LHC constraints on two-Higgs doublet models

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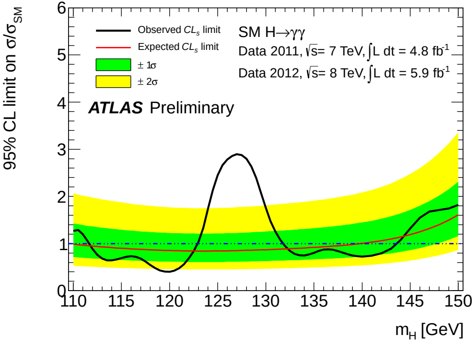
SM scalar sector

- Recently, a SM-like scalar particle has been discovered at the LHC



- It could just be the SM Higgs... Game Over?
- Are there more scalars?

Two-Higgs doublet models

- The Higgs basis:

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

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

- When the potential is CP-conserving:

$$\begin{pmatrix} h \\ H \\ A \end{pmatrix} = \begin{pmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} & 0 \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

- $\tilde{\alpha} \equiv \alpha - \beta$, $v = \sqrt{v_1^2 + v_2^2} \approx 246$ GeV, $\tan\beta \equiv v_2/v_1$.

Yukawa Lagrangian

- The general Yukawa Lagrangian in the Higgs basis:

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \Big\{ \bar{Q}'_L \, (M'_d \Phi_1 \, + \, Y'_d \Phi_2) \, d'_R \, + \, \bar{Q}'_L \, (M'_u \Phi_1 \, + \, Y'_u \Phi_2) u'_R \\ + \, \bar{L}'_L \, (M'_l \Phi_1 \, + \, Y'_l \Phi_2) \, l'_R \Big\}$$

- with M'_f and Y'_f complex independent matrices (non simultaneously diagonalizable) $\Rightarrow$ tree level FCNCs.

- One usually imposes a discrete $\mathcal{Z}_2$ symmetry on the Higgs doublets: $\phi_1 \to \phi_1 \, , \; \phi_2 \to -\phi_2$ (in a generic basis), etc.

- However, a more general approach is to impose alignment in the flavour space: $Y'_f \sim M'_f$.

Yukawa Lagrangian

- Now we can simultaneously diagonalize both matrices and:

$$Y_{d,l} = \varsigma_{d,l}\, M_{d,l} \qquad\qquad Y_u = \varsigma_u^*\, M_u$$

- The Yukawa Lagrangian now reads:

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

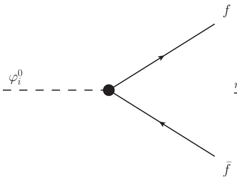
- If the Higgs potential is CP-conserving then the neutral Yukawas read:

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

$$y_u^h = \cos\tilde{\alpha} + \varsigma_u^*\,\sin\tilde{\alpha} \qquad y_u^H = -\sin\tilde{\alpha} + \varsigma_u^*\,\cos\tilde{\alpha} \qquad y_u^A = -i\,\varsigma_u^*$$

Yukawa Lagrangian

- The complex parameters still allow for new sources of CP-violation in the neutral Yukawa sector:

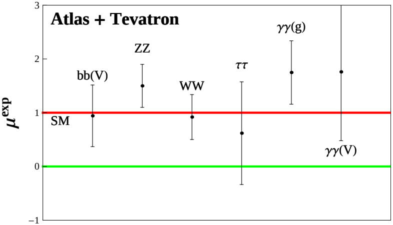


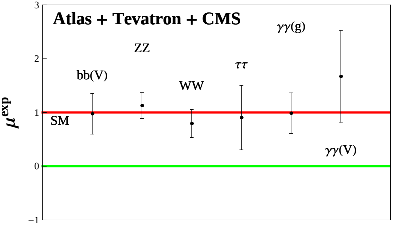
$$\frac{m_f}{v}\, Re(y_f^{\varphi_i^0}) + i\,\gamma_5\, \frac{m_f}{v}\, Im\,(y_f^{\varphi_i^0})$$

- SM: $Re(y_f^{\varphi_i^0}) = 1$ and $Im(y_f^{\varphi_i^0}) = 0$.
- For real ς_f we can recover the usual $\mathcal{Z}_2$ models:

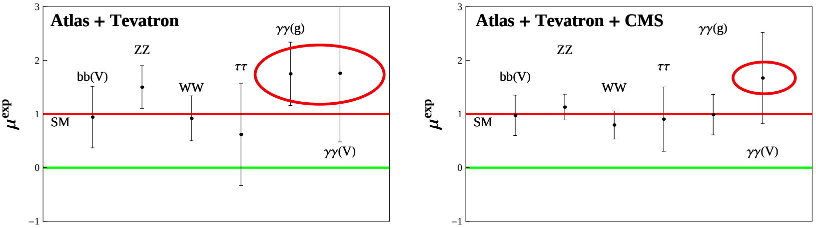
Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

Experimental data

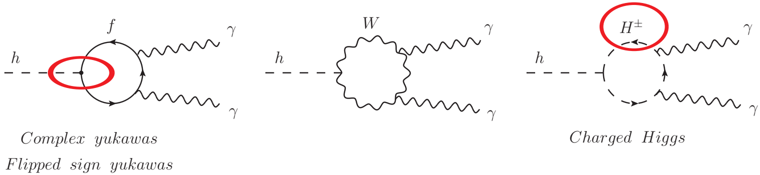




Experimental data

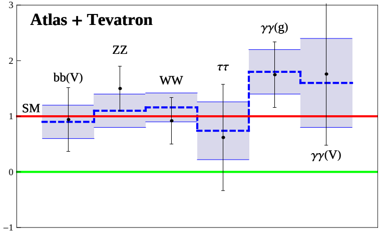


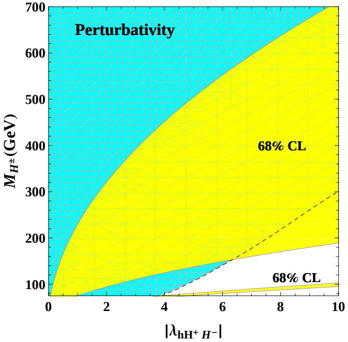
- Its origin might be new interesting physics:



χ^2 fit, CP-conserving potential & yukawas

- With a charged Higgs: $\mathcal{L}_{hH^+H^-} = -v\,\lambda_{hH^+H^-}\, hH^+H^-$

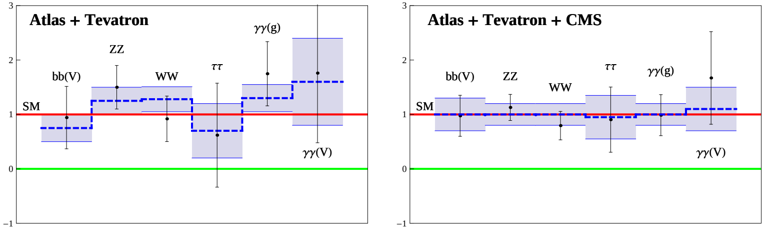




$$y_W^h = 0.98^{+0.2}_{-0.6} \qquad y_u^h = 1.0^{+0.4}_{-0.3} \qquad |y_d^h| = 0.9 \pm 0.4 \qquad |y_l^h| = 0.7 \pm 0.6$$

χ^2 fit, CP-conserving potential & yukawas

- Without a charged Higgs:



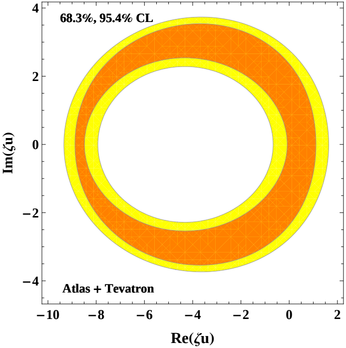
Atlas + Tevatron:

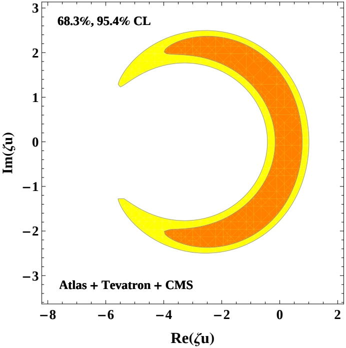
$$y_W^h = 0.98^{+0.2}_{-0.6} \quad y_u^h = 0.9 \pm 0.2 \quad y_d^h = [-1, -0.5] \cup [0.5, 1] \quad y_l^h = [-1, 1]$$

Atlas + Tevatron + CMS:

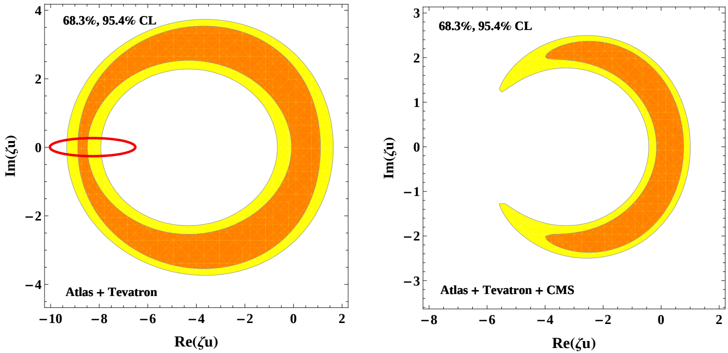
$$y_W^h = 0.98^{+0.2}_{-0.6} \quad y_u^h = 0.95 \pm 0.25 \quad |y_d^h| = 0.95 \pm 0.3 \quad |y_l^h| = 0.95 \pm 0.3$$

χ^2 fit, CP-conserving potential, complex y_u





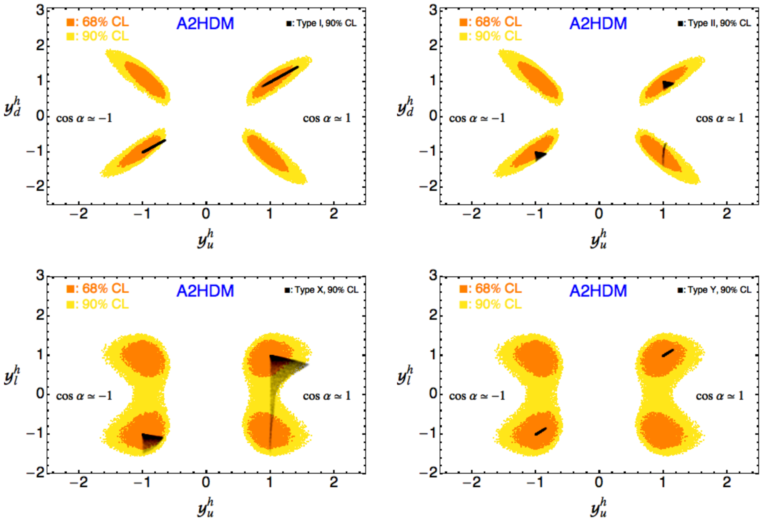
χ^2 fit, CP-conserving potential, complex y_u



- $y_u^h = \cos\tilde{\alpha} + \varsigma_u^* \sin\tilde{\alpha}$
- You can flip the sign of $y_t^h \Rightarrow W$ and t loops make positive interference $\Rightarrow$ excess in $h \to \gamma\gamma$.

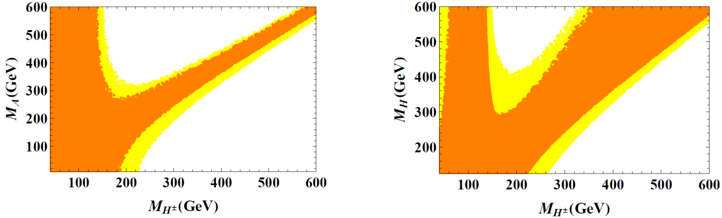
χ^2 fit, CP-conserving potential & yukawas

- ATHDM and $\mathcal{Z}_2$ types with Atlas + Tevatron + CMS:



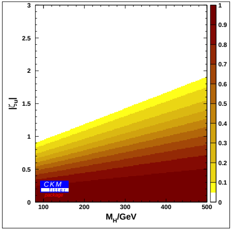
Conclusions

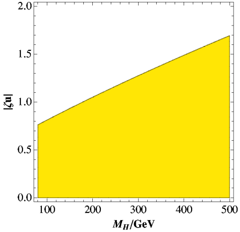
- Other interesting possibilities $M_h = M_A = 126$ GeV, 126 GeV boson is CP-even CP-odd mixture $h - A$, etc...[1]
- With more data and smaller errors we will be able to distinguish among all these possibilities.
- We can now put constraints on the properties of H, $H^{\pm}$, A, i.e., using the oblique parameters S, T and U:

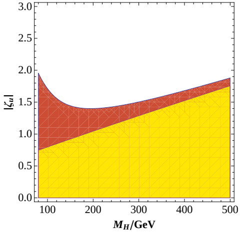


Backup slides

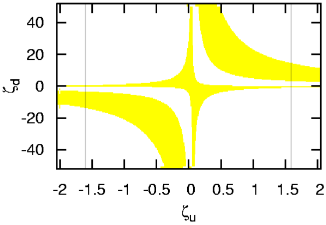
- Included flavour constraints: R_b, ϵ_K, $\bar{B}-B$ mixing







- Flavour constraints to include in the future: $B \to X_s \gamma$



- The one loop corrections introduce some misalignment. Using the renormalization-group equations one finds FCNCs structures:

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

- The leptonic coupling ς_l does not introduce any FCNC interaction.
- Assuming the alignment to be exact at some scale μ_0 ($C(\mu_0) = 0$), a non-zero value is generated when running to another scale:

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

- These effects are very suppressed by $m_q m_q'/v^3$ and by the quark mixing factors, avoiding the stringent experimental constraints.

Backup slides

- The χ^2 used for the fit is defined as:

$$\chi^2 = \sum_{a \neq b} \left(\frac{(\mu_a - \hat{\mu}_a)^2}{\sigma_a^2} + \frac{(\mu_b - \hat{\mu}_b)^2}{\sigma_b^2} - 2\rho_{ab} \frac{(\mu_a - \hat{\mu}_a)\,(\mu_b - \hat{\mu}_b)}{\sigma_a\,\sigma_b} \right)$$

- $\hat{\mu}_a$ and σ_a are the experimental signal strength and error; ρ_{ab} is the correlation coefficient and:

$$\mu_a^{\varphi_i^0} = \frac{\sigma(pp \to \varphi_i^0)}{\sigma(pp \to h)_{SM}} \frac{\mathrm{Br}(\varphi_i^0 \to a)}{\mathrm{Br}(h \to a)_{SM}}$$

$$\frac{\mathrm{Br}(\varphi_i^0 \to a)}{\mathrm{Br}(h \to a)_{SM}} = \frac{1}{\rho(\varphi_i^0)} \frac{\Gamma(\varphi_i^0 \to a)}{\Gamma(h \to a)_{SM}}$$

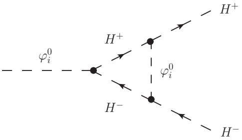
$$\Gamma(\varphi_i^0) = \rho(\varphi_i^0)\Gamma_{SM}(h) \tag{1}$$

Backup slides

- For THDMs with a general potential $\lambda_{\varphi_i^0 H^+ H^-}$ is a free parameter. When the potential is CP-conserving ($\lambda_i \in \mathbb{R}$):

$$\lambda_{hH^+H^-} = \lambda_3 \cos\tilde{\alpha} + \lambda_7 \sin\tilde{\alpha}$$
$$\lambda_{HH^+H^-} = -\lambda_3 \sin\tilde{\alpha} + \lambda_7 \cos\tilde{\alpha}$$

- As it depends on yet unknown parameters we can calculate the one-loop correction:



$$(\lambda_{\varphi_i^0 H^+ H^-})_{\text{eff}} = \lambda_{\varphi_i^0 H^+ H^-}\,(1+\Delta)$$

- and impose $\Delta \leqslant 50\%$.

References

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[4] M. Jung, A. Pich and P. Tuzón, Charged-Higgs phenomenology in the Aligned two-Higgs-doublet model, arXiv:1006.0470

[4] Atlas Collaboration, ATLAS-CONF-2013-034, March 13, 2013

[5] CMS Collaboration, CMS PAS HIG-13-005

[6] CDF, D0 Collaborations, Higgs Boson Studies at the Tevatron, arXiv:1303.6346