Electroweak Symmetry Breaking

Two-Higgs-Doublet Models

Antonio Pich

IFIC, Univ. Valencia - CSIC

LAPP, Annecy-le-Vieux, 12-13 November 2014

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

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

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

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

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

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

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

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

$\downarrow$ **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 $\longrightarrow$ **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, 0908.1554

Require alignment in Flavour Space of Yukawa couplings:

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

$$\Downarrow$$

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

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

- 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

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

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

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

$\mathcal{Z}_2$ 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

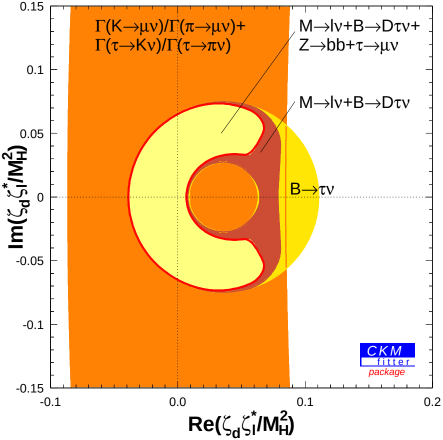
$$
\begin{aligned}
\mathcal{L}_{\mathrm{FCNC}} &= \frac{C(\mu)}{4\pi^2 v^3}\,(1+\varsigma_u^*\varsigma_d)\sum_i \varphi_i^0(x) \\
&\times \Big\{ (\mathcal{R}_{i2}+i\,\mathcal{R}_{i3})\,(\varsigma_d-\varsigma_u)\,\left[\bar{d}_L\, V_{\mathrm{CKM}}^\dagger M_u M_u^\dagger\, V_{\mathrm{CKM}} M_d\, d_R\right]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

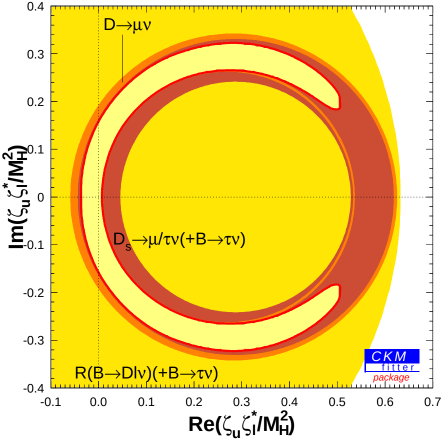
- $C(\mu) = C(\mu_0) - \log(\mu/\mu_0)$
- Vanish in all $\mathcal{Z}_2$ models as it should
- Suppressed by $m_q m_{q'}^2/(4\pi^2 v^3)$ and $V_{\mathrm{CKM}}^{qq'}$ ⟶ $\bar{s}_L b_R\,,\ \bar{c}_L t_R$

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

(95% CL)

Jung-Pich-Tuzón, 1006.0470

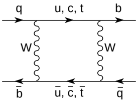


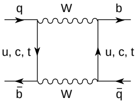


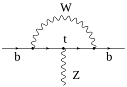
Tree-level $H^\pm$ exchange

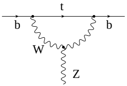
$(M_H \equiv M_{H^\pm}\ ,\ \text{GeV}^{-2}\ \text{units})$

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



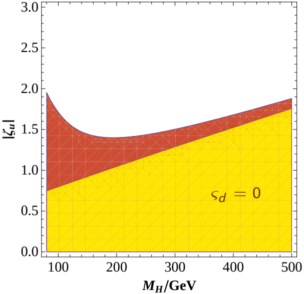




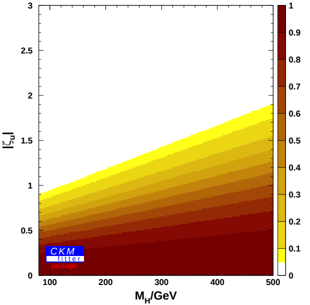


Virtual $H^{\pm}$ / $W^{\pm}$. Top-dominated contributions

ΔM_{B_s} $(|\varsigma_d| < 50)$



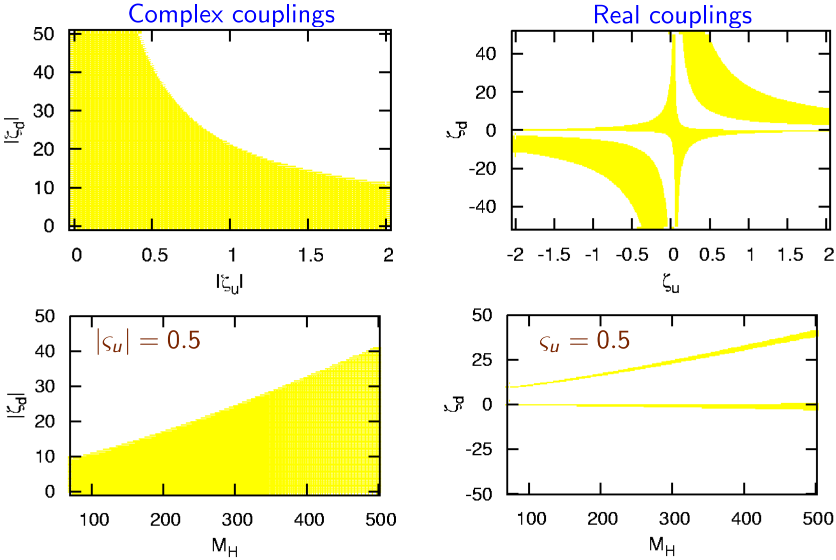
$Z \to b\bar{b}$ $(|\varsigma_d| < 50)$



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

Jung-Pich-Tuzón, 1006.0470

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

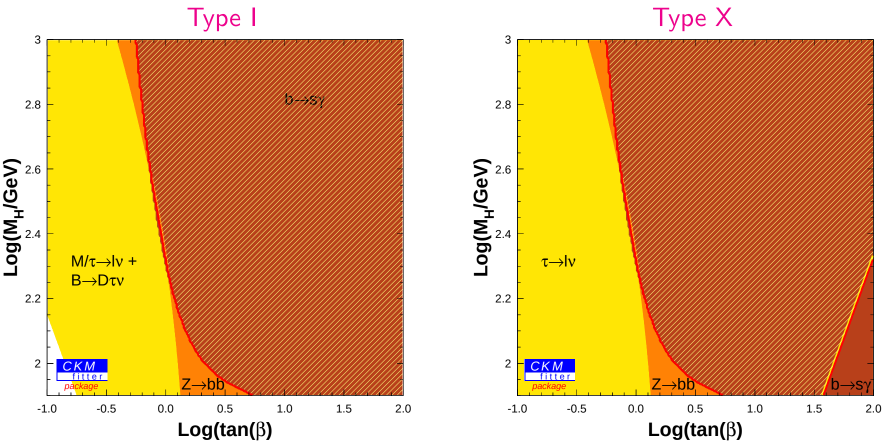


$C_i^{\mathrm{eff}}(\mu_W) = C_{i,SM} + |\varsigma_u|^2 \; C_{i,uu} - (\varsigma_u^* \varsigma_d \;\;) \; C_{i,ud}$

Jung-Pich-Tuzón, 1006.0470, 1011.5154

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

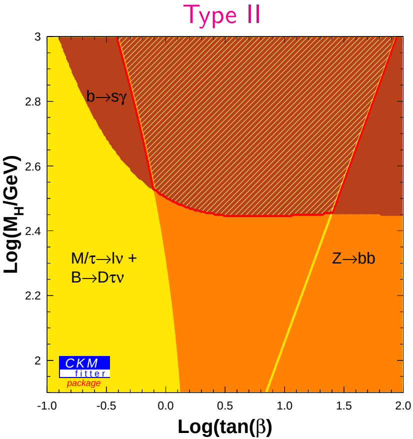
Jung-Pich-Tuzón, 1006.0470

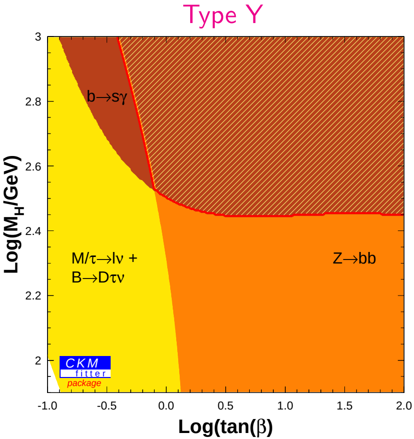


$\varsigma_u = \varsigma_d = \varsigma_l = \cot\beta$ $\qquad$ $\varsigma_u = \varsigma_d = -\varsigma_l^{-1} = \cot\beta$

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

Jung-Pich-Tuzón, 1006.0470





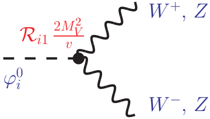
$$\varsigma_u = -\varsigma_d^{-1} = -\varsigma_l^{-1} = \cot\beta \qquad \varsigma_u = -\varsigma_d^{-1} = \varsigma_l = \cot\beta$$

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

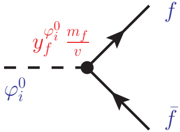
In agreement with previous analyses

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

Scaling factors for Higgs Production & Decay



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



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

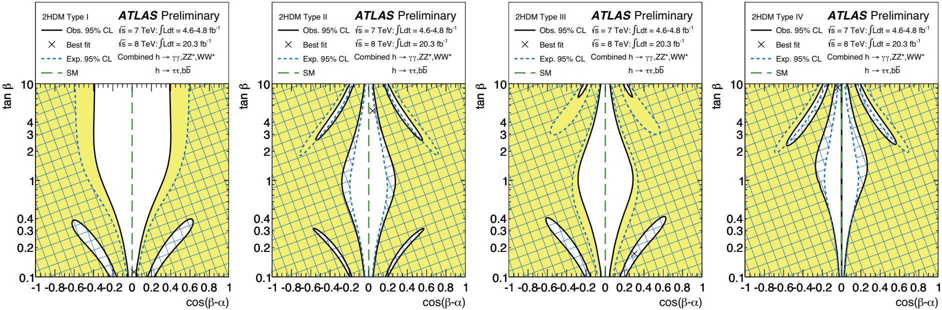
$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\,\mathcal{R}_{i3})\,\varsigma_{d,l}$$

- **CP Symmetry:**

$$g_{h_i VV} = \cos\tilde{\alpha}\; g_{hVV}^{\mathrm{SM}} \qquad , \qquad g_{HVV} = -\sin\tilde{\alpha}\; g_{hVV}^{\mathrm{SM}}$$

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

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



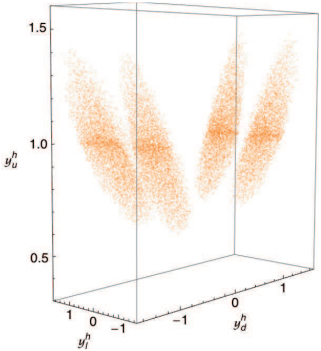
$$g_{VVh}/g_{VVh}^{\mathrm{SM}} = \cos\tilde{\alpha} \equiv \sin(\beta - \alpha)$$

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

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 (III)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y (IV)	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

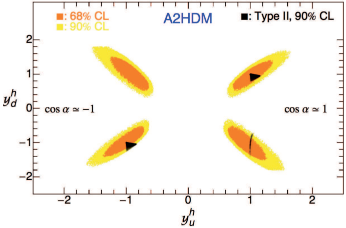
A Light CP-even Higgs at 126 GeV

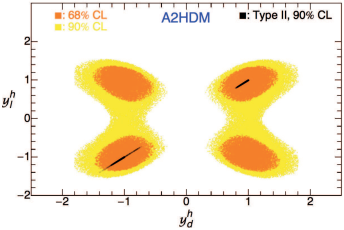
Celis-Ilisie-Pich, 1302.4022, 1310.7941

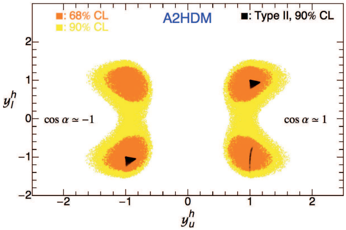


CP conserved

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







A Light CP-even Higgs at 126 GeV

Celis-Ilisie-Pich, 1302.4022, 1310.7941

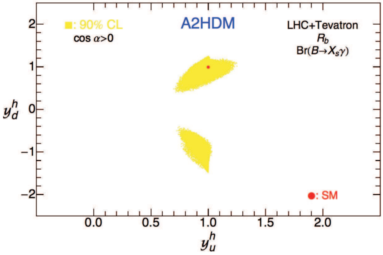
CP conserved

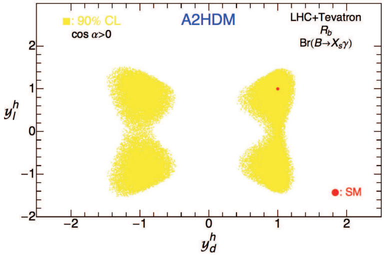
LHC + Tevatron + R_b **+** $b \to s\gamma$

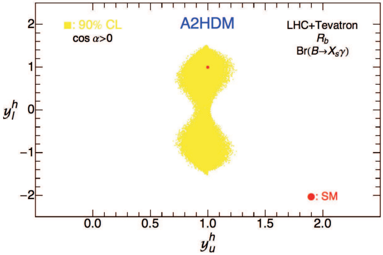
$M_{H^\pm} \in [80,\, 500]$ GeV

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

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



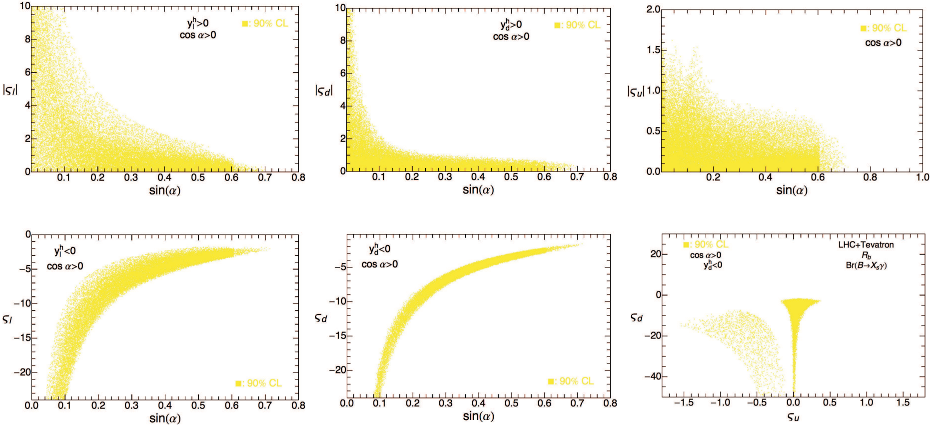




A Light CP-even Higgs at 126 GeV

Celis-Ilisie-Pich, 1302.4022, 1310.7941

CP conserved

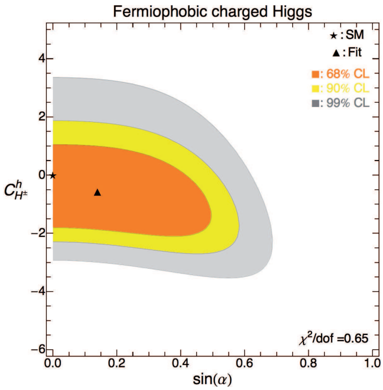


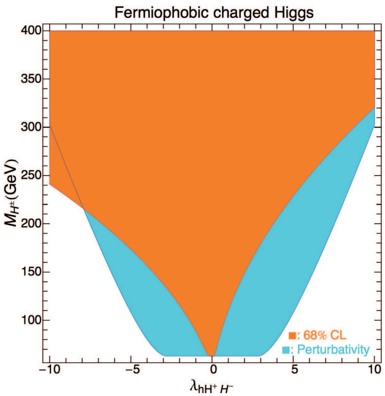
Strong constraints on the A2HDM parameters

Fermiophobic Charged Higgs

Celis-Ilisie-Pich, 1302.4022, 1310.7941

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



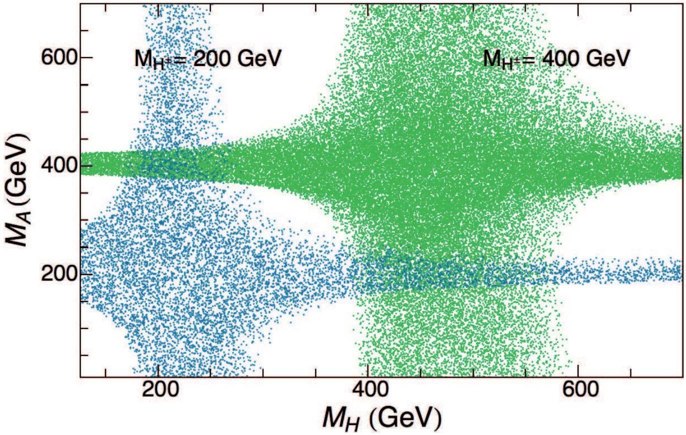


$$\mathcal{L}_{hH^+H^-} = -v\,\lambda_{hH^+H^-}\; h\, H^+ H^- \,, \qquad C^h_{H^\pm} = \frac{v^2}{2M^2_{H^\pm}}\,\lambda_{hH^+H^-}\;\mathcal{A}(4M^2_{H^\pm}/M_h^2)$$

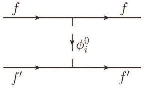
Oblique Constraints (S, T, U)

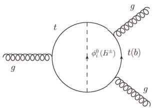
Celis-Ilisie-Pich, 1302.4022, 1310.7941

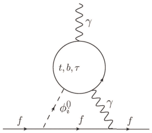
$\cos\tilde{\alpha} \in [0.8,\ 1]$



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

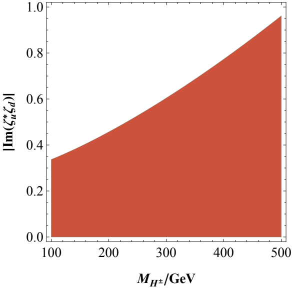
$$\sum_i \,\mathrm{Re}(y_f^{\varphi_i^0})\,\mathrm{Im}(y_{f'}^{\varphi_i^0}) \;\propto\; \mathrm{Im}(\varsigma_f^* \varsigma_{f'})$$

Cancelation exact in the equal-mass and decoupling limits

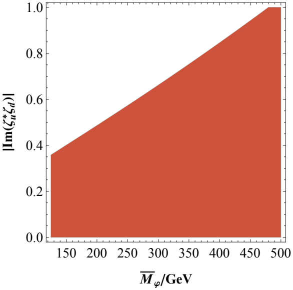
Neutron EDM

Jung-Pich, 1308.6283

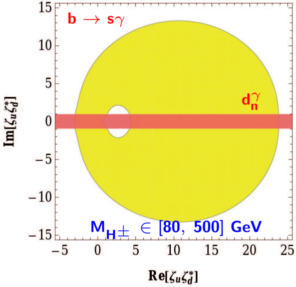
Charged contribution



Neutral contribution



Comparison with $b \to s\,\gamma$

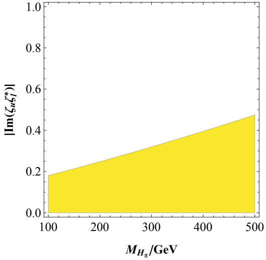


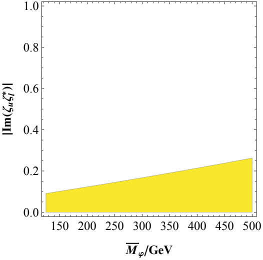
$\mathrm{Im}(\varsigma_u \varsigma_d^*)$ strongly constrained, but not tiny

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

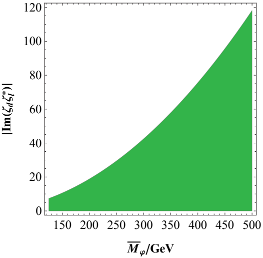
Electron EDM

Jung-Pich, 1308.6283





Mercury EDM



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

Neutral and charged scalars within LHC reach

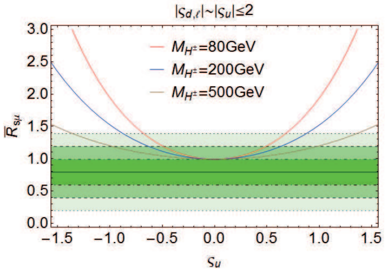
Backup Slides

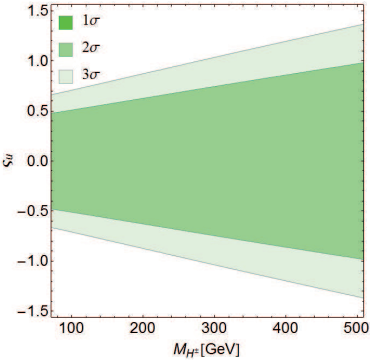
$B^0_{s,d} \to \mu^+\mu^-$

Li-Lu-Pich, 1404.5865

$$\overline{\mathcal{B}}(B^0_s \to \mu^+\mu^-)_{\rm exp.} = (2.9 \pm 0.7) \times 10^{-9}$$ [SM: $(3.65 \pm 0.23) \times 10^{-9}$]

$$\overline{\mathcal{B}}(B^0_d \to \mu^+\mu^-)_{\rm exp.} = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}$$ [SM: $(1.06 \pm 0.09) \times 10^{-10}$]





$\bar{R}_{s\mu} \equiv \overline{\mathcal{B}}(B^0_s \to \mu^+\mu^-)/\overline{\mathcal{B}}(B^0_s \to \mu^+\mu^-)_{\rm SM}$

$B^0_{s,d} \to \mu^+\mu^-$

Mass1:

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

$M_A = 80$ GeV

$M_H = 130$ GeV

Mass2:

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

$M_A = 200$ GeV

$M_H = 200$ GeV

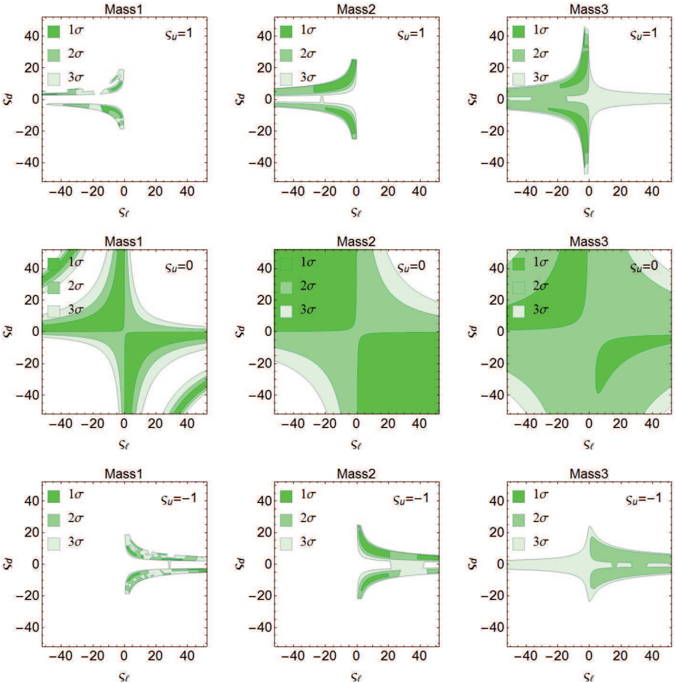
Mass3:

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

$M_A = 500$ GeV

$M_H = 500$ GeV

Li-Lu-Pich, 1404.5865



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

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

→ **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

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

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

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

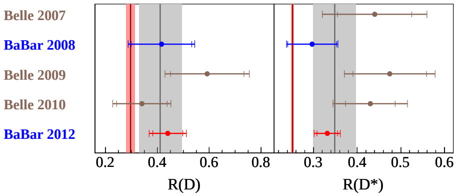
$$\Delta_{ij} = \frac{m_P^2}{M_{H^\pm}^2}\, \varsigma_l^*\, \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

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

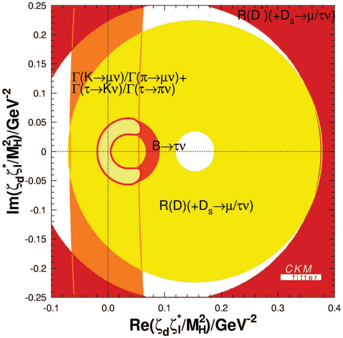
$$\delta_{ij} \equiv -\frac{\varsigma_l^*}{M_{H^\pm}^2}\, \frac{m_i \varsigma_u - m_j \varsigma_d}{m_i - m_j}$$

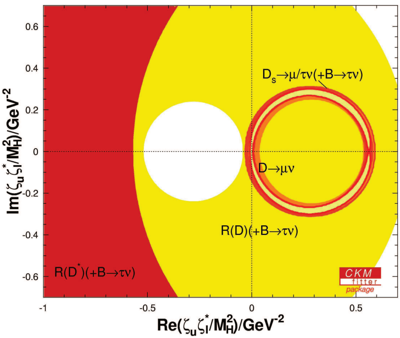
$B \to D^{(*)}\tau\nu_\tau$ and $B \to \tau\nu_\tau$ decays

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



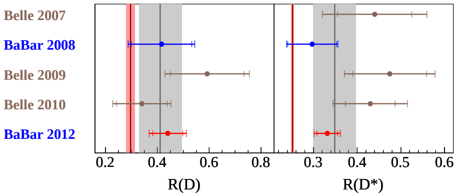
Celis-Jung-Li-Pich, 1210.8443



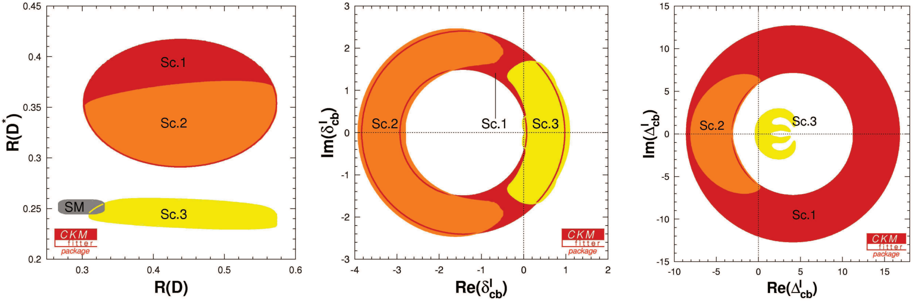


$B \to D^{(*)}\tau\nu_\tau$ and $B \to \tau\nu_\tau$ decays

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



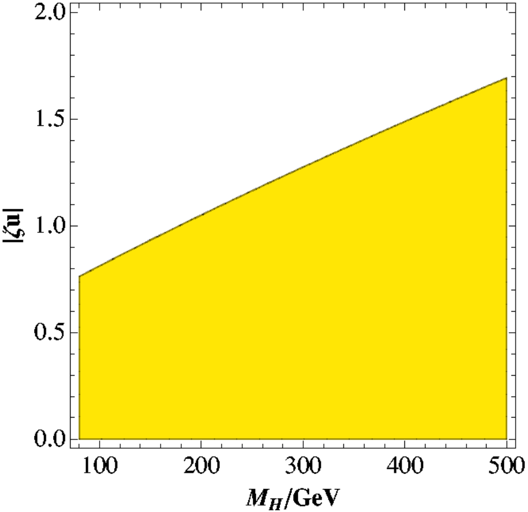
Celis-Jung-Li-Pich, 1210.8443



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

Constraints from ϵ_K (95% CL)

Jung-Pich-Tuzón, 1006.0470



Higgs Signal Strengths:

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

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

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

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

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

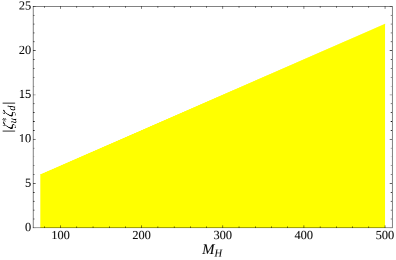
$$x_f = 4m_f^2/M_{\varphi_i^0}^2 \qquad ; \qquad x_W = 4M_W^2/M_{\varphi_i^0}^2$$

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

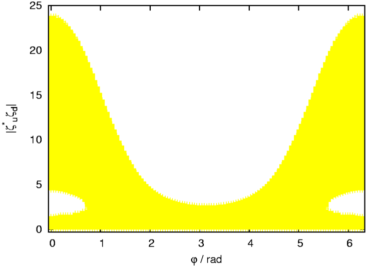
Jung-Pich-Tuzón, 1011.5154

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

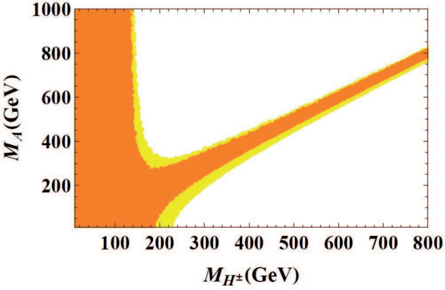


- Stronger constraint for small Scalar Masses
- For $\varphi \equiv \arg(\varsigma_u^* \varsigma_d) = \pi \; (0)$ constructive (destructive) interference
- Important restriction on CP asymmetries

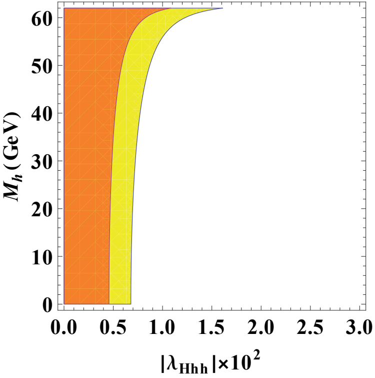
A Heavy CP-even Higgs at 126 GeV

Celis-Ilisie-Pich, 1302.4022

S, T, U



Invisible Width $(H \to hh)$



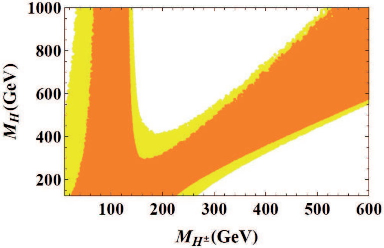
$\sin\tilde{\alpha} \approx 1 \quad \Rightarrow \quad g_{hVV} \ll 1$

Degenerate CP-even and CP-odd Higgses

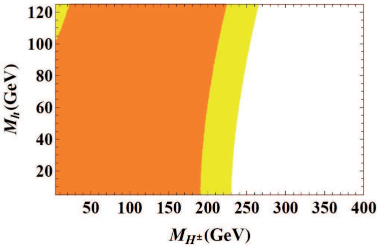
Celis-Ilisie-Pich, 1302.4022

$S,\ T,\ U$ Constraints

$M_h\ =\ M_A\ =\ 126$ GeV



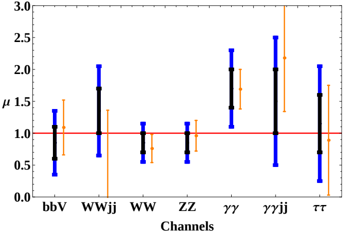
$M_H\ =\ M_A\ =\ 126$ GeV



$\mathbf{M_h\ =\ M_A\ =\ 126}$ GeV

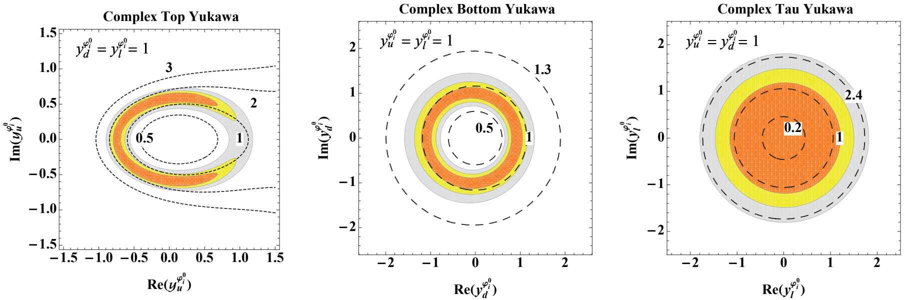
$$\cos\tilde{\alpha} = 0.98 \pm 0.2 \quad , \quad \varsigma_u = -1.1\,^{+0.5}_{-1.4}$$

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



Complex Yukawa Couplings

Celis-Ilisie-Pich, 1302.4022

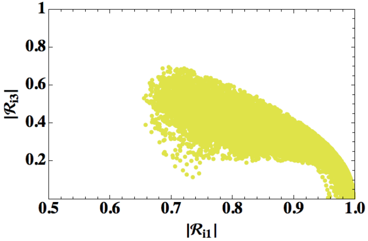


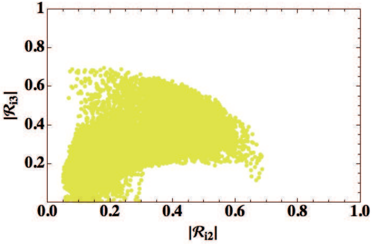
Dashed lines = constant $\mu^{\varphi_i^0}_{\gamma\gamma}$ | constant $\mu^{\varphi_i^0}_{bbV}$ | constant $\mu^{\varphi_i^0}_{\tau\tau V}$

$\mathcal{R}_{i1} = 0.95\,,$ 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 $|\varsigma_{d,l}| < 10$