Slight excess of a 130 GeV charged scalar decay to charm and bottom quarks at the LHC

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Charged Higgs in 3HDM (Three-Higgs-Doublet-Model)
With A.G. Akeroyd, S. Moretti

[*Based on previous works with A.G. Akeroyd, S. Moretti, T. Shindou. arXiv:1810.05403,2009.05779.*]

- Existence of Charged Higgs boson?

	SPIN 0	SPIN 1/2	SPIN 1
Charge 0	H	ν_e, ν_μ, ν_τ	γ, Z, g
Charge ± 1	$H^\pm$?	$e^\pm, \mu^\pm, \tau^\pm, u, d, c, s, t, b$	$W^\pm$

Motivation for 3HDM:

- Rich scalar structure.
- Extra source of CP-violation in the charged sector (Not NFC 2HDM)
- ATLAS search with a local 3σ (global 1.6σ) excess around $M_{H^\pm} = 130$ GeV ($t \to H^+ b > H^+ \to c\bar{b}$) [ATLAS-CONF-2021-037]
  $\to$ (If it is genuine) 2HDM? 3HDM?

Charge Higgs and Yukawa sector in 3HDM (with three VEVs)

	2HDM (NFC)	3HDM (NFC) $Z_2 \times Z_2$
Physical states	$G^\pm, H^\pm$	$G^\pm, H_1^\pm, H_2^\pm$
U_{mix}	$\tan\beta(v_2/v_1)$	$\tan\beta(v_i), \tan\gamma(v_i), \theta_{(H_1^\pm, H_2^\pm)}, \delta_{\text{CP}}$
Number of Yukawa types	Four	Five

- Charged Higgs Yukawa sector [Y. Grossman 1994]:

$$\mathcal{L}_{H_i^\pm} = -\sum_{i=1}^{2} H_i^+ \{ \frac{\sqrt{2}V_{ud}}{v_{sm}} \bar{u}(m_d X_i P_R + m_u Y_i P_L) d + \frac{\sqrt{2}m_l}{v_{sm}} Z_i \bar{\nu}_L l_R \} + H.c.$$

- Yukawa couplings for H_i^+ (with $i = 1, 2$) can be written as:

$$X_i = U^\dagger_{d\,i+1}/U^\dagger_{d1}, \qquad Y_i = -U^\dagger_{u\,i+1}/U^\dagger_{u1}, \qquad Z_i = U^\dagger_{\ell\,i+1}/U^\dagger_{\ell 1}\,.$$

	u	d	ℓ
3HDM(Type I)	2	2	2
3HDM(Type II)	2	1	1
3HDM(Lepton-specific)	2	2	1
3HDM(Flipped)	2	1	2
3HDM(Democratic)	2	1	3

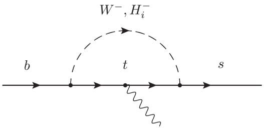
- $Z \to \bar{b}b \to |Y| < 0.8$ ($M_{H^\pm} \sim 100$ GeV)

  [M.Jung, A.Pich, P.Tuzťon,2010]

- LFU $\to |Z| \to 40$.

- $b \to s\gamma$
  $\mathcal{B}^{\text{exp}}_{s\gamma} = (3.32 \pm 0.15) \times 10^{-4}$.
  $\mathcal{B}^{\text{theo}}_{s\gamma} = (3.40 \pm 0.17) \times 10^{-4}$ (α_s^2, NNLO).

  [World Average, HFLAV Collaboration, Yasmine Sara Amhis et al, 2018]



$\to$ $M_{H^\pm} \approx 100$ GeV
-1.1< $Re(XY^*)$ <0.7 (assume $|Y|^2$ small) [M. Trott and M. B. Wise, 2010]

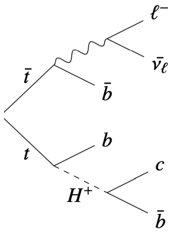
$\to$ (2HDM $b \to s\gamma$ at NLO)

[F.Borzumati,C.Greub, 1998] [M. Ciuchini , G. Degrassi , P. Gambino , G.F. Giudice, 1998]

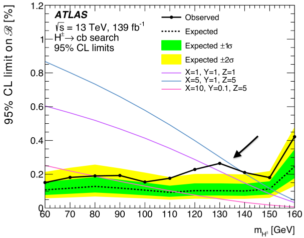
$\to$ (extrapolate to 3HDM) [A.Andrew,S.Moretti,T.Shindou,M.Song, 2021]

$$C^{\text{eff}}(\mu_b, M_{H^\pm_{1,2}}) \propto C^{\text{eff}}_{SM} + \sum_{i=1}^{2} \left[(X_i Y_i^*) C^{\text{eff}}_{i,XY}(M_{H_i^\pm}) + |Y_i|^2 C^{\text{eff}}_{i,YY}(M_{H_i^\pm}) \right]$$

$\sqrt{s}$	ATLAS	CMS
7 TeV (5 fb^{-1})	$cs, \tau\nu$	$\tau\nu$
8 TeV (20 fb^{-1})	$\tau\nu$	$cs, cb, \tau\nu$
13 TeV (36 fb^{-1})	$\tau\nu$	$cs, \tau\nu$
13 TeV (139 fb^{-1})	cb	-



- $[\mathcal{B}(t \to H^{\pm} b) \times \mathcal{B}(H^{\pm} \to cb),\ M_{H^{\pm}}] \longrightarrow$ 3σ local excess. [ATLAS-CONF-2021-037][2302.11739]
- $M_{H^{\pm}} = 130$ GeV $\to 0.16\% \pm 0.06\%$ (Best fit)



Collider constraints (ATLAS and CMS) $\mathcal{B}(t \to H^\pm b) \times \mathcal{B}(H^\pm \to cb/cb + cs/\tau\nu)) \to \mathcal{B}(t)\mathcal{B}(H^\pm)$

- Other decays (fermionic) would suppress (due to fermion mass or CKM elements)
- $\mathcal{B}(H^\pm \to cs) \to \mathcal{B}(H^\pm \to cb + cs)$

If ATLAS search on $M_{H^\pm} = 130$ GeV is genuine:

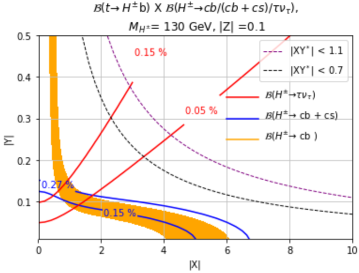
$\to$ $0.1\% \leq \mathcal{B}(t) \times \mathcal{B}(H^\pm_{130} \to cb) \leq 0.22\%$. [ATLAS, 2023] [2302.11739]

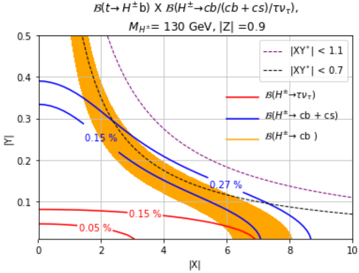
$\to$ $\mathcal{B}(t) \times \mathcal{B}(H^\pm_{130} \to \tau\nu) \leq 0.15\%$.

$\to$ $\mathcal{B}(t) \times \mathcal{B}(H^\pm_{130} \to cb + cs) \leq 0.27\%$.

- Not possible for NFC 2HDM
  $\to$ ($b \to s\gamma$ and three $\mathcal{B}(t)\mathcal{B}(H^\pm_{130})$).
- The Flipped 3HDM could accommodate the excess with $M_{H_2^\pm} > 700$ GeV.

Model independent $|X|_{(d)}, |Y|_{(u)}, |Z|_{(\ell)}$ with $\mathcal{B}(t)\mathcal{B}(H^{\pm}_{130})$





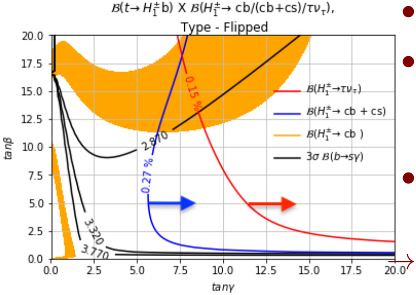
- Large $|X|_{(d)}$, small $|Y|_{(u)}$ and $|Z|_{(\ell)}$ (Γ_t satisfied).
- Flipped 2HDM ($\tan\beta, \cot\beta, -\cot\beta$) ruled out due to $b \to s\gamma$

$\to$ exceed 500 GeV ($M_{H^\pm} \approx M_A$, $\tan\beta > 20$ in MSSM)

[*ATLAS/CMS, 2014*]

$\to$ $M_{H^\pm} > 358$ GeV ($\tan\beta \to \infty$, 99% C.L.). [*M. Misiak, et al, 2015*]

CPC($\delta_{CP} = 0$) Flipped 3HDM, $H_1^\pm = 130, H_2^\pm = 700$ GeV via $[\tan\gamma, \tan\beta]$



$X_i/Y_i/Z_i \propto \tan\beta, \tan\gamma, \theta_{(H_1^\pm, H_2^\pm)}, \delta_{CP}$

- $\theta_{(H_1^\pm, H_2^\pm)} \to -\pi/2$
- Large $H_2^\pm$ ($>$ 700 GeV or more) scenario would probe the 130 GeV ($H_1^\pm$) excess.
- (3σ bound) $b \to s\gamma$ evaded due to contribution cancellation $(H_1^\pm, H_2^\pm)$.

→ Destructive interference ($H^\pm$ and $\chi_i^\pm$,MSSM).

- Γ_t prefers large $\tan\beta, \tan\gamma$.

Summary

- Two physical charged scalars ($H^{\pm}_{1,2}$) in 3HDM (only one in 2HDM).
- $M_{H^{\pm}} < m_t$ ($t \to H^{\pm} b$ follows $H^{\pm} \to cb$) at CMS ($\sqrt{s} = 8$ TeV with 20fb^{-1}) and ATLAS ($\sqrt{s} = 13$ TeV with 139fb^{-1}).
- A local excess around 3σ with $M_{H^{\pm}} = 130$ GeV has been observed by $\mathcal{B}(t) \times \mathcal{B}(H^{\pm} \to cb)$ (ATLAS).
- NFC 2HDM (4 types) not possible to probe the excess.
- In a CPC (no CP-violation) Flipped 3HDM, $M_{H_2^{\pm}} > 700$ GeV could accommodate 130 GeV excess (evade $b \to s\gamma$) .
- Destructive effect survives $b \to s\gamma$ constraint.
- Forthcoming CMS/ATLAS (full Run-II) analysis for the first sign of $H^{\pm}$.

Thanks

Scalar potential of 3HDM ($Z_2 \times Z_2$)

$$
\begin{aligned}
V &= \sum_{i=1}^{3} m_{ii}^2(\Phi_i^\dagger \Phi_i) - (\sum^{ij=12,13,23} m_{ij}^2(\Phi_i^\dagger \Phi_j) + H.c) \\
&+ \frac{1}{2}\sum_{i=1}^{3} \lambda_i(\Phi_i^\dagger \Phi_i)^2 + \sum^{ij=12,13,23} \lambda_{ij}(\Phi_i^\dagger \Phi_i)(\Phi_j^\dagger \Phi_j) \\
&+ \sum^{ij=12,13,23} \lambda'_{ij}(\Phi_i^\dagger \Phi_j)(\Phi_j^\dagger \Phi_i) + \frac{1}{2}[\sum^{ij=12,13,23} \lambda''_{ij}(\Phi_i^\dagger \Phi_j)^2 + H.c]
\end{aligned}
$$

CP violation in charged sector (4 out of 6 physical phases in V)

- two are removed by field redefinition.

$$\mathrm{Im}(m_{13}^2) = -\frac{v_2}{v_3}\mathrm{Im}(m_{12}^2) + \frac{v_1 v_2^2}{2v_3}\mathrm{Im}(\lambda''_{12}) + \frac{v_1 v_3}{2}\mathrm{Im}(\lambda''_{13})$$

$$\mathrm{Im}(m_{23}^2) = \frac{v_1}{v_3}\mathrm{Im}(m_{12}^2) - \frac{v_1^2 v_2}{2v_3}\mathrm{Im}(\lambda''_{12}) + \frac{v_2 v_3}{2}\mathrm{Im}(\lambda''_{23}).$$

$$\mathrm{Im}(\lambda''_{13}) = -\frac{v_2^2}{v_3^2}\mathrm{Im}(\lambda''_{12})$$

$$\mathrm{Im}(\lambda''_{23}) = \frac{v_1^2}{v_3^2}\mathrm{Im}(\lambda''_{12})$$

$$\mathrm{Im}(m_{12}^2) = v_1 v_2 \mathrm{Im}(\lambda''_{12}).$$

- $\delta_{\mathrm{cp}}^{H_{12}^{\pm}} \propto \mathrm{Im}(\lambda''_{12})$

Mixing matrix U in 3HDM

- The matrix U can be written explicitly as a function of four parameters $\tan\beta$, $\tan\gamma$, θ, and δ, where

$$\tan\beta = v_2/v_1, \qquad \tan\gamma = \sqrt{v_1^2 + v_2^2}/v_3\,.$$

- v_1, v_2, and v_3 are the vacuum expectation values of the three Higgs doublets.
- θ is the mixing angle between H_1^+ and H_2^+
- δ is the CP-violating phase.
- The explicit form of U given as

[*C. Albright, J. Smith and S. H. H. Tye 1980*] [*G. Cree, H. E.Logan 2011*]

$$\begin{pmatrix} s_\gamma c_\beta & s_\gamma s_\beta & c_\gamma \\ -c_\theta s_\beta e^{-i\delta} - s_\theta c_\gamma c_\beta & c_\theta c_\beta e^{-i\delta} - s_\theta c_\gamma s_\beta & s_\theta s_\gamma \\ s_\theta s_\beta e^{-i\delta} - c_\theta c_\gamma c_\beta & -s_\theta c_\beta e^{-i\delta} - c_\theta c_\gamma s_\beta & c_\theta s_\gamma \end{pmatrix}$$

Here s, c denote the sine or cosine of the respective parameter.

Decay of $H^{\pm}$ (fermionic modes)

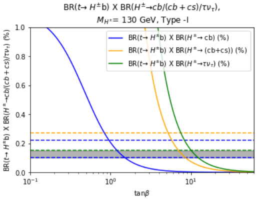
- $$\Gamma(H^{\pm} \to \ell^{\pm}\nu) = \frac{G_F m_{H^{\pm}} m_{\ell}^2 |Z|^2}{4\pi\sqrt{2}} \ ,$$
- $$\Gamma(H^{\pm} \to ud) = \frac{3 G_F V_{ud} m_{H^{\pm}} (m_d^2 |X|^2 + m_u^2 |Y|^2)}{4\pi\sqrt{2}} \ .$$
- The mass of quarks are calculated at the scale of $m_{H^{\pm}}$
- $|X| \gg |Y|, |Z|, BR(H^{\pm} \to cb)$ could be dominant ($\sim$ 80%).

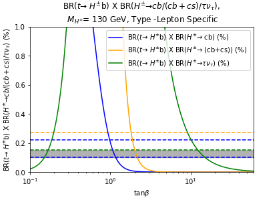
Pertubative and uniformity, (S,T,U) constraints

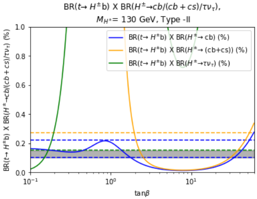
[*H.Logan,S.Moretti,Diana*]

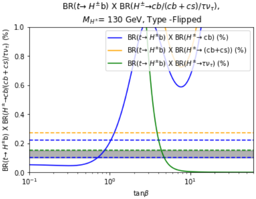
- Pertubative $\rightarrow 0.53 < \tan\beta < 92$ with $\tan\gamma$ =1, but will expand as $\tan\gamma$ increases.
- $\Gamma_{H^{\pm}\rightarrow tb} < M_{H^{\pm}}/2, \tan\beta > 0.34$
- $\Gamma_{H^{\pm}\rightarrow \tau\nu} < M_{H^{\pm}}/2, \tan\beta < 125.$
- S,T,U are more detailed studied in [*J.Kalinowski, et al, 2023*].

NFC 2HDM scenarios $\mathcal{B}(t \to H^{\pm} b) \times \mathcal{B}(H^{\pm} \to cb/cb + cs/\tau\nu_{\tau})$









Some other stuffs

- $\mathcal{R}(D^{(*)})$ $\left(\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu_\tau})/\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu_\ell})\right)$ in 3.4σ beyond SM.
  It is $\propto |XZ|$ and would not proceed for the excess.
- $cb \to H^\pm$ search analysis at the LHC.

  [*J. Hernández-Sánchez, C. G. Honorato, et al, 2112.09173*]

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