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

arXiv: 2202.03522

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21/01/2024 27th LHC mini Workshop, Zhuhai

Charged Higgs in 3HDM (Three-Higgs-Doublet-Model)
arXiv: 2202.03522

[*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 $\neq 0$	$H^\pm$?	$e^\pm, \mu^\pm, \tau^\pm, (u, d, c, s, t, b)$	$W^\pm$

Motivation for 3HDM:

- Rich scalar structure.
- Extra CP-violation source in the charged sector.
  (Not NFC 2HDM, CP source from neutral scalar mixing)
- 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; JHEP 09 (2023) 004*]

$\rightarrow$ (If it is genuine) NFC 2HDM? 3HDM?

Charged Higgs in NFC 2HDM (Z_2 symmetry)

$$\begin{aligned} V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c}) \\ &+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 \\ &+ \lambda_4|\Phi_1\Phi_2|^2 + \frac{1}{2}\left(\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c}\right) \end{aligned}$$

- Two complex scalar doublets ($v_1^2 + v_2^2 = v_{\text{SM}}^2 = (246\ \text{GeV})^2$)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1^{\text{even}} + i\phi_1^{\text{odd}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2^{\text{even}} + i\phi_2^{\text{odd}} \end{pmatrix},$$

- Charged Higgs mass term (2 by 2 mixing matrix $\Rightarrow \tan\beta = v_2/v_1$):

$$[M_{H^\pm}^2]_{ij} = \left.\frac{\partial^2 V}{\partial\phi_i^+\partial\phi_j^-}\right|_{\text{minimum}} \Rightarrow M_{G^\pm,H^\pm}^2 = 0,\ \frac{v^2}{v_1 v_2}m_{12}^2 - (\lambda_4+\lambda_5)v^2$$

NFC	u	d	ℓ	$g_{H^\pm}^u$	$g_{H^\pm}^d$	$g_{H^\pm}^\ell$
2HDM(Type I)	2	2	2	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
2HDM(Type II)	2	1	1	$\cot\beta$	$\tan\beta$	$\tan\beta$
2HDM(Lepton-specific)	2	2	1	$\cot\beta$	$-\cot\beta$	$\tan\beta$
2HDM(Flipped)	2	1	2	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Charged scalar 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

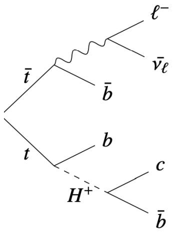
Decay of $H^{\pm}$ (fermionic modes) with $|X|_{(d)}, |Y|_{(u)}, |Z|_{(\ell)}$

$$\Gamma(H^{\pm} \to \ell^{\pm}\nu) = \frac{G_F m_{H^{\pm}} m_{\ell}^2 |Z|_{(\ell)}^2}{4\pi\sqrt{2}} ,$$

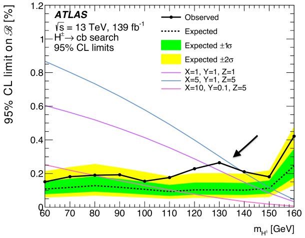
$$\Gamma(H^{\pm} \to ud) = \frac{3 G_F V_{ud} m_{H^{\pm}} (m_d^2 |X|_{(d)}^2 + m_u^2 |Y|_{(u)}^2)}{4\pi\sqrt{2}} .$$

- $m_t > M_{H^{\pm}}$, $cb, cs, \tau\nu$ are dominant.
- Others (fermionic) are suppressed (due to fermion mass or CKM elements).
- $H^{\pm}_{130} \to h^0/H^0 W^*$ with $h^0/H^0 \sim 125$ GeV have small mass splitting and phase space (suppressed).
- $|X|_{(d)} \gg |Y|_{(u)}, |Z|_{(\ell)}, BR(H^{\pm} \to cb)$ could be dominant ($\sim$ 80%).

$\sqrt{s}$	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	-

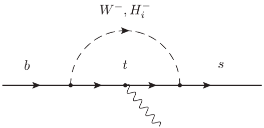


- $[\mathcal{B}(t \to H^{\pm} b) \times \mathcal{B}(H^{\pm} \to cb),\ M_{H^{\pm}}] \longrightarrow$ 3σ local excess. [ATLAS-CONF-2021-037; JHEP 09 (2023) 004]
- $M_{H^{\pm}} = 130$ GeV $\to 0.16\% \pm 0.06\%$ (Best fit)



Pheno constraints on Yukawa couplings $|X|_{(d)}, |Y|_{(u)}, |Z|_{(\ell)}$

- $Z \to \bar{b}b \to |Y|_{(u)} < 0.8, |X|_{(d)} < 50$ $(M_{H^\pm} \sim 100$ GeV$)$ [M.Jung, A.Pich, P.Tuzťon,2010].
- LFU $\to |Z|_{(\ell)} < 40$ [G.Cree, H.Logan, 2011].
- $b \to s\gamma$
  $\mathcal{B}^{\text{exp}}_{s\gamma} = (3.32 \pm 0.15) \times 10^{-4}$.
  $\mathcal{B}^{\text{theo}}_{s\gamma} = (3.40 \pm 0.17) \times 10^{-4}$ $(\alpha_s^2$, 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 in QCD)

[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]

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

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

- $\mathcal{B}(H^\pm \to cs)$ (was assumed dominant)
  $\Rightarrow \mathcal{B}(H^\pm \to cb + cs)$ (cb and cs are comparable)

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

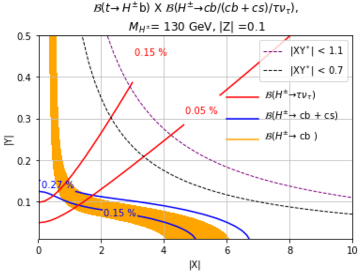
$\to$ $0.1\% \le \mathcal{B}(t) \times \mathcal{B}(H^\pm_{130} \to cb) \le 0.22\%$. [ATLAS, 2023] [JHEP 09 (2023) 004]

$\to$ $\mathcal{B}(t) \times \mathcal{B}(H^\pm_{130} \to \tau\nu) \le 0.15\%$. ($\le 0.05\%$ full Run-II expected limit).

$\to$ $\mathcal{B}(t) \times \mathcal{B}(H^\pm_{130} \to cb + cs) \le 0.27\%$. ($\le 0.15\%$ full Run-II expected limit).

- 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 $|X|_{(d)}, |Y|_{(u)}$ with $\mathcal{B}(t)\mathcal{B}(H^{\pm}_{130})$, $|Z|_{(\ell)} = 0.1, 0.9$

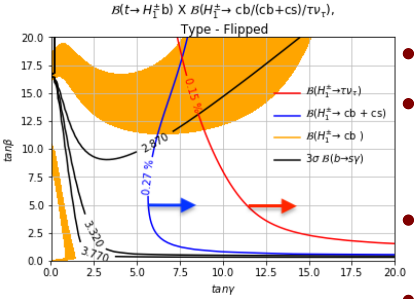


- Large $|X|_{(d)}$, small $|Y|_{(u)}$ and $|Z|_{(\ell)}$ (Γ_t satisfied).
- Flipped 2HDM $(\tan\beta, \cot\beta, -\cot\beta)$ ruled out due to $b \to s\gamma$

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

[ATLAS/CMS, 2014]

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



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

- $\theta_{(H_1^\pm, H_2^\pm)} \to -\pi/2$
- 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 ($H_1^\pm, H_2^\pm$).
- 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 $b \to s\gamma$) .

$\rightarrow$ Destructive interference ($H^{\pm}_{1,2}$) survives $b \to s\gamma$ constraint.

- Expect forthcoming CMS (full Run-II) analysis to clarify the anomaly.

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*]

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

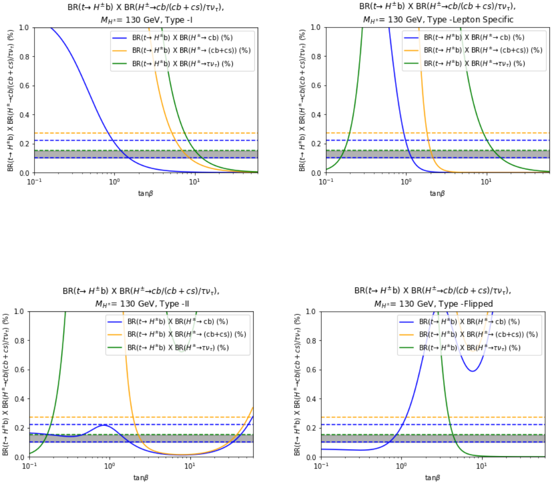
Here s, c denote the sine or cosine of the respective parameter.

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

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

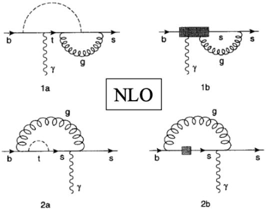
- Pertubative $\rightarrow 0.53 < \tan\beta < 92$ with $\tan\gamma = 1$, but will expand as $\tan\gamma$ increases.
- $\Gamma_{H^\pm \rightarrow tb} < M_{H^\pm}/2, \tan\beta > 0.34$
- $\Gamma_{H^\pm \rightarrow \tau\nu} < M_{H^\pm}/2, \tan\beta < 125.$
- S,T,U are more detailed studied in [*J.Kalinowski,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

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



$b \to s\gamma$ for 2HDM at NLO [*Misiak et al, 2015;M.Stefano, 2017*]

Limits from b→sγ in 2HDM



Now NNLO QCD results for SM and 2HDM (Misiak et al)

2HDM-II (tanβ→ infinity):

$$M_{H^\pm} > 480\,\text{GeV} \quad \text{at } 95\%\ \text{C.L.}\,,$$
$$M_{H^\pm} > 358\,\text{GeV} \quad \text{at } 99\%\ \text{C.L.}$$

Models II and Y $m_{H^\pm} \gtrsim 360\ GeV$ Best available bound on the charged Higgs mass — Any tanβ

Effective Hamiltonian for $\bar{B} \to X_s \gamma$ [F. Borzumati, C.Greub, 1998]

$$
\begin{aligned}
H_{\text{eff}} &= -\frac{4G_f}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i^8 C_i(\mu) O_i(\mu) \\
O_1 &= (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T_a b_L), \qquad O_2 = \bar{s}_L \gamma_\mu c_L \bar{c}_L \gamma^\mu b_L, \\
O_3 &= (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q), \qquad O_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T_a q) \\
O_5 &= (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\rho b_L) \sum_q (\bar{q} \gamma^\mu \gamma^\mu \gamma^\nu \gamma^\rho q), O_6 = (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\rho T^a b_L) \sum_q (\bar{q} \gamma^\mu \gamma^\mu \gamma^\nu \gamma^\rho T_a q) \\
O_7 &= \frac{e m_b}{16\pi^2} \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R, \qquad O_8 = \frac{g_s m_b}{16\pi^2} \bar{s}_L \sigma_{\mu\nu} G_a^{\mu\nu} t_a b_R
\end{aligned}
$$

- $O_{1,2} \to$ current-current operators.
- $O_{2-6} \to$ QCD penguin operators.
- $O_{7,8} \to b \to s\gamma$ and $b \to s\gamma g$.
- On-shell matrix elements [H. D. Politzer, 1980].
- Off-shell scenario [M. Ciuchini, et al 1998].

Some other stuffs

- $cb \to H^{\pm}$ search analysis at the LHC.

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

List of References

- *[ATLAS-CONF-2021-037][JHEP 09 (2023) 004]*
- *[Y. Grossman, 1994] [hep-ph/9401311]*
- *[M. Trott and M. B. Wise] [1009.2813]*
- *[F.Borzumati,C.Greub, 1998] [[hep-ph/9802391]*
- *[M. Ciuchini , G. Degrassi , P. Gambino , G.F. Giudice, 1998][hep-ph/9710335]*
- *[World Average, HFLAV Collaboration, Yasmine Sara Amhis et al, 2018][1909.12524]*
- *[M. Misiak, et al, 2015] [1503.01789]*
- *[ATLAS/CMS, 2014][1409.6064,1408.3316]*
- *[C. Albright, J. Smith and S. H. H. Tye 1980][Phys. Rev. D 21, 711 (1980)]*
- *[G. Cree and H.E. Logan,2011][1106.4039]*
- *[J.Kalinowski, et al, 2023][2112.12699]*
- *[H. D. Politzer, 1980] [Nucl. Phys. B 172 (1980) 349]*
- *[M. Ciuchini, et al 1998] [hep-ph/9710335]*