1210.8443



Sc1:  $R(D)$  and  $R(D^*)$  only



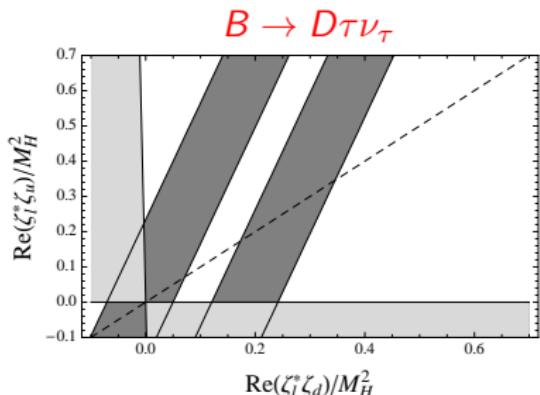
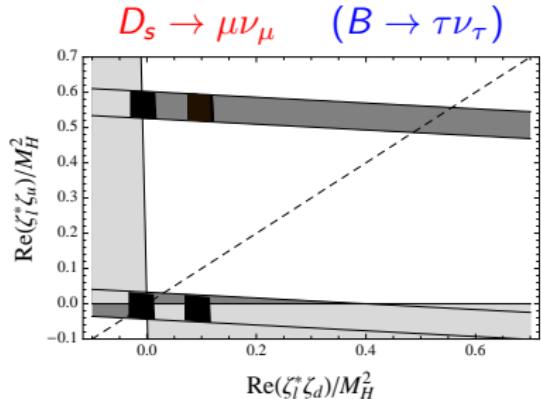
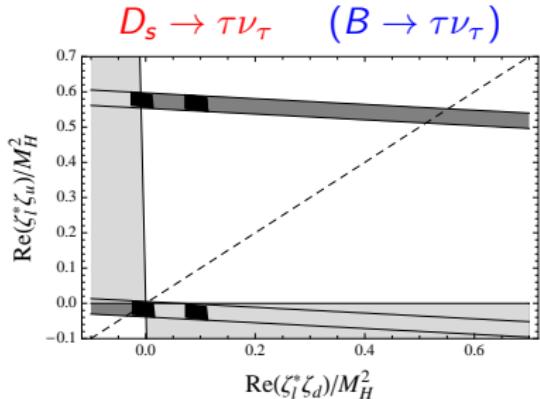
Sc2:  $R(D)$ ,  $R(D^*)$ ,  $\text{Br}(B \rightarrow \tau\nu_\tau)$



Sc3: All data except  $R(D^*)$

# Real Couplings:

Jung-Pich-Tuzón, 1006.0470



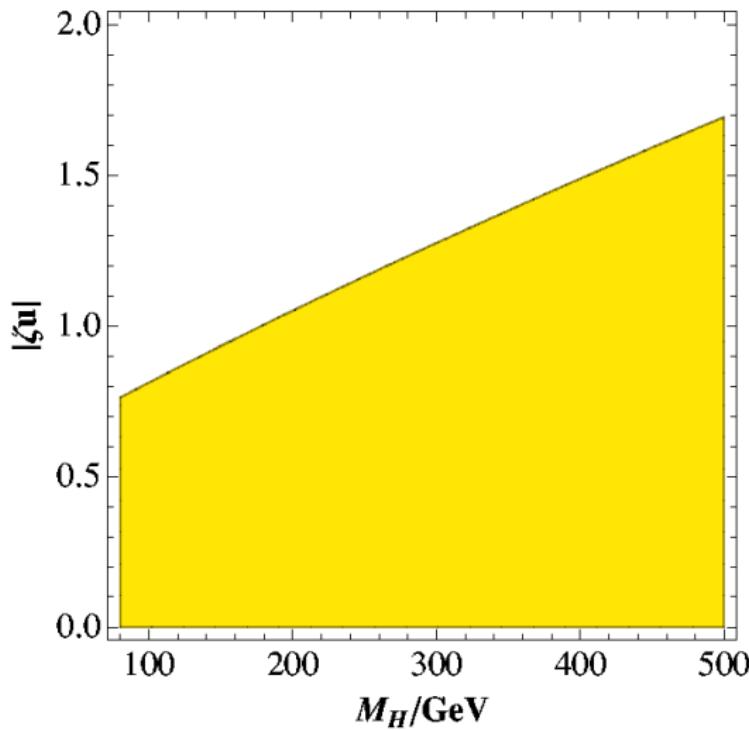
(95% CL,  $\text{GeV}^{-2}$  units)

Type I/X: Dashed Line

Types II/Y: Lighter grey area ,  $\tan \beta \in [0.1, 60]$

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

Jung-Pich-Tuzón, 1006.0470



# Higgs Signal Strengths:

$$\mu_f^{\varphi_i^0} \equiv \frac{\sigma(pp \rightarrow \varphi_i^0) \text{Br}(\varphi_i^0 \rightarrow f)}{\sigma(pp \rightarrow h)_{\text{SM}} \text{Br}(h \rightarrow f)_{\text{SM}}}$$

$$\mu_{f,jj}^{\varphi_i^0} \equiv \frac{\sigma(pp \rightarrow jj \varphi_i^0) \text{Br}(\varphi_i^0 \rightarrow f)}{\sigma(pp \rightarrow jj h)_{\text{SM}} \text{Br}(h \rightarrow f)_{\text{SM}}} \quad ; \quad \mu_{f,V}^{\varphi_i^0} \equiv \frac{\sigma(pp \rightarrow V \varphi_i^0) \text{Br}(\varphi_i^0 \rightarrow f)}{\sigma(pp \rightarrow V h)_{\text{SM}} \text{Br}(h \rightarrow f)_{\text{SM}}}$$

$$\frac{\text{Br}(\varphi_i^0 \rightarrow X)}{\text{Br}(h \rightarrow X)_{\text{SM}}} = \frac{1}{\rho(\varphi_i^0)} \frac{\Gamma(\varphi_i^0 \rightarrow X)}{\Gamma(h \rightarrow X)_{\text{SM}}} \quad ; \quad \rho(\varphi_i^0) = \frac{\Gamma(\varphi_i^0)}{\Gamma_{\text{SM}}(h)}$$

$$C_{gg}^{\varphi_i^0} = \frac{\sigma(gg \rightarrow \varphi_i^0)}{\sigma(gg \rightarrow h)_{\text{SM}}} = \frac{\left| \sum_q \text{Re}(y_q^{\varphi_i^0}) \mathcal{F}(x_q) \right|^2 + \left| \sum_q \text{Im}(y_q^{\varphi_i^0}) \mathcal{K}(x_q) \right|^2}{\left| \sum_q \mathcal{F}(x_q) \right|^2}$$

$$C_{\gamma\gamma}^{\varphi_i^0} = \frac{\Gamma(\varphi_i^0 \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}} = \frac{\left| \sum_f \text{Re}(y_f^{\varphi_i^0}) N_C^f Q_f^2 \mathcal{F}(x_f) + \mathcal{G}(x_W) \mathcal{R}_{i1} + C_{H^\pm}^{\varphi_i^0} \right|^2 + \left| \sum_f \text{Im}(y_f^{\varphi_i^0}) N_C^f Q_f^2 \mathcal{K}(x_f) \right|^2}{\left| \sum_f N_C^f Q_f^2 \mathcal{F}(x_f) + \mathcal{G}(x_W) \right|^2}$$

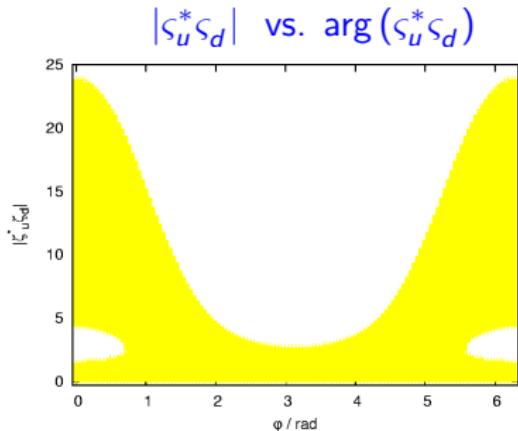
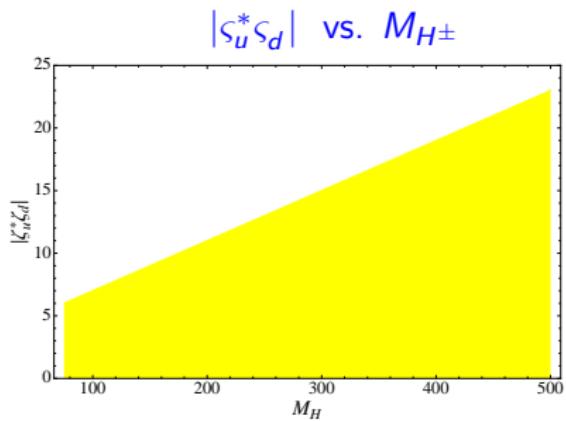
$$x_f = 4m_f^2/M_{\varphi_i^0}^2 \quad ; \quad x_W = 4M_W^2/M_{\varphi_i^0}^2$$

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

Jung-Pich-Tuzón, 1011.5154

**Important Correlations:**

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

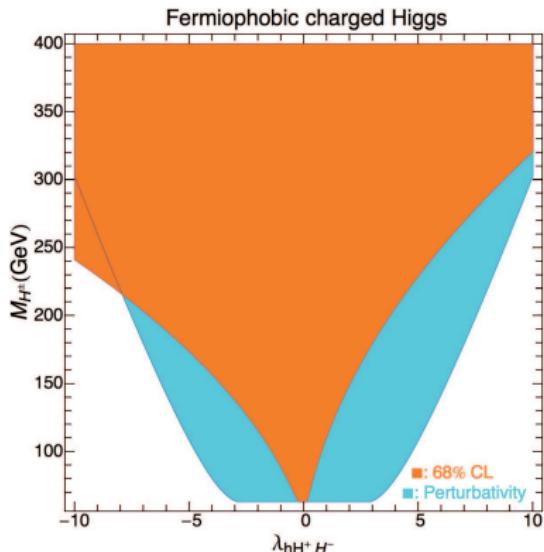
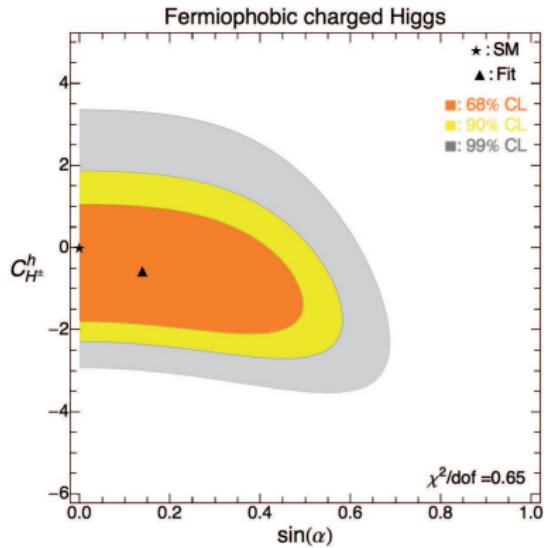


- Stronger constraint for small Scalar Masses
- For  $\varphi \equiv \arg(\zeta_u^* \zeta_d) = \pi$  (0) constructive (destructive) interference
- Important restriction on CP asymmetries

# Fermiophobic Charged Higgs

Celis-Illisie-Pich, 1302.4022, 1310.7941

$$s_f = 0 \quad \rightarrow \quad y_f^{\varphi_i^0} = g_{\varphi_i^0 VV} / g_{\varphi_i^0 VV}^{\text{SM}} = \mathcal{R}_{i1}$$

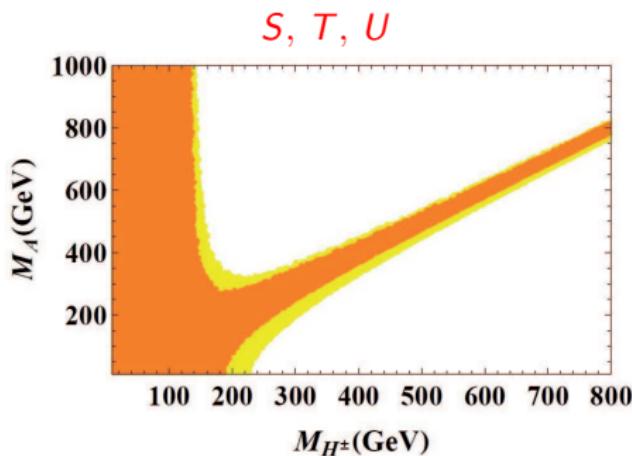


$$\mathcal{L}_{hH^+H^-} = -v \lambda_{hH^+H^-} h H^+ H^- ,$$

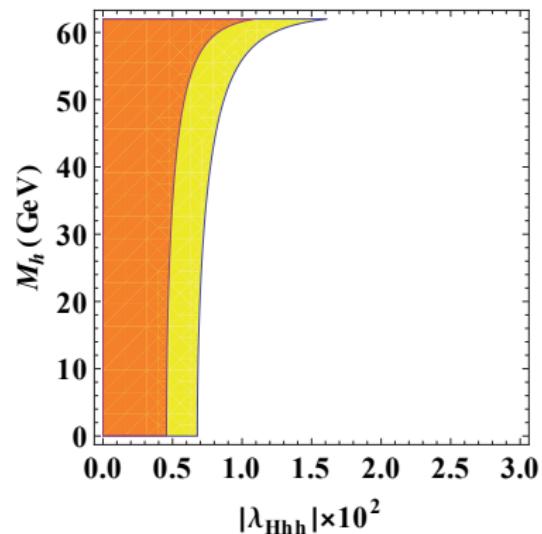
$$C_{H^\pm}^h = \frac{v^2}{2M_{H^\pm}^2} \lambda_{hH^+H^-} \mathcal{A}(4M_{H^\pm}^2/M_h^2)$$

# A Heavy CP-even Higgs at 125 GeV

Celis-Illisie-Pich, 1302.4022



Invisible Width  $(H \rightarrow hh)$



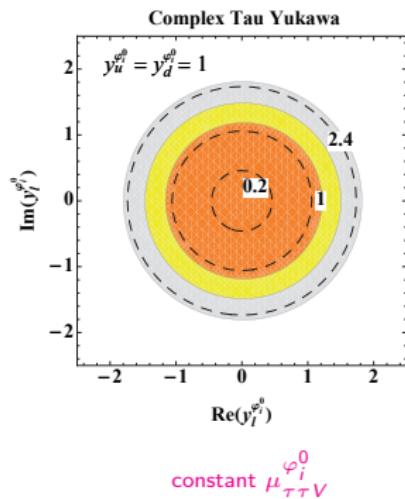
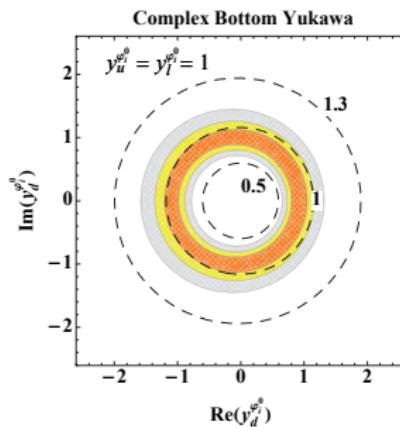
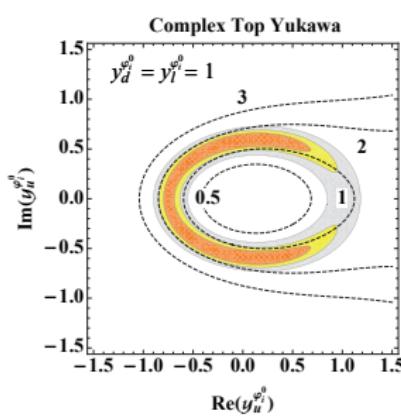
$$\sin \tilde{\alpha} \approx 1$$



$$g_{hvv} \ll 1$$

# Complex Yukawa Couplings

Celis-Illisie-Pich, 1302.4022



$$\mathcal{R}_{i1} = 0.95, \quad \text{parameters not shown set to SM}$$