LHC & Flavour Constraints on Two-Higgs-Doublet Models

Antonio Pich

IFIC, Univ. Valencia - CSIC

Scalars 2013, Warsaw, Poland, 12–16 September 2013

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

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

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

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

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

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

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

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

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

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

Gauge couplings: $g_{\varphi_i^0 VV} \;=\; \mathcal{R}_{i1}\, g_{hVV}^{\mathrm{SM}}$

$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 \;=\; \left(g_{hVV}^{\mathrm{SM}}\right)^2$$

Standard Model

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

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

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

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

No Flavour-Changing Neutral Currents

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:

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

$$\Downarrow$$

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

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

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

- 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 $\varsigma_f = 0$ $(\xi_f = \tan\beta)$

- ς_f are arbitrary complex numbers

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

A2HDM: General phenomenological setting without tree-level FCNCs

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

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

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

$\mathcal{Z}_2$ 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

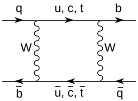
General 2HDM 1-loop Renormalization Group Eqs. known Cvetic et al, Ferreira et al

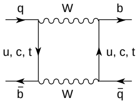
↓ Jung-Pich-Tuzón, Braeuninger-Ibarra-Simonetto

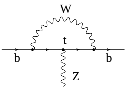
$$\begin{aligned}
\mathcal{L}_{\rm FCNC} \;&=\; \frac{C(\mu)}{4\pi^2 v^3}\,(1+\varsigma_u^*\varsigma_d)\,\sum_i \varphi_i^0(x) \\
&\times\;\Big\{(\mathcal{R}_{i2}+i\,\mathcal{R}_{i3})\,(\varsigma_d-\varsigma_u)\,\left[\bar d_L\, V_{\rm CKM}^\dagger M_u M_u^\dagger\, V_{\rm CKM} M_d\, d_R\right] \\
&\quad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

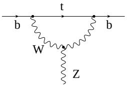
- $C(\mu) \;=\; C(\mu_0) - \log\left(\mu/\mu_0\right)$
- Vanish in all $\mathcal{Z}_2$ models as it should
- Suppressed by $m_q m_{q'}^2/(4\pi^2 v^3)$ and $V_{\rm CKM}^{qq'}$ ➡ $\bar s_L b_R$, $\bar c_L t_R$

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



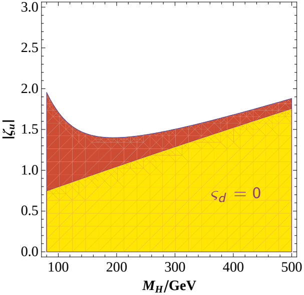






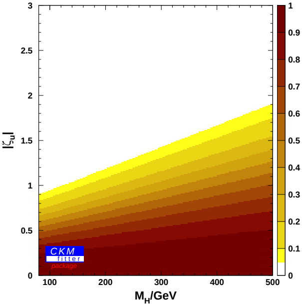
Virtual $\mathrm{H}^{\pm}\,/\,\mathrm{W}^{\pm}$. Top-dominated contributions

ΔM_{B_s} $\quad (|\varsigma_d| < 50)$



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

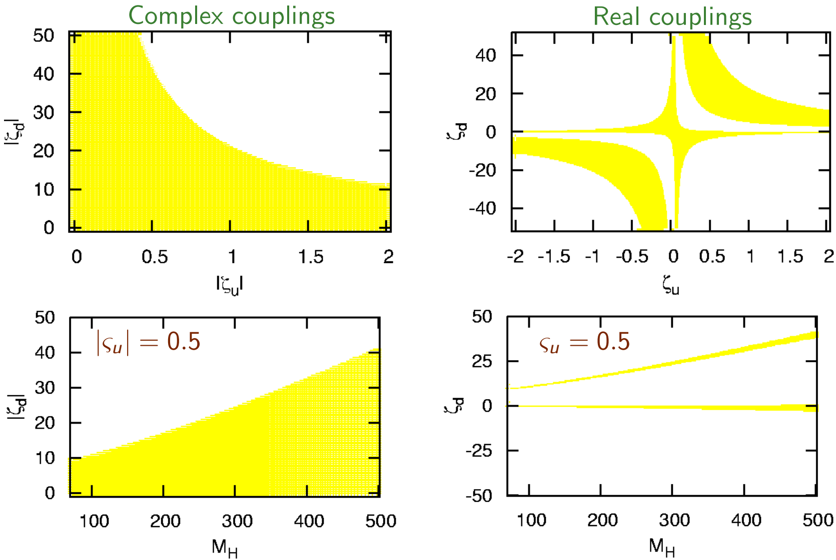
$Z \to b\bar{b}$ $\quad (|\varsigma_d| < 50)$



Jung-Pich-Tuzón

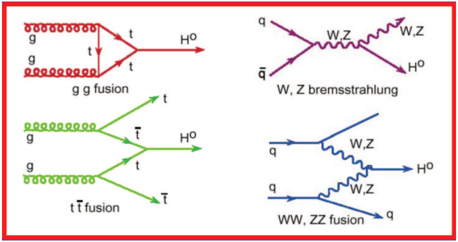
Constraints from $b \to s\gamma$ (95% CL)

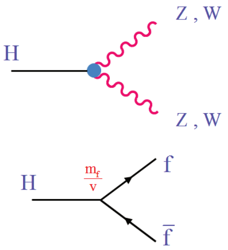
Jung-Pich-Tuzón



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

Scaling factors for Higgs Production & Decay





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

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

- **CP Symmetry:** $g_{h_i VV} = \cos\tilde\alpha\; g_{hVV}^{\rm SM}\,, \qquad g_{HVV} = -\sin\tilde\alpha\; g_{hVV}^{\rm SM}$

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

Higgs Signal Strengths:

$$\mu_f^{\varphi_i^0} \equiv \frac{\sigma(pp \to \varphi_i^0)\,\mathrm{Br}(\varphi_i^0 \to f)}{\sigma(pp \to h)_{\mathrm{SM}}\,\mathrm{Br}(h \to f)_{\mathrm{SM}}}$$

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

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

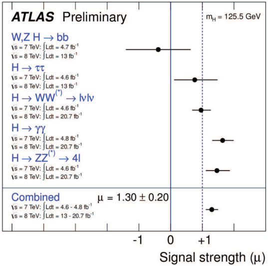
$$C_{gg}^{\varphi_i^0} = \frac{\sigma(gg \to \varphi_i^0)}{\sigma(gg \to h)_{\mathrm{SM}}} = \frac{\left|\sum_q \mathrm{Re}(y_q^{\varphi_i^0})\,\mathcal{F}(x_q)\right|^2 + \left|\sum_q \mathrm{Im}(y_q^{\varphi_i^0})\,\mathcal{K}(x_q)\right|^2}{\left|\sum_q \mathcal{F}(x_q)\right|^2}$$

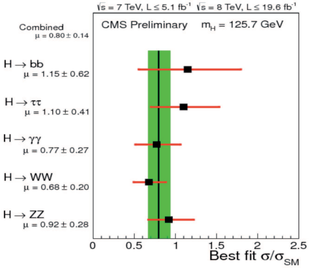
$$C_{\gamma\gamma}^{\varphi_i^0} = \frac{\Gamma(\varphi_i^0 \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\mathrm{SM}}} = \frac{\left|\sum_f \mathrm{Re}(y_f^{\varphi_i^0})\,N_C^f\,Q_f^2\,\mathcal{F}(x_f) + \mathcal{G}(x_W)\mathcal{R}_{i1} + \mathcal{C}_{H^\pm}^{\varphi_i^0}\right|^2 + \left|\sum_f \mathrm{Im}(y_f^{\varphi_i^0})\,N_C^f\,Q_f^2\,\mathcal{K}(x_f)\r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

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

Signal Strengths

$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$



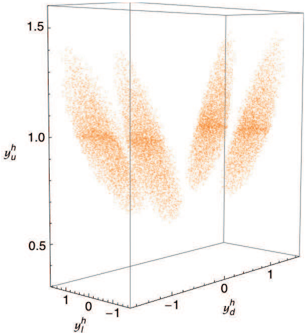


Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	$0.2\,^{+0.7}_{-0.6}$	1.15 ± 0.62
$H \to \tau\tau$	$0.7\,^{+0.7}_{-0.6}$	1.10 ± 0.41
$H \to \gamma\gamma$	$1.55\,^{+0.33}_{-0.28}$	0.77 ± 0.27
$H \to WW^*$	$0.99\,^{+0.31}_{-0.28}$	0.68 ± 0.20
$H \to ZZ^*$	$1.43\,^{+0.40}_{-0.35}$	0.92 ± 0.28
Combined	$\mathbf{1.23 \pm 0.18}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = \mathbf{0.96 \pm 0.11}$$

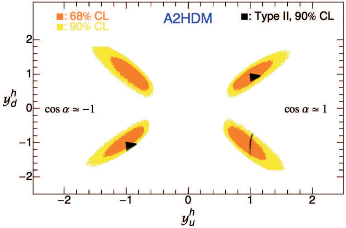
A Light CP-even Higgs at 126 GeV

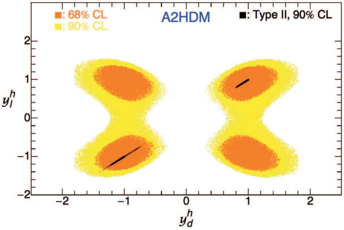
Celis-Ilisie-Pich

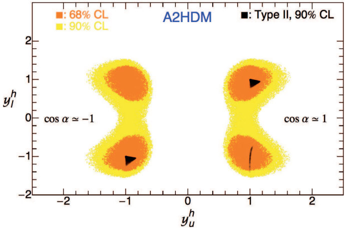


CP conserved

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







A Light CP-even Higgs at 126 GeV

Celis-Ilisie-Pich

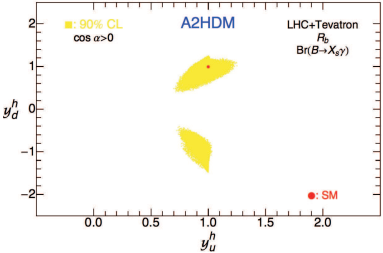
CP conserved

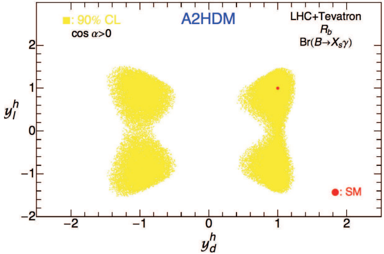
LHC + Tevatron + R_b + $b \to s\gamma$

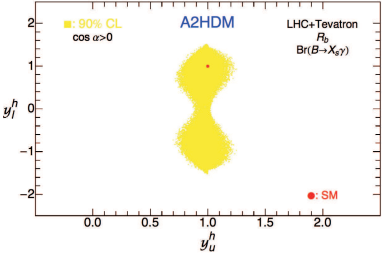
$$M_{H^\pm} \in [80,\, 500]\ \mathrm{GeV}$$

$$|\varsigma_{d,l}| < 50$$

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



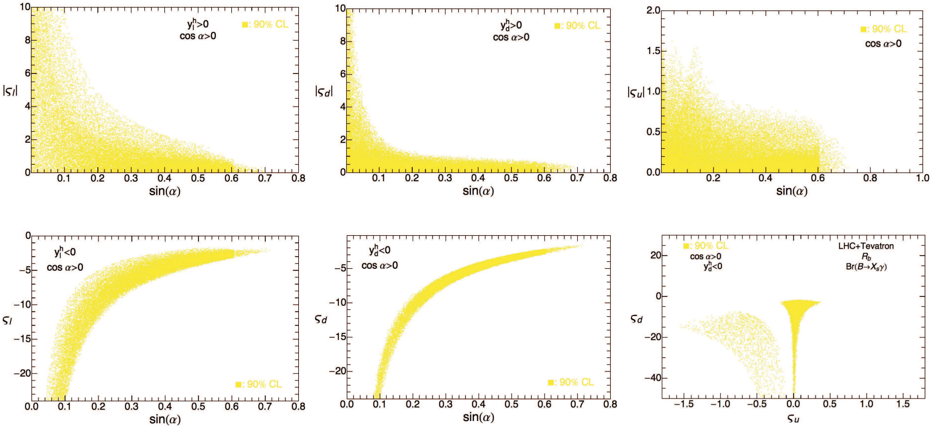




A Light CP-even Higgs at 126 GeV

Celis-Ilisie-Pich

CP conserved

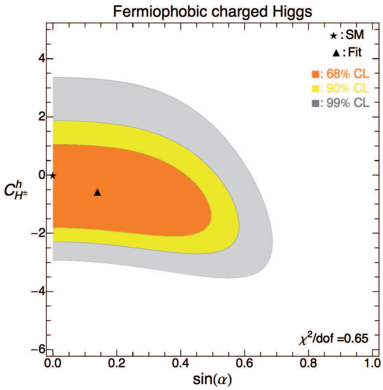


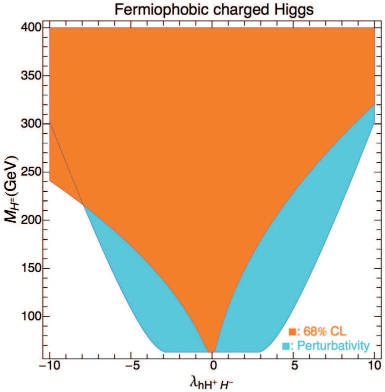
Strong constraints on the A2HDM parameters

Fermiophobic Charged Higgs

Celis-Ilisie-Pich

$$\varsigma_f = 0 \quad \longrightarrow \quad y_f^{\varphi_i^0} = g_{\varphi_i^0 VV} / g^{\mathrm{SM}}_{\varphi_i^0 VV} = \mathcal{R}_{i1}$$



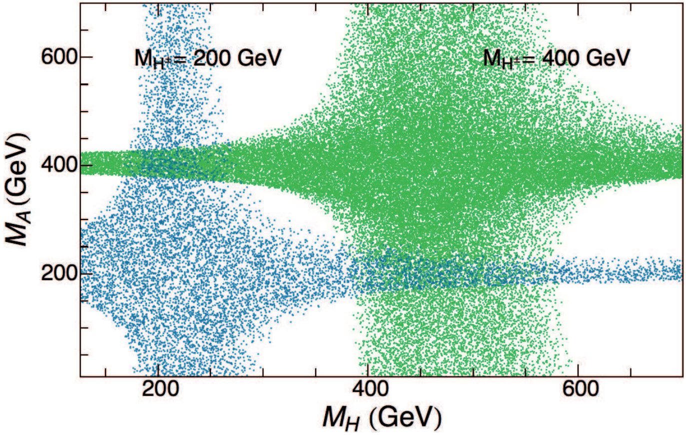


$$\mathcal{L}_{hH^+H^-} = -v\,\lambda_{hH^+H^-}\; h\,H^+H^- \,, \qquad C^h_{H^\pm} = \frac{v^2}{2M^2_{H^\pm}}\,\lambda_{hH^+H^-}\;\mathcal{A}(4M^2_{H^\pm}/M_h^2)$$

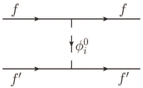
Oblique Constraints (S, T, U)

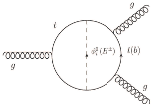
$\cos\tilde{\alpha} \in [0.8,\ 1]$

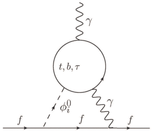
Celis-Ilisie-Pich



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 φ_i^0 contributions:** **Jung-Pich**

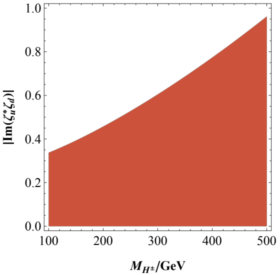
$$\sum_i \mathrm{Re}(y_f^{\varphi_i^0})\, \mathrm{Im}(y_{f'}^{\varphi_i^0}) \;\propto\; \mathrm{Im}(\varsigma_f^* \varsigma_{f'})$$

Cancelation exact in the equal-mass and decoupling limits

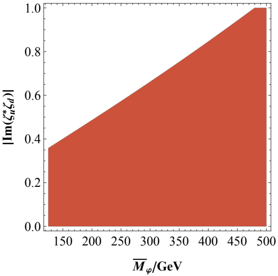
Neutron EDM

Jung-Pich, 1308.6283

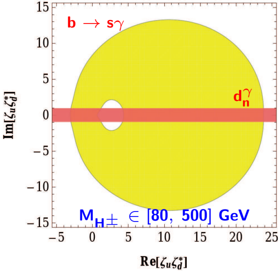
Charged contribution



Neutral contribution



Comparison with $b \to s\gamma$

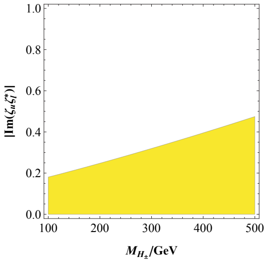


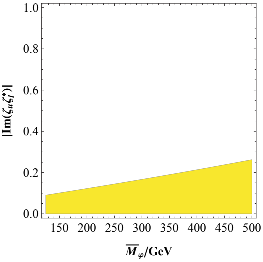
$\mathrm{Im}(\varsigma_u \varsigma_d^*)$ strongly constrained, but not tiny

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

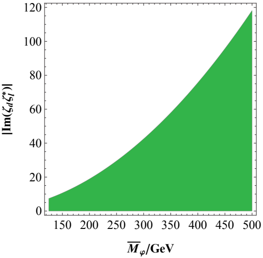
Electron EDM

Jung-Pich, 1308.6283





Mercury EDM



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
- **Satisfies flavour constraints with** $\varsigma_f \sim \mathcal{O}(1)$
- **Sizeable flavour-blind phases allowed by EDMs**
- **Interesting collider phenomenology**

Backup Slides

Minimal Flavour Violation in 2HDMs

$SU(N_G)^5$ Flavour Symmetry in the Gauge Sector $(Q_L,\ u_R,\ d_R,\ L_L,\ l_R)$

Chivukula-Georgi '87

Spurion Formalism:

D'Ambrosio et al, Buras et al

- $\Gamma_1 \sim \left(N_G, 1, \overline{N}_G, 1, 1\right)$
- $\Delta_1 \sim \left(N_G, \overline{N}_G, 1, 1, 1\right)$ ⟶ **Aligned Yukawas are also invariant**
- $\Pi_1 \sim \left(1, 1, 1, N_G, \overline{N}_G\right)$

Allowed Operators:

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

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

Phenomenological Constraints

Jung-Pich-Tuzón

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

$$\longrightarrow \quad \boxed{|\varsigma_l|/M_{H^\pm} < 0.40\ \mathrm{GeV}^{-1} \quad (95\%\ \mathrm{CL})}$$

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

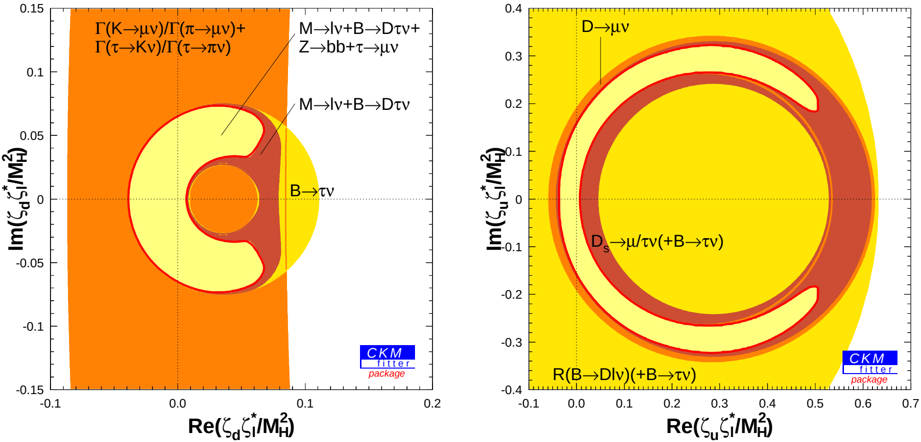
$$\Delta_{ij} = \frac{m_P^2}{M_{H^\pm}^2}\, \varsigma_l^* \, \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

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

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

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

Jung-Pich-Tuzón

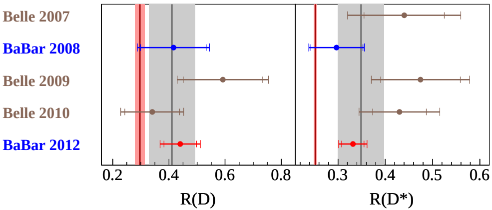


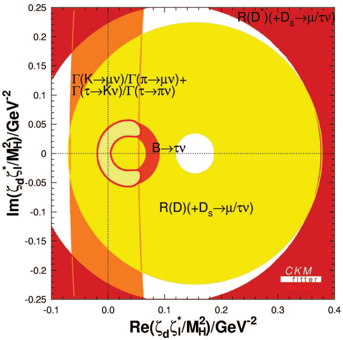
(GeV^{-2} units)

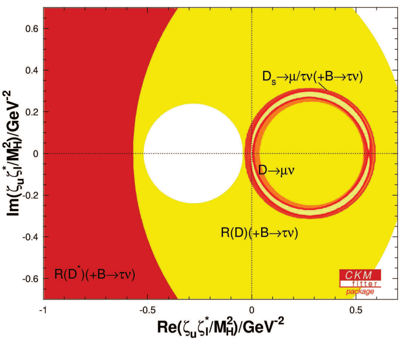
$B \to D^{(*)}\tau\nu_\tau$ and $B \to \tau\nu_\tau$ decays

Celis-Jung-Li-Pich

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

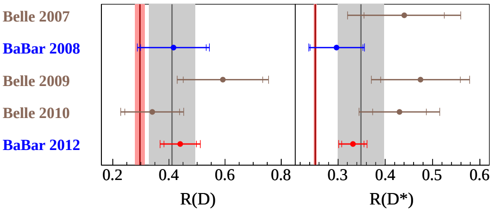




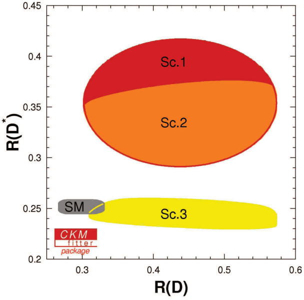


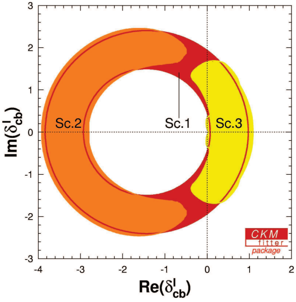
$B \to D^{(*)}\tau\nu_\tau$ and $B \to \tau\nu_\tau$ decays

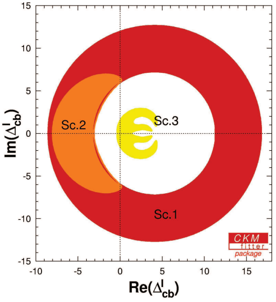
$$R(D^{(*)}) \equiv \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$



Sc1: $R(D)$ and $R(D^*)$ only ; Sc1: $R(D)$, $R(D^*)$, $\mathrm{Br}(B \to \tau\nu_\tau)$; Sc3: All data except $R(D^*)$



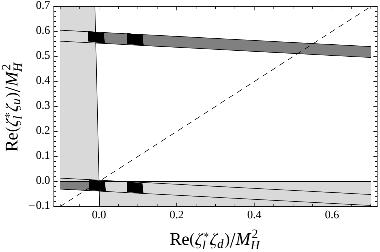




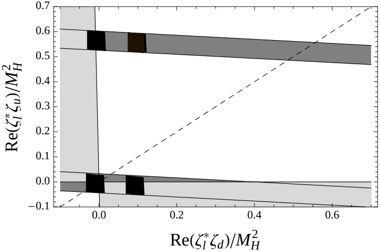
Real Couplings:

Jung-Pich-Tuzón

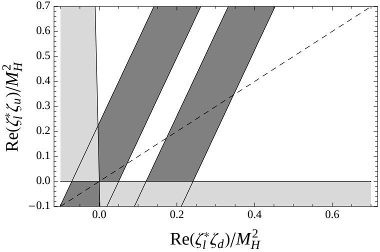
$D_s \to \tau\nu_\tau \quad (B \to \tau\nu_\tau)$



$D_s \to \mu\nu_\mu \quad (B \to \tau\nu_\tau)$



$B \to D\tau\nu_\tau$



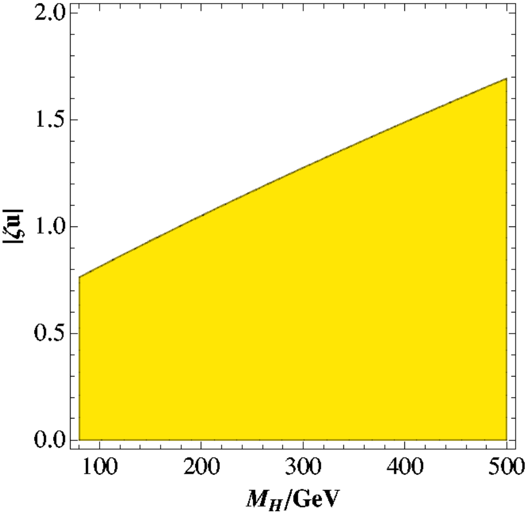
(95% CL, GeV^{-2} units)

Type I/X: Dashed Line

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

Constraints from ϵ_K (95% CL)

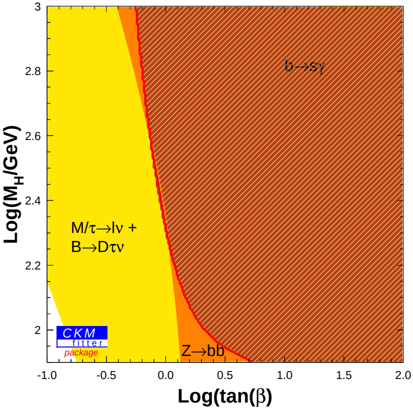
Jung-Pich-Tuzón



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

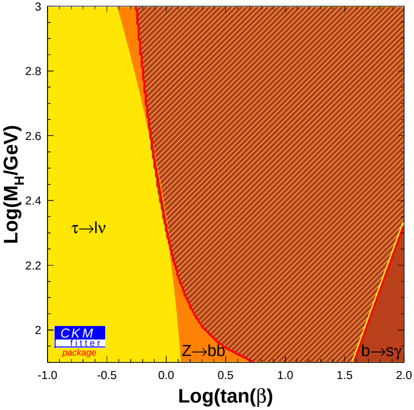
Jung-Pich-Tuzón

Type I



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

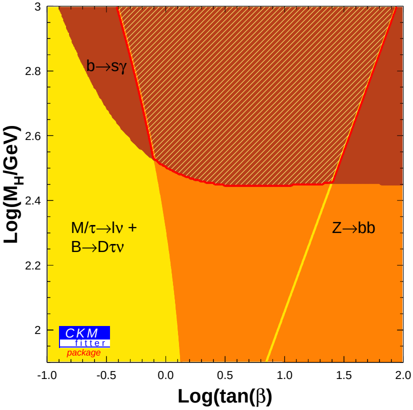
Type X



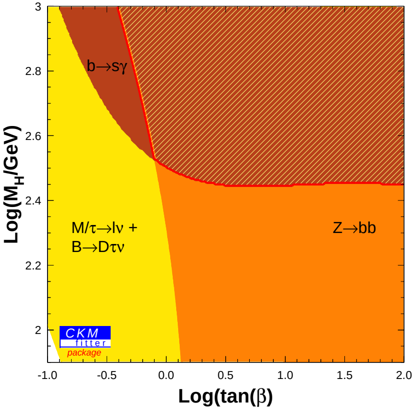
$$\varsigma_u = \varsigma_d = -\varsigma_l^{-1} = \cot\beta$$

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

Type II



Type Y



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

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

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

In agreement with previous analyses

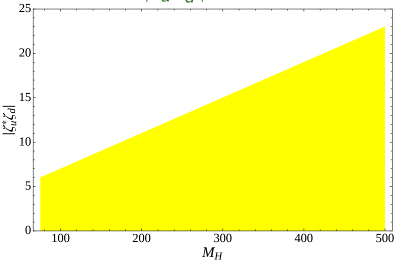
Aoki et al, Wahab et al, Deschamps et al, Flacher at al, Bona et al, Mahmoudi-Stal, Misiak et al ...

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

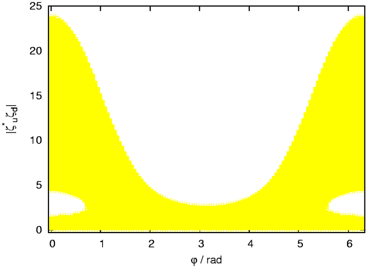
Jung-Pich-Tuzón

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

$|\varsigma_u^* \varsigma_d|$ vs. $M_{H^\pm}$

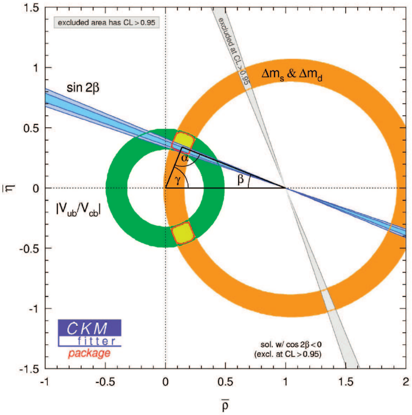


$|\varsigma_u^* \varsigma_d|$ vs. $\arg(\varsigma_u^* \varsigma_d)$



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

CKM Fit within the A2HDM

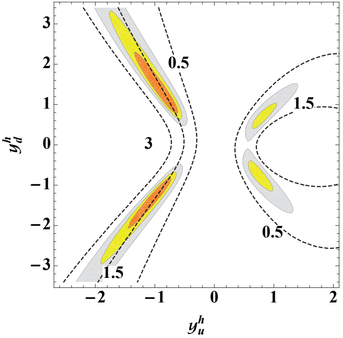


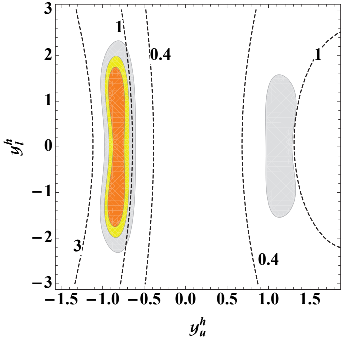
- **Only the constraints from $|V_{ub}/V_{cb}|$ and $\Delta m_s/\Delta m_d$ survive**
- γ from tree-level decays excludes the 2$^{\mathrm{nd}}$ solution
- $\Delta m_s/\Delta m_d \; = \; (\Delta m_s/\Delta m_d)|_{\mathrm{SM}} \, + \, \mathcal{O}[(m_s - m_d)\,\varsigma_d/M_W]$

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	
$f_{B_d}\sqrt{\hat{B}_{B_s^0}}/(f_{B_s}\sqrt{\hat{B}_{B_s^0}})$	$1.258 \pm 0.025 \pm 0.043$	
$\hat{B}_K$	$0.732 \pm 0.006 \pm 0.043$	
$\|V_{ud}\|$	0.97425 ± 0.00022	
λ	0.2255 ± 0.0010	$\left(1 - \|V_{ud}\|^2\right)^{1/2}$
$\|V_{ub}\|$	$(3.8 \pm 0.1 \pm 0.4) \cdot 10^{-3}$	$b \to ul\nu$ (excl. + incl.)
A	$0.80 \pm 0.01 \pm 0.01$	$b \to cl\nu$ (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
$\rho^2\|_{B\to Dl\nu}$	$1.18 \pm 0.04 \pm 0.04$	
$\Delta\|_{B\to Dl\nu}$	0.46 ± 0.02	
$f_+^{K\pi}(0)$	0.965 ± 0.010	

A Light CP-even Higgs at 126 GeV

Celis-Ilisie-Pich, 1302.4022

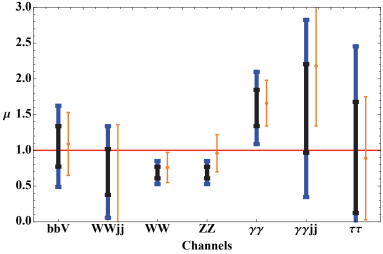




$$\cos\tilde{\alpha} = 0.99^{+0.01}_{-0.04} \quad , \quad y_u^h = -0.8^{+0.1}_{-0.3}$$

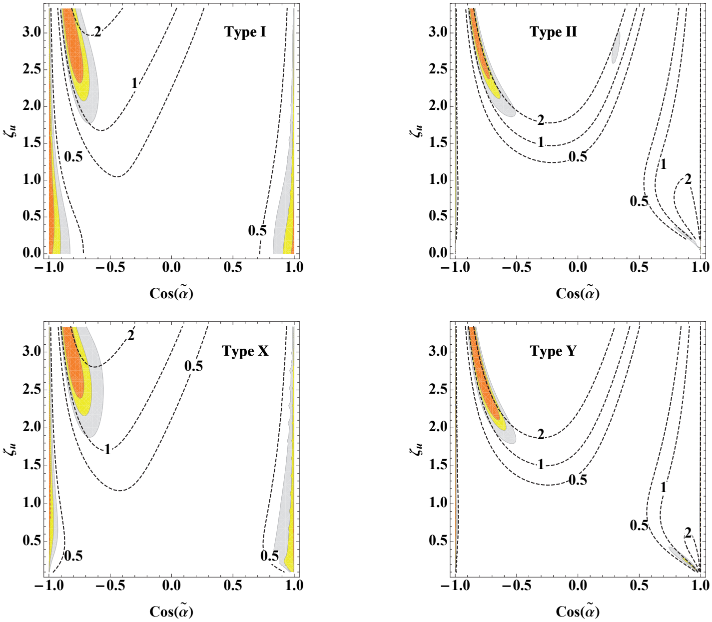
$$\left|y_d^h\right| = 1.1 \pm 0.3 \quad , \quad \left|y_l^h\right| = 0.9 \pm 0.5$$

$$\Rightarrow \quad \sin\tilde{\alpha} < 0.37 \quad , \quad |y_u^H| > 4.6$$



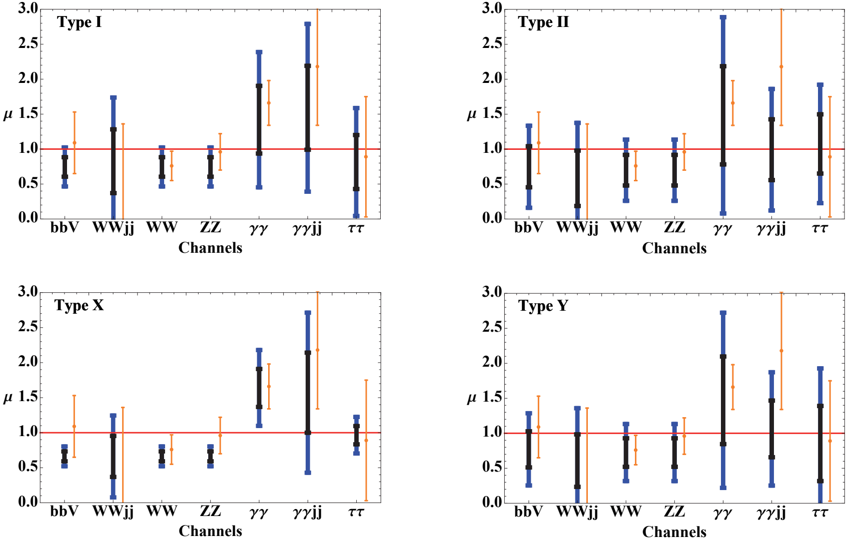
Global Fit within $\mathcal{Z}_2$ Models

Celis-Ilisie-Pich, 1302.4022



Global Fit within $\mathcal{Z}_2$ Models

Celis-Ilisie-Pich, 1302.4022



Good agreement, but in a region excluded by flavour data

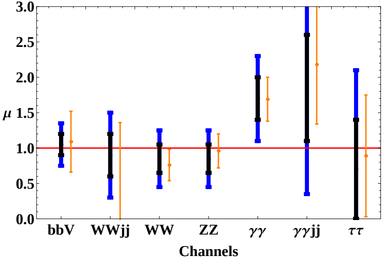
A Charged Higgs and the 2γ Excess

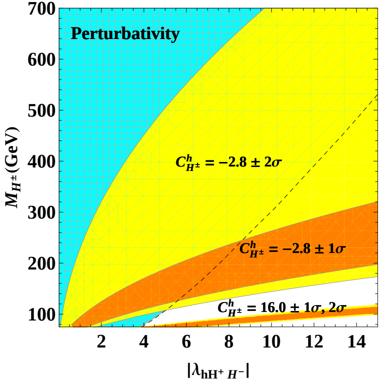
Celis-Ilisie-Pich, 1302.4022

$$\cos\tilde{\alpha} = 0.98^{+0.02}_{-0.06} \quad , \quad C^h_{H^\pm} = (-2.8 \pm 1.3) \cup (16.0 \pm 1.3)$$

$$y^h_u = 1.0 \pm 0.2 \quad , \quad \left|y^h_d\right| = 1.1 \pm 0.3 \quad , \quad \left|y^h_l\right| = 0.8 \pm 0.5$$

Excellent fit



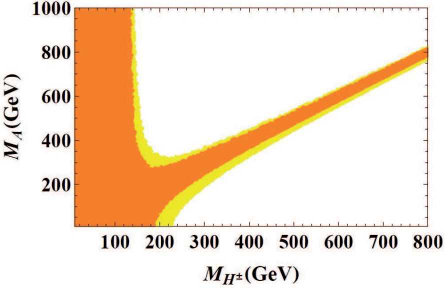


Perturbativity ➡ $M_{H^\pm} < 250$ GeV **(68% CL)**

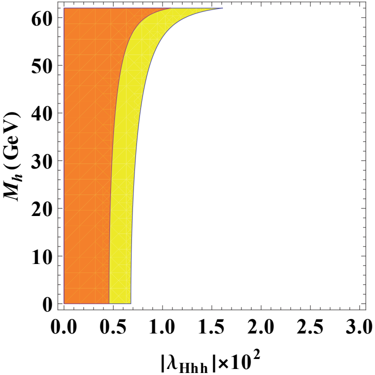
A Heavy CP-even Higgs at 126 GeV

Celis-Ilisie-Pich, 1302.4022

$S,\ T,\ U$



Invisible Width $(H \to hh)$



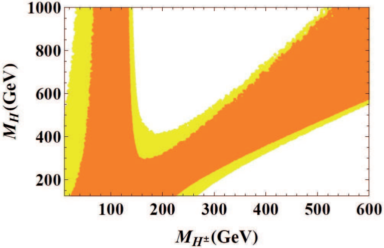
$\sin\tilde{\alpha} \approx 1 \quad \Rightarrow \quad g_{hVV} \ll 1$

Degenerate CP-even and CP-odd Higgses

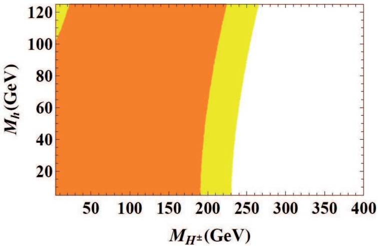
Celis-Ilisie-Pich, 1302.4022

S, T, U Constraints

$M_h = M_A = 126$ GeV



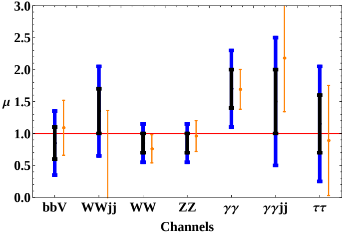
$M_H = M_A = 126$ GeV



$M_h = M_A = 126$ GeV

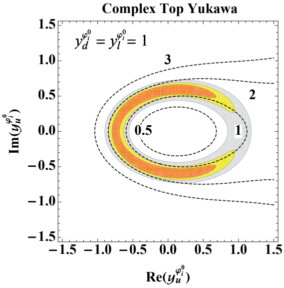
$$\cos\tilde{\alpha} = 0.98 \pm 0.2 \quad , \quad \varsigma_u = -1.1\,^{+0.5}_{-1.4}$$

$$|\varsigma_d| = 1.2 \pm 1.2 \quad , \quad \varsigma_l = -0.2\,^{+0.6}_{-0.4}$$

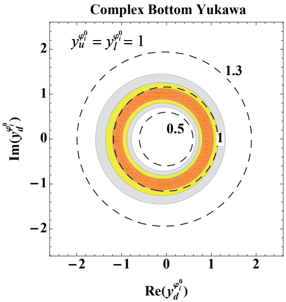


Complex Yukawa Couplings

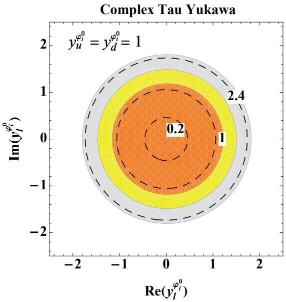
Celis-Ilisie-Pich, 1302.4022



Dashed lines = constant $\mu_{\gamma\gamma}^{\varphi_i^0}$



constant $\mu_{bbV}^{\varphi_i^0}$

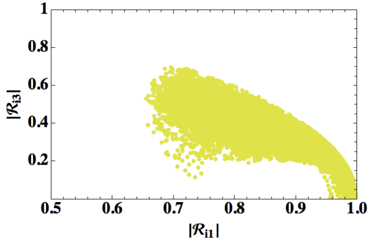


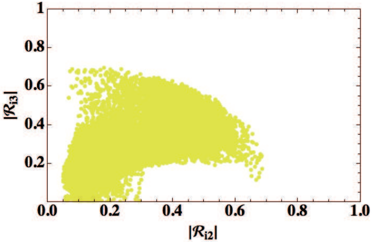
constant $\mu_{\tau\tau V}^{\varphi_i^0}$

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

CP-even & CP-odd Scalar Mixing

Celis-Ilisie-Pich, 1302.4022





90% CL bounds for real ς_f, with $|\varsigma_u| < 2$ and $|\varsigma_{d,l}| < 10$