Decay of charged Higgs bosons into c and b quarks in multi-Higgs doublet models

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1. Introduction

- A neutral scalar (spin=0) has been found at the LHC.
- Searches for additional neutral scalars of high priority now.
- There might exist charged scalars, $H^\pm$.
- Classify elementary particles by their electric charge and spin:

	Spin 0	Spin 1/2	Spin 1
Neutral	h^0	ν_e, ν_μ, ν_τ	γ,Z,g
Charged	($H^\pm$)?	$e^\pm, \mu^\pm, \tau^\pm, u, d, s, c, b, t$	$W^\pm$

$\longrightarrow$ Why not a charged, spin 0 particle, $H^\pm$?

2. The Two Higgs Doublet Model (2HDM)

Introduce a second $I = 1/2$, $Y = 1$ doublet to the SM Lagrangian:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \phi_1^{0,r} + i\phi_1^{0,i})/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \phi_2^{0,r} + i\phi_2^{0,i})/\sqrt{2} \end{pmatrix}.$$

$\tan\beta = v_2/v_1$, where $v_1^2 + v_2^2 = v^2 = 2m_W^2/g$.

Four types of 2HDM (without tree-level flavour changing scalar currents)

	X	Y	Z
Type I	$-\cot\beta$	$\cot\beta$	$-\cot\beta$
Type II	$\tan\beta$	$\cot\beta$	$\tan\beta$
Lepton-specific	$-\cot\beta$	$\cot\beta$	$\tan\beta$
Flipped	$\tan\beta$	$\cot\beta$	$-\cot\beta$

$$\mathcal{L}_{H^\pm} = -\left\{\frac{\sqrt{2}V_{ud}}{v}\bar{u}\,(m_d X P_R + m_u Y P_L)\,d\,H^+ + \frac{\sqrt{2}m_\ell}{v} Z \overline{\nu_L} \ell_R H^+ + H.c.\right\}$$

3. The Three Higgs Doublet Model (3HDM)

- A multi-Higgs doublet model (MHDM) has n scalar doublets.
- A MHDM has $n-1$ physical charged scalars $H^\pm$.
- Phenomenology of $H^\pm$ in a 3HDM has received much less attention than $H^\pm$ in 2HDMs.
- We consider "democratic" 3HDM; u, d, ℓ obtain mass from v_u, v_d, v_ℓ respectively.
- The mass matrix of the charged scalars is diagonalised by the $n \times n$ matrix U:

$$\begin{pmatrix} G^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \phi_d^+ \\ \phi_u^+ \\ \phi_\ell^+ \end{pmatrix}.$$

- I will assume $H_2^\pm$ to be the lightest and relabel it as $H^\pm$.
- In a 3HDM X, Y and Z are not simply given by $\tan\beta$ or $\cot\beta$.
- They are defined in terms of the 3X3 matrix U:

$$X = \frac{U_{d2}}{U_{d1}}, \quad Y = -\frac{U_{u2}}{U_{u1}}, \quad Z = \frac{U_{e2}}{U_{\ell 1}}$$

- In a 2HDM, U is a 2X2 matrix with one parameter ($\tan\beta$).
- In a 3HDM X,Y,Z are not strongly correlated.
- U can be parametrised by four parameters

i) $\tan\beta = v_u/v_d$ ii) $\tan\gamma = \sqrt{v_d^2 + v_u^2}/v_\ell$ iii) An angle θ iv) a phase δ.

4. Flavour constraints on $|X|$, $|Y|$ and $|Z|$

- $Z \to b\bar{b}$: $|Y| < 0.72 + 0.24\left(\frac{m_{H^\pm}}{100\mathrm{GeV}}\right)$.
- $b \to s\gamma$: $-1.1 < \mathrm{Re}XY^* < 0.7$ for $m_{H^\pm} = 100$ GeV .
- In 2HDM in which u and d quarks receive mass from different doublets (e.g. Type II) one has $XY^* = 1 \longrightarrow m_{H^\pm} > 300$ GeV and so $t \to H^\pm b$ is not possible.
- In 3HDM $H^\pm$ can be light since XY^* is arbitrary.

5. Possibility of large BR($H^\pm \to cb$)

Partial decay widths of $H^\pm$:

$$\Gamma(H^\pm \to \ell^\pm\nu) = \frac{G_F m_{H^\pm} m_\ell^2 |Z|^2}{4\pi\sqrt{2}}; \quad \Gamma(H^\pm \to ud) = \frac{3G_F m_{H^\pm} V_{ud}(m_d^2|X|^2 + m_u^2|Y|^2)}{4\pi\sqrt{2}}$$

- For $m_{H^\pm} > m_t$ the channel $H^\pm \to tb$ dominates in all 2HDMs and in 3HDM.
- For $m_{H^\pm} < m_t$, a distinctive signal of $H^\pm$ from a 3HDM would be:

Large BR($H^\pm \to cb$) Grossman 94, AGA/Stirling 94

- The necessary condition is: $|X| >> |Y|, |Z|$ (not allowed in most 2HDMs).
- $m_{H^\pm} < m_t$ respects limits from $b \to s\gamma$ ($XY^* \neq 1$ in 3HDM in general).
- $|X| >> |Y|, |Z|$ is possible in flipped 2HDM, but $b \to s\gamma$ ensures $m_{H^\pm} > 300$ GeV.
- For $|X| >> |Y|, |Z|$ the ratio of the two dominant decays, BR($H^\pm \to cb$) and BR($H^\pm \to cs$), approaches a constant value:

$$\frac{\mathrm{BR}(H^\pm \to cb)}{\mathrm{BR}(H^\pm \to cs)} = R_{bs} \sim \frac{|V_{cb}|^2 m_b^2}{|V_{cs}|^2 m_s^2}$$

- Main uncertainty in R_{bs} is from strange quark mass, m_s (unique feature in $H^\pm$ phenomenology).

6. BR($H^\pm \to cb$) and BR($H^\pm \to cs$) in 3HDM

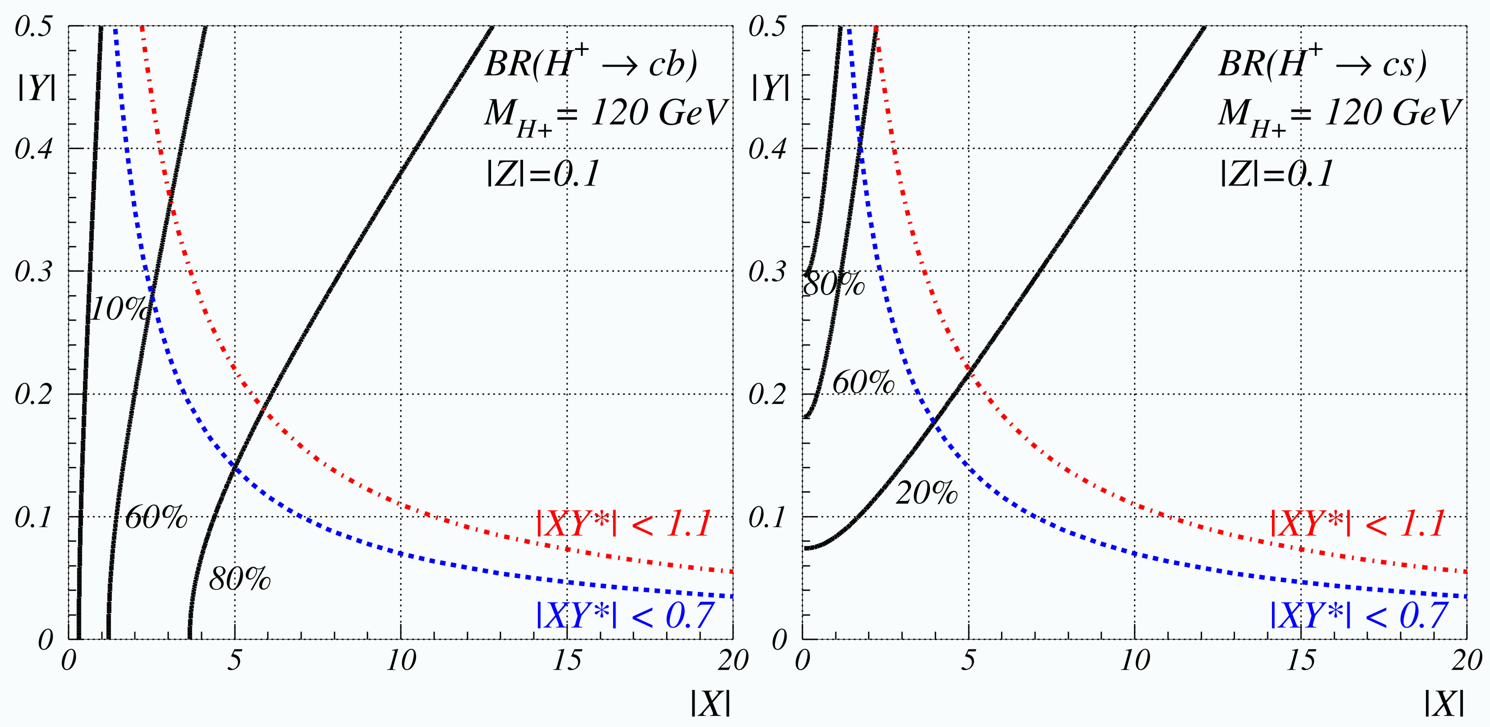

Figure: BR($H^\pm \to cb$) (left panel) and BR($H^\pm \to cs$) (right panel), with $b \to s\gamma$ constraint.

7. ATLAS searches for $t \to H^\pm b$ followed by $H^\pm \to cs$

- Top quarks are produced in pairs e.g. $gg \to t\bar{t}$; then $t/\bar{t} \to Wb$ (with $W \to e\nu$ or $\mu\nu$) and $\bar{t}/t \to H^\pm b$.
- $H^\pm \to cs$ gives two (non-b quark) jets. Candidate signal events are e.g. $b\bar{b}e\nu$ plus two non-b jets.
- Signal is a peak at $m_{H^\pm}$ in invariant mass distribution of non-b jets. Main background from $t/\bar{t} \to Wb$ and $W \to ud/cs$ would give a peak at m_W.

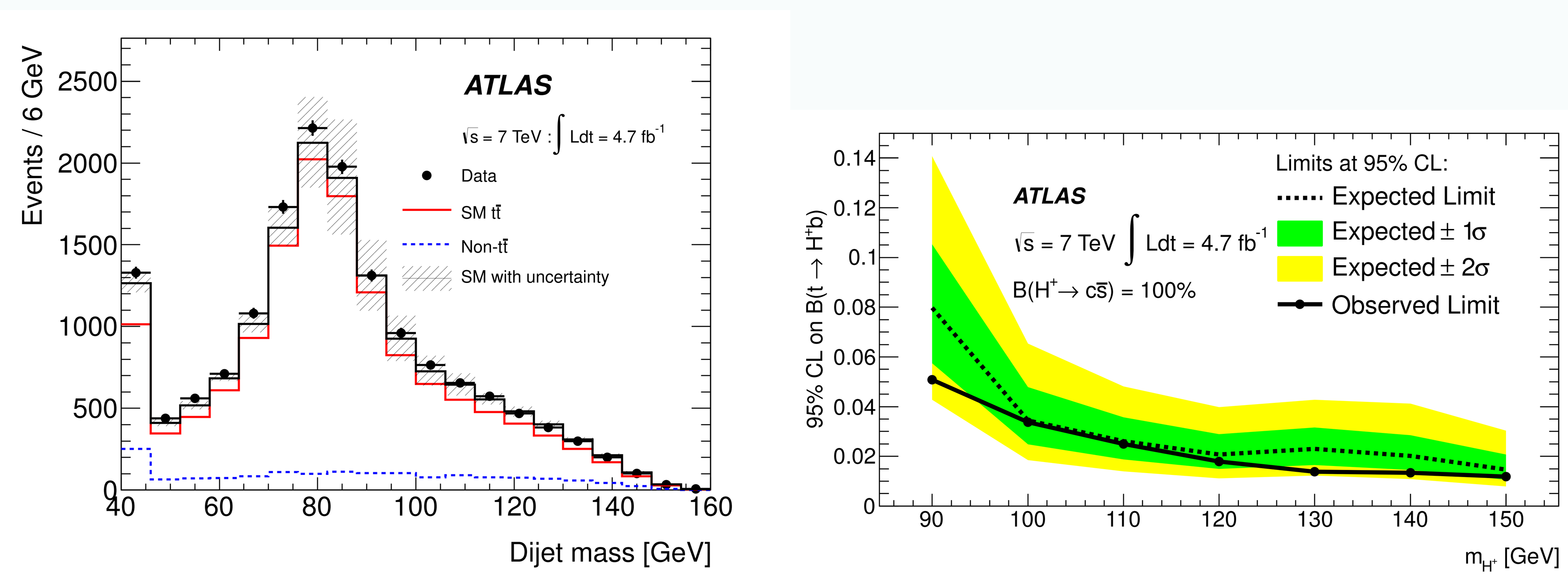

Figure: Left panel: Comparison of simulation and data; Right panel: Excluded region in the plane [$m_{H^\pm}$,BR($t \to H^\pm b$)], assuming BR($H^\pm \to cs$) = 100%.

- ATLAS search also applies to case of dominant $H^\pm \to cb$. Background from $W \to cb$ has very small rate. If tag b quark from $H^\pm \to cb$, the backgrounds $W \to ud/cs$ are reduced. Estimate gain in sensitivity as:

$$\frac{[S/\sqrt{B}]_{\rm btag}}{[S/\sqrt{B}]_{\rm \not{b}tag}} \sim \frac{\epsilon_b\sqrt{2}}{\sqrt{(\epsilon_j + \epsilon_c)}} \sim 2.13$$

- b-tagging efficiency $\epsilon_b = 0.5$; c-quark mistagged as a b-quark $\epsilon_c = 0.1$; light quark (u, d, s) mistagged as a b-quark $\epsilon_j = 0.01$.

8. BR($t \to H^\pm b$) multiplied by BR($H^\pm \to cb$)

$$\Gamma(t \to H^\pm b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2|Y|^2 + m_b^2|X|^2][1 - m_{H^\pm}^2/m_t^2]^2$$

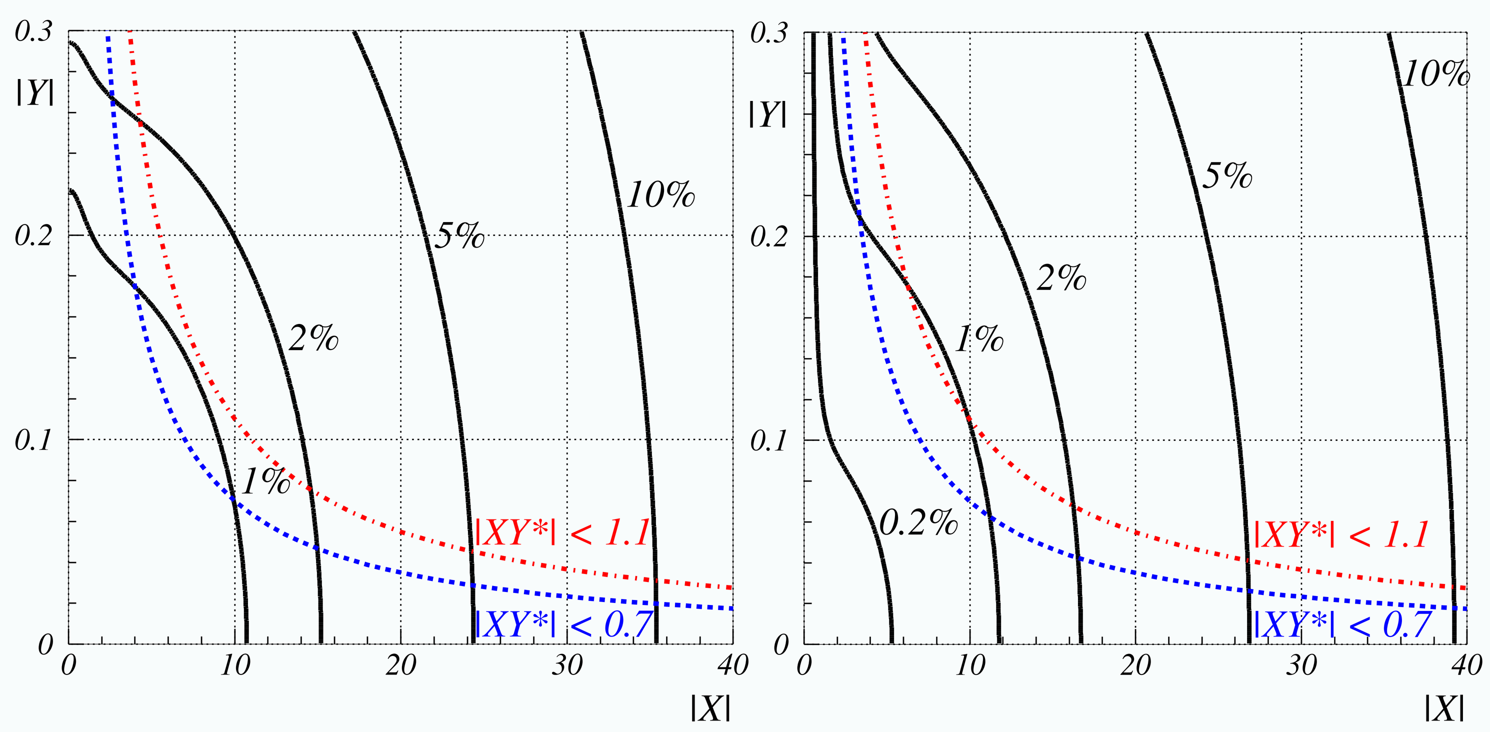

Figure: Left panel: Contours of BR($t \to H^\pm b$) multiplied by [BR($H^\pm \to cb$) + BR($H^\pm \to cs$)]; Right panel: BR($t \to H^\pm b$) multiplied by BR($H^\pm \to cb$).

- Constraints from $t \to H^\pm b$ on plane [$|X|, |Y|$] are competitive with those from $b \to s\gamma$.
- Current limit BR($t \to H^\pm b$) < 2% rules out two regions which cannot be excluded from $b \to s\gamma$: i) $15 < |X| < 40$ and $0 < |Y| < 0.04$, and ii) $0 < |X| < 4$ and $0.3 > |Y| > 0.8$
- Tagging the b quark from $H^\pm \to cb$ would possibly allow sensitivity to BR($t \to H^\pm b$) < 0.5% .
- $t \to H^\pm b$ and $H^\pm \to cb$ could provide stronger constraints on the [$|X|, |Y|$] plane than $b \to s\gamma$ (or perhaps discover $H^\pm \to cb$...).
- Dedicated search for $t \to H^\pm b$ and $H^\pm \to cb$ has yet to be performed.

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