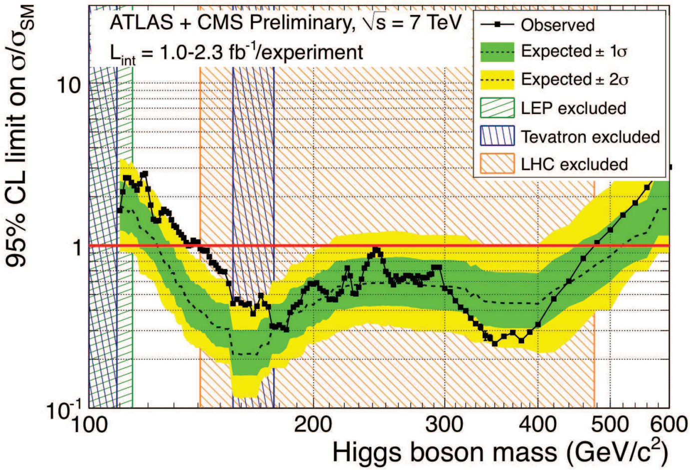
Constraints on Multi-Higgs-Doublet Models: Flavour Alignment

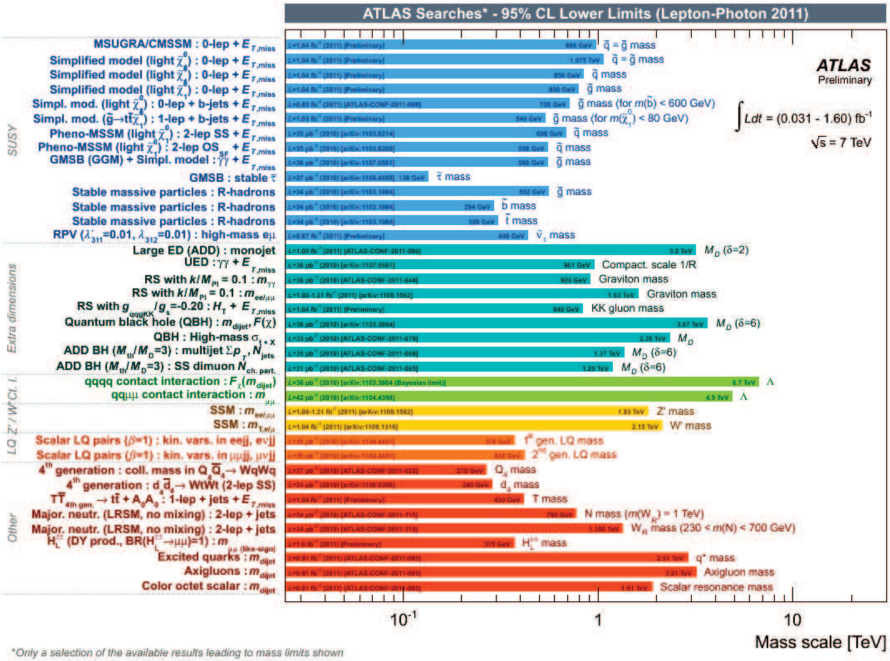
Antonio Pich

IFIC, Univ. Valencia - CSIC

HCP 11, Paris, 18 November 2011

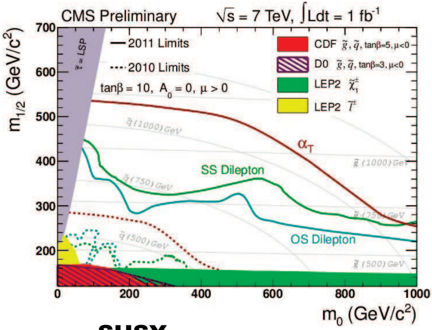


Excluded: $\mathbf{M_H}$ (GeV) $\in$ **[141 , 476]**

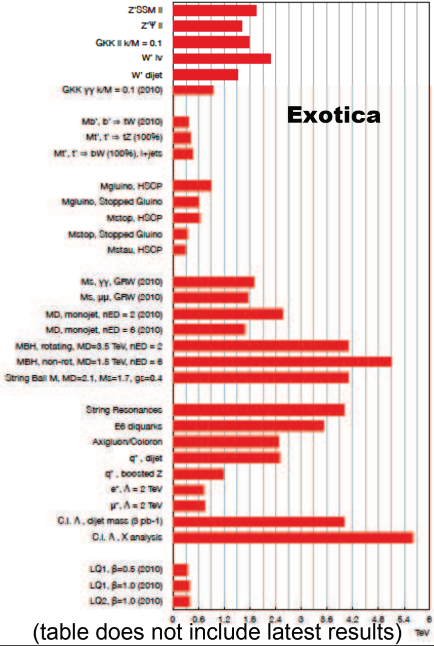


H. Bachacou, Lepton-Photon 2011

Summary (CMS)



SUSY

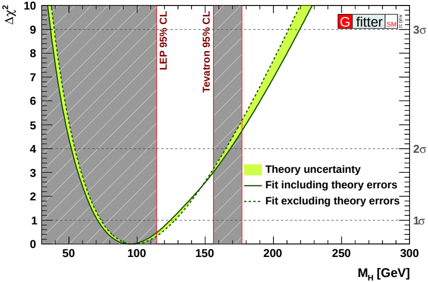


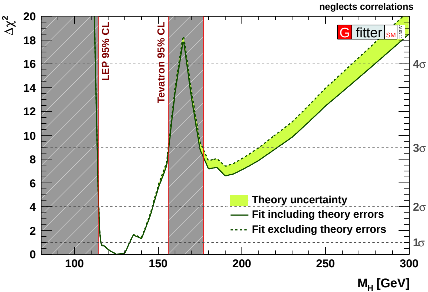
(only a selection of results)

(table does not include latest results)

Possible Scenarios:

❶ **Light SM Higgs:** M_H (GeV) $\in$ [114.4 , 141]





Favoured by EW precision tests

Possible Scenarios:

1. **Light SM Higgs.**

   Favoured by EW precision tests

2. **Alternative perturbative EW SSB.**

   Scalar Doublets and singlets (ρ)

3. **Heavy Higgs.**

   Non-perturbative EW SSB

4. **No Higgs.**

   Dynamical EW SSB

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

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

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

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

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

Yukawa Interactions in 2HDMs

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

↓ **SSB**

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

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)

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

➡ **CP conserved in the scalar sector**

Aligned 2HDM

(Pich - Tuzón '09)

Require alignment in Flavour Space of Yukawa couplings:

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

$$\Downarrow$$

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

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

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

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

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

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

- ς_f are arbitrary complex numbers

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

A2HDM: General phenomenological setting without tree-level FCNCs

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

$\mathcal{Z}_2$ 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)

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 '02, Buras et al '10)

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

$\Rightarrow$ **Aligned Yukawas are also invariant**

Allowed Operators:

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

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

FCNCs at one Loop

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

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

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

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

Phenomenological Constraints

Jung-Pich-Tuzón

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

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

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

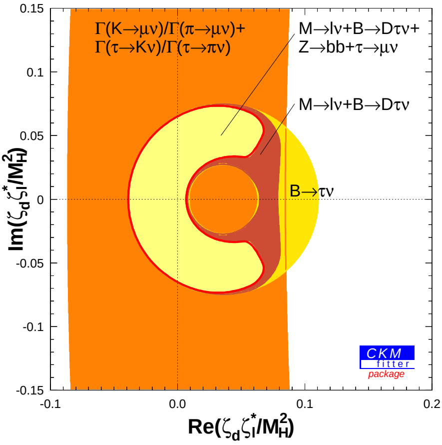
$$\Delta_{ij} = \frac{m_P^2}{M_{H^\pm}^2}\, \varsigma_l^* \, \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

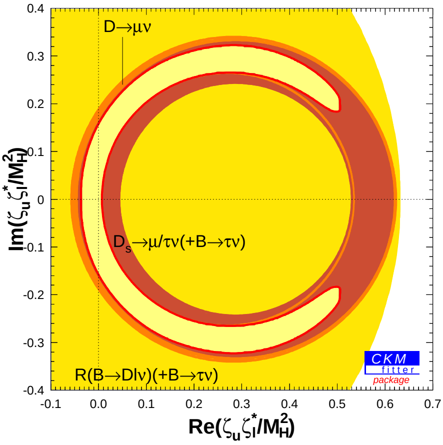
- $\Gamma(P \to P' l^-\bar{\nu}_l)$ $\rightarrow$ Scalar form factor: $\quad \tilde{f}_0(t) = f_0(t)\,(1 + \delta_{ij}\, t)$

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

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

Jung-Pich-Tuzón



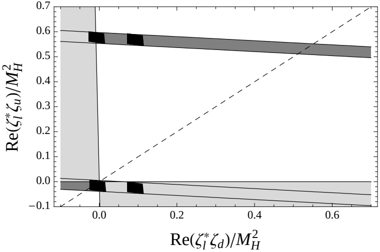


(GeV^{-2} units)

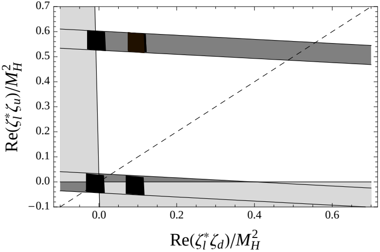
Real Couplings:

Jung-Pich-Tuzón

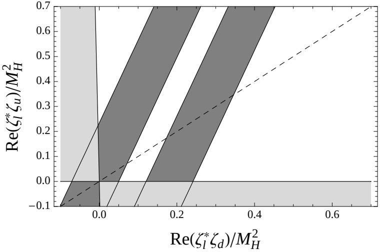
$D_s \to \tau\nu_\tau \quad (B \to \tau\nu_\tau)$



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



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



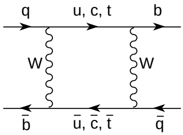
(95% CL, GeV^{-2} units)

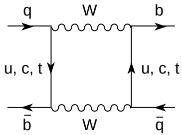
Type I/X: Dashed Line

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

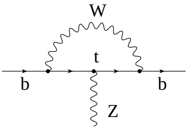
1-Loop Constraints on $H^\pm$ Couplings

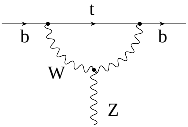
B^0–$\bar{B}^0$ Mixing





$Z \to b\bar{b}$



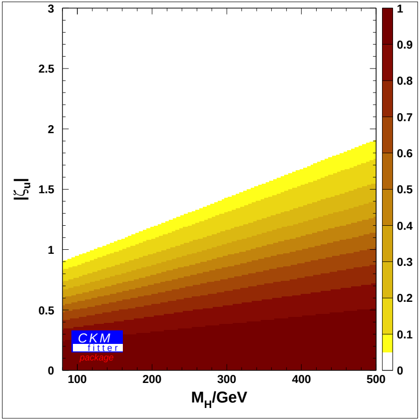


Virtual $\mathbf{H^\pm / W^\pm}$. Top-dominated contributions

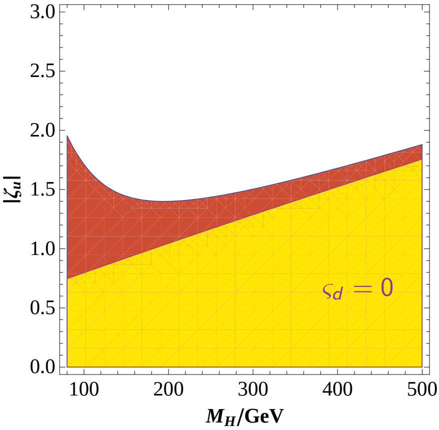
Constraints from $Z \to b\bar{b}$ and ΔM_{B_s} (95% CL)

Jung-Pich-Tuzón

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



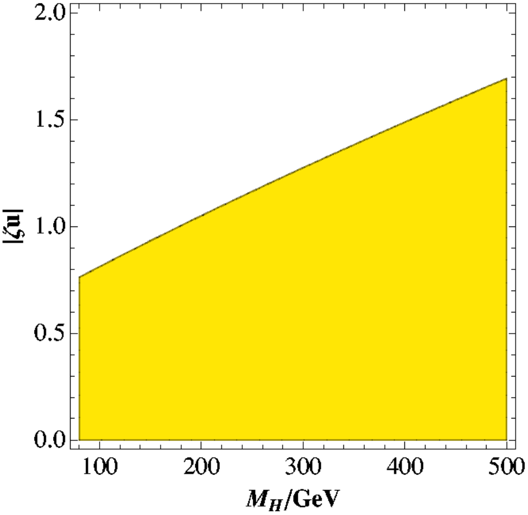
ΔM_{B_s} $(|\varsigma_d| < 50)$



$|\varsigma_u|/M_{H^\pm} < 0.011\ \text{GeV}^{-1}$ $\xrightarrow{\tau}$ $|\varsigma_u \varsigma_l^*|/M_{H^\pm}^2 < 0.005\ \text{GeV}^{-2}$

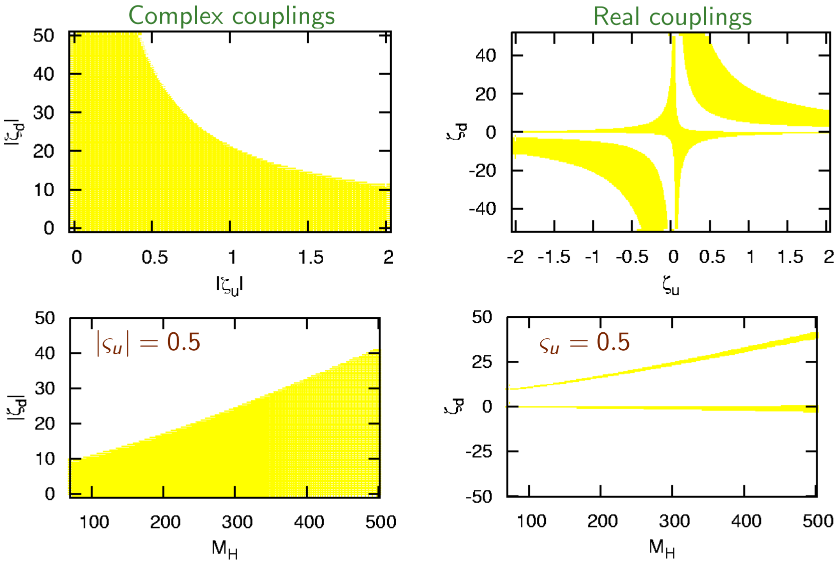
Constraints from ϵ_K (95% CL)

Jung-Pich-Tuzón



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

Jung-Pich-Tuzón

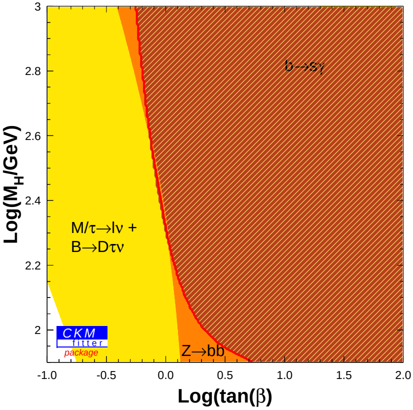


$$C_i^{\mathrm{eff}}(\mu_W) = C_{i,SM} + |\varsigma_u|^2 \; C_{i,uu} - (\varsigma_u^* \varsigma_d \;) \; C_{i,ud}$$

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

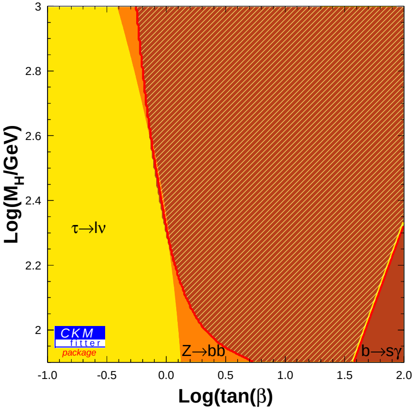
Jung-Pich-Tuzón

Type I



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

Type X

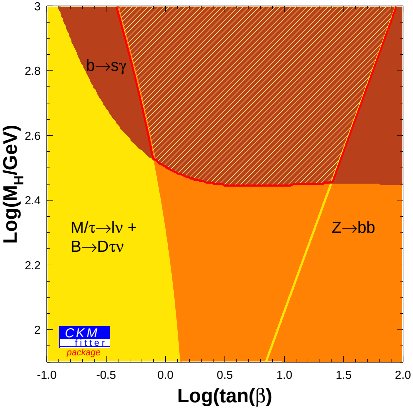


$$\varsigma_u = \varsigma_d = -\varsigma_l^{-1} = \cot\beta$$

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

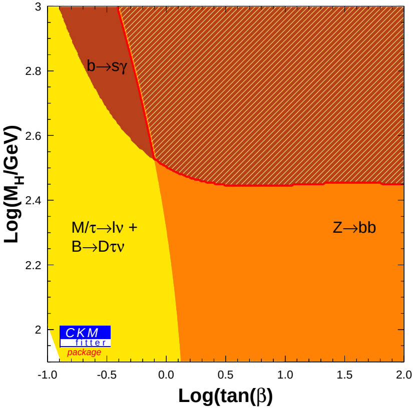
Jung-Pich-Tuzón

Type II



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

Type Y



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

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

In agreement with previous analyses

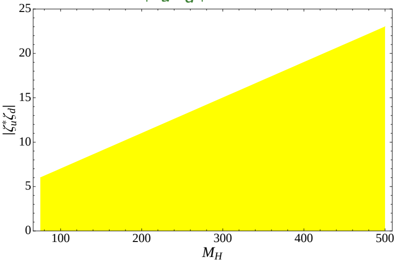
(Aoki et al, Wahab et al, Deschamps et al, Flacher at al, Bona et al, Mahmoudi-Stal, Misiak et al . . .)

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

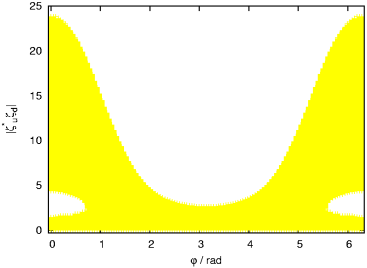
Jung-Pich-Tuzón

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

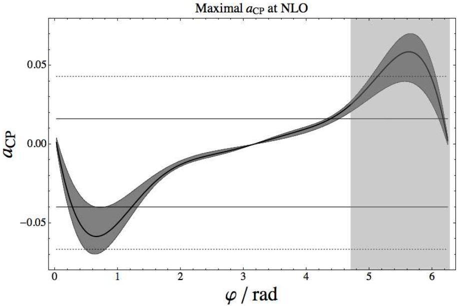


- Stronger constraint for small Scalar Masses
- For $\varphi \equiv \arg(\varsigma_u^* \varsigma_d) = \pi \; (0)$ constructive (destructive) interference
- Important restriction on CP asymmetries

Direct CP Asymmetry in $b \to s\gamma$

Jung-Pich-Tuzón

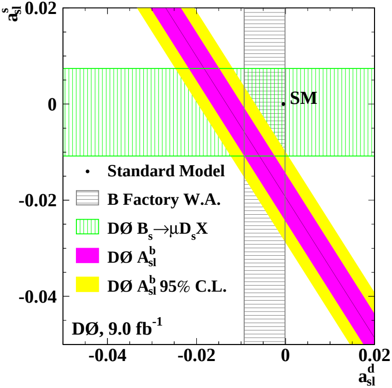
- Small in the SM (Ali et al '98, Kagan-Neubert '98, Hurth et al '05)
- Potentially large in general 2HDMs (Borzumati-Greub '98)
- However, **strongly constrained by Br($b \to s\gamma$)**



$$a_{CP} \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

Compatible with measurement, but it could be sizeable

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



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

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

- LHCb does not confirm a large ϕ_s in $B_s \to J/\Psi\phi$ (D0/CDF)
- D0 data seems to require new-physics contribution in $\Delta\Gamma_s$

Average of $B_s \to J/\psi\phi$ and $B_s \to J/\psi f_0$

LHCb-CONF-2011-056

Simultaneous fit to both samples:

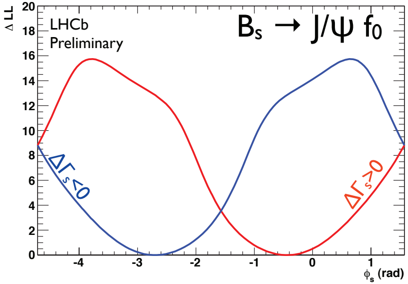
LHCb Preliminary

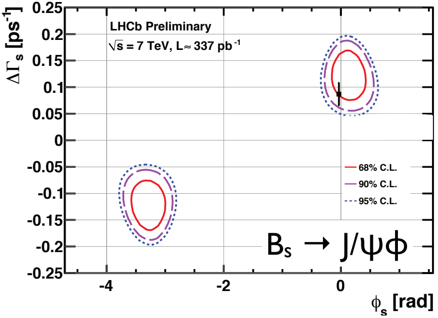
$\phi_s = 0.03 \pm 0.16 \pm 0.07$ rad

With present statistics, no evidence for deviation from the SM.

Next steps:

1) Increase statistics (luminosity)
2) Add same-side Kaon tagging
3) Break ambiguity by looking at relative S-wave phase vs. M(KK) in $J/\psi\phi$





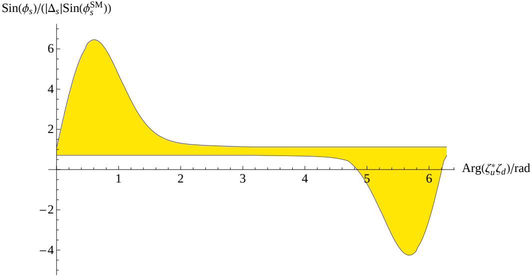
33

G. Raven, Lepton-Photon 2011

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

Jung-Pich-Tuzón

Maximum possible enhancement from $H^\pm$ exchanges:



$$\frac{a_{sl}}{a_{sl}|_{SM}} = \frac{\sin\phi}{|\Delta| \sin\phi^{SM}}$$

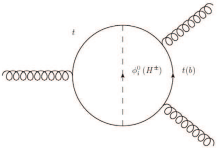
$$\phi \equiv \arg\left(-M_{12}/\Gamma_{12}\right)$$

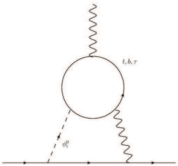
$$\Delta \equiv M_{12}/M_{12}^{\rm SM}$$

H$^\pm$ contributions to ΔM are too small to explain the D0 asymmetry

Electric Dipole Moments

- **Highly sensitive to flavour-blind CP-violating phases**
- Stringent experimental bounds: neutron, Thallium, Mercury . . .
- 1-loop $H^{\pm}$ contributions very suppressed by light-quark masses
- Contributions from 4-fermion operators are small (Buras et al)
  (also induced by ϕ_i^0 exchange with 1-loop FCNC vertices)
- **Two-loop contributions dominate** (Weinberg '89, Dicus '90, Barr-Zee '90)

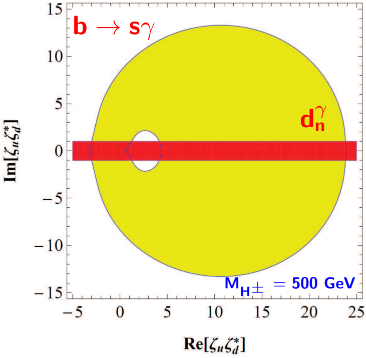


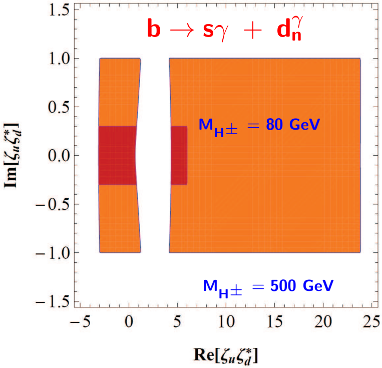


Neutron EDM dominated by $H^\pm$ contribution to $\mathcal{L}_W$

$$\mathcal{L}_W = -\frac{C_W}{6}\, f_{abc}\, \epsilon^{\mu\nu\alpha\beta}\, G^a_{\mu\rho} G^{b\,\rho}_{\nu} G^c_{\alpha\beta} \qquad , \qquad C_W \sim \mathrm{Im}(\varsigma_u \varsigma_d^*)$$

Jung-Pich, preliminary



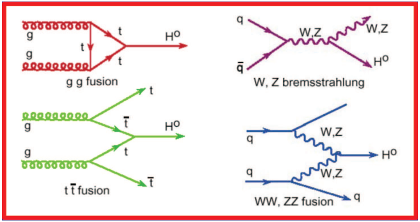


$\mathrm{Im}(\varsigma_u \varsigma_d^*)$ strongly constrained, but not tiny

Higgs Production (CP assumed)

$y_t^{h^0} = \cos\tilde{\alpha} + \varsigma_u \sin\tilde{\alpha}$

$y_t^{H^0} = -\sin\tilde{\alpha} + \varsigma_u \cos\tilde{\alpha}$

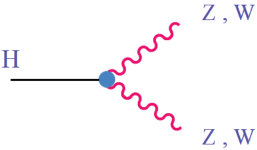


$\lambda_{W,Z}^{h^0} = \cos\tilde{\alpha}$

$\lambda_{W,Z}^{H^0} = -\sin\tilde{\alpha}$

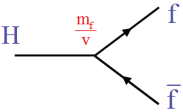
- **Charged Higgs:** $Z \to H^+ H^-,\; t \to H^+ b,\; W^+ \to H^+ h^0\,(H^0)$
- **CP-odd A^0:** $t\bar{t} \to A^0,\; W^+ \to H^+ A^0,\; Z^0 \to A^0 h^0\,(H^0)$
- **CP-violation:** φ_i^0 mixing $(h^0,\, H^0,\, A^0)$, ς_f

Higgs Decay (CP assumed)



$$\lambda_{W,Z}^{h^0} = \cos\tilde{\alpha}$$

$$\lambda_{W,Z}^{H^0} = -\sin\tilde{\alpha}$$



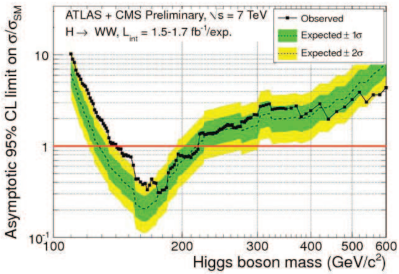
$$y_t^{h^0} = \cos\tilde{\alpha} + \varsigma_u \sin\tilde{\alpha}$$

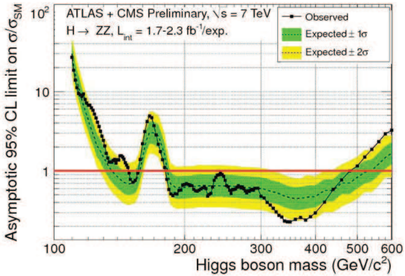
$$y_t^{H^0} = -\sin\tilde{\alpha} + \varsigma_u \cos\tilde{\alpha}$$

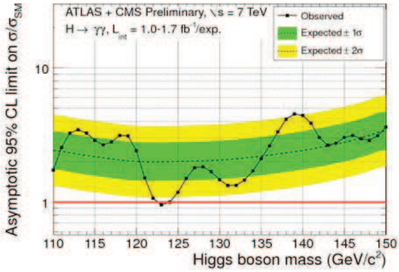
- $h^0\,(H^0) \to W^\pm H^\mp, \quad h^0\,(H^0) \to Z\,A^0, \quad H^0 \to h^0 A^0$
- $H^+ \to t\bar{b}, \quad H^+ \to W^+ h^0\,(H^0)$
- $A^0 \to t\bar{t}, \quad A^0 \to W^\pm H^\mp, \quad A^0 \to Z^0 h^0\,(H^0), \quad A^0 \to h^0 H^0$

Scaling factors for A-2HDM Higgs h^0

Rolandi, HCP 11





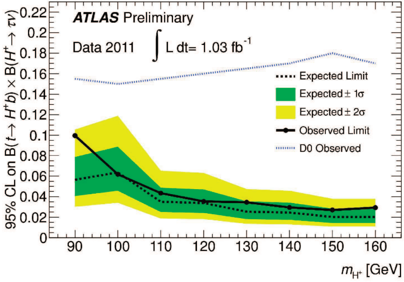


$$|y_t^{h^0}| = |\cos\tilde{\alpha} + \varsigma_u \sin\tilde{\alpha}| \; < \; 0.25 - 1$$

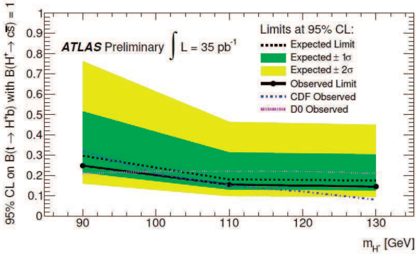
for $\quad M_{h^0} \in [141, 476]$

$$Br(h^0 \to ZZ, WW) \approx 1$$

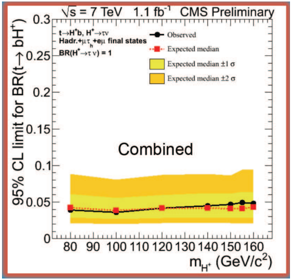
Charged Higgs



O. Igonkina, HCP 11



A. Savin, HCP 11



$$\mathrm{Br}(t \to H^+ b) \approx \frac{|\varsigma_u|^2}{|\varsigma_u|^2 + R} + \mathcal{O}(m_b^2/m_t^2)$$

$$R = \left(\frac{m_t^2 - M_{W\pm}^2}{m_t^2 - M_{H\pm}^2}\right)^2 \left(1 + 2\,\frac{M_{W\pm}^2}{m_t^2}\right) (1 + \delta_{\mathrm{QCD}})$$

$$\mathrm{Br}(H^+ \to \tau^+ \nu_\tau) \approx 1 - \mathrm{Br}(H^+ \to c\bar{s}) \approx$$

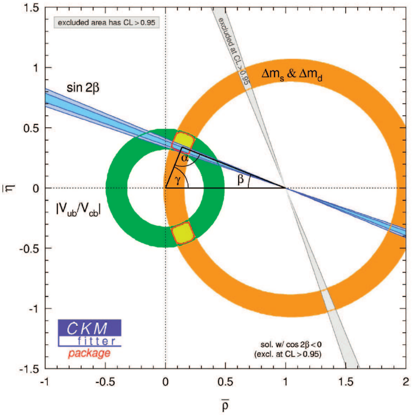
$$\left\{1 + (1.8\,|\varsigma_u|^2 + 0.012\,|\varsigma_d|^2)/|\varsigma_l|^2\right\}^{-1}$$

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

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 $2^{\rm nd}$ solution
- $\Delta m_s/\Delta m_d \; = \; (\Delta m_s/\Delta m_d)|_{\rm SM} \, + \, \mathcal{O}[(m_s - m_d)\, \varsigma_d / M_W]$

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

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

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

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

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

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

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