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$H^{\pm} \to cb$ in models with two or more Higgs doublets

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Searches for light $H^{\pm}$s via $t \to H^{\pm}b$ are being carried out at the LHC. Herein, it is normally assumed that the dominant decay channels are $H^{\pm} \to \tau\nu$ and $H^{\pm} \to cs$ and separate data analyses are performed with comparable sensitivity to the underlying model assumptions. However, the $H^{\pm} \to cb$ decay rate can be as large as 80% in models with two or more Higgs doublets with natural flavour conservation, while satisfying the constraint from $b \to s\gamma$ for $m_{H^{\pm}} < m_t$. Despite the current search strategy for $H^{\pm} \to cs$ is also sensitive to $H^{\pm} \to cb$, a significant gain in sensitivity could be obtained by tagging the b quark from the decay $H^{\pm} \to cb$.

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1. Introduction

At the Large Hadron Collider (LHC), if $m_{H^{\pm}} < m_t$, $H^{\pm}$ states would mostly [1] be produced in $t \to H^{\pm}b$ decays [2]. Searches in this channel are being performed by the LHC experiments, assuming the decay modes $H^{\pm} \to cs$ and $H^{\pm} \to \tau\nu$. Since no signal has been observed, constraints are obtained on the parameter space of a variety of models, chiefly 2-Higgs Doublet Models (2HDMs) [3]. Searches in these channels so far carried out at the LHC include: 1) $H^{\pm} \to cs$ with 4.7 fb^{-1} by ATLAS [4] and with 19.7 fb^{-1} by CMS [5]; 2) $H^{\pm} \to \tau\nu$ with 19.5 fb^{-1} by ATLAS [6] and with 19.7 fb^{-1} by CMS [7]. Although the current limits on $H^{\pm} \to cs$ can be applied to the decay $H^{\pm} \to cb$ as well (as discussed in [8] in the Tevatron context), a further improvement in sensitivity to $t \to H^{\pm}b$ with $H^{\pm} \to cb$ could be obtained by tagging the b quark which originates from $H^{\pm}$ [8, 9, 10].

We will estimate the increase in sensitivity to BR($H^{\pm} \to cb$) in a specific scenario, for definiteness, a 3-Higgs Doublet Model (3HDM) (see, e.g. [11])[1]. Reasons to consider a 3HDM could be the following: 1) the existence already of 3 generations of quarks and leptons; 2) (scalar) dark matter (in presence of inert Higgs doublets) and a non-SM like sector.

2. Charged Higgs bosons in the 3HDM

We will consider here the 'democratic' 3HDM [11] wherein the fermionic states u, d, ℓ obtain mass from v_u, v_d, v_ℓ (the three different Vacuum Expectation Values (VEVs)), respectively. The mass matrix of the charged scalars is diagonalised by the 3×3 matrix unitary U:

$$\begin{pmatrix} G^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \phi_d^+ \\ \phi_u^+ \\ \phi_\ell^+ \end{pmatrix}. \tag{2.1}$$

Henceforth, we will assume $H_2^{\pm}$ to be the lightest state and relabel it as $H^{\pm}$.

The Yukawa couplings of the $H^{\pm}$ in a 3HDM are given through the following Lagrangian

$$\mathscr{L}_{H^{\pm}} = -\left\{ \frac{\sqrt{2}V_{ud}}{v} \overline{u}\,(m_d X P_R + m_u Y P_L)\, d H^+ + \frac{\sqrt{2}m_e}{v} Z \overline{\nu_L} \ell_R H^+ + H.c. \right\}. \tag{2.2}$$

In a 3HDM, X, Y and Z are defined in terms of the matrix elements of U,

$$X = \frac{U_{12}}{U_{11}}, \;\; Y = -\frac{U_{22}}{U_{21}}, \;\; Z = \frac{U_{32}}{U_{31}}, \tag{2.3}$$

and are mildly constrained from the theoretical side, as the unitarity of U leads to the relation

$$|X|^2|U_{11}|^2 + |Y|^2|U_{12}|^2 + |Z|^2|U_{13}|^2 = 1. \tag{2.4}$$

[1] As explained in [12], in the Aligned Two Higgs Doublet Model (A2HDM) [13] one can also have a large BR($H^{\pm} \to cb$) [10] with $m_{H^{\pm}} < m_t$, so that our numerical results for the 3HDM apply directly to the A2HDM too. In contrast, while large values of BR($H^{\pm} \to cb$) are also possible in the so called Type III 2HDM [8, 14, 15], they only occur for $m_{H^{\pm}} > m_t$ due to the constraints from $b \to s\gamma$ requiring $m_{H^{\pm}} > 300$ GeV [16, 17, 18]. Finally, in the three other versions of the 2HDM (Type I, II and IV), in which BR($H^{\pm} \to \tau\nu$) and BR($H^{\pm} \to cs$) dominate, one has that BR($H^{\pm} \to cb$) is always $< 1\%$ (due to a small V_{cb}).

Hence, the magnitudes of X, Y and Z cannot all be simultaneously less or more than 1. This is due to the fact that all three VEVs cannot be simultaneously large or small, as $v_d^2 + v_u^2 + v_\ell^2 = (246\ \text{GeV})^2$. Further theory constraints can be imposed via the usual requirements of VV scattering unitarity ($V = W^{\pm}$ or Z), perturbativity, vacuum stability, positivity of mass eigenstates and of the Hessian, Electro-Weak Symmetry Breaking (EWSB) (now in presence of an $m_h = 125$ GeV SM-like Higgs boson), etc. (see [19, 20, 21] for details), though all these primarily affect the neutral Higgs sector of a 3HDM.

Indeed, are the phenomenological constraints those which impinge greatly on the allowed values of X, Y and (less so) Z. The main limits come from the following low energy processes:

- $Z \to b\bar{b}$: $|Y| < 0.72 + 0.24\left(\frac{m_{H^{\pm}}}{100\text{GeV}}\right)$;
- $b \to s\gamma$: $-1.1 < \text{Re}(XY^*) < 0.7$, e.g. for $m_{H^{\pm}} = 100$ GeV.

In essence, in the democratic 3HDM $H^{\pm}$ can be light since XY^* is arbitrary. As for LHC constraints enforced by the Higgs boson search (and coupling measurements), these are rather loose as the $H^{\pm}$ state only enters via loop effects (e.g. in $\gamma\gamma$ and $Z\gamma$ decays).

3. Results

In the light of the previous discussion, a distinctive signal of the $H^{\pm}$ boson from a 3HDM would then be a large BR($H^{\pm} \to cb$) with the charged Higgs boson emerging from an (anti)top decay (since $m_{H^{\pm}} < m_t$). The necessary condition for this is: $|X| >> |Y|, |Z|$. (In the numerical analysis we fix $m_{H^{\pm}} = 120$ GeV and $|Z| = 0.1$.) We illustrate in Fig. 1 the BR($H^{\pm} \to cb$) and BR($H^{\pm} \to cs$) in a 3HDM. Over the strip between the lines $|XY^*| = 0.7$ and 1.1 (notice that this area does not correspond to the entire region surviving $b \to s\gamma$ constraints), it is clear the predominance of the former over the latter.

As mentioned, both ATLAS and CMS have searched for $t \to H^{\pm}b$ and $H^{\pm} \to cs$. The procedure is simple. Top quarks are produced in pairs via $q\bar{q}, gg \to t\bar{t}$. One (anti)top then decays via $t/\bar{t} \to Wb$, with $W \to e\nu$ or $\mu\nu$. The other (anti)top decays via $t/\bar{t} \to H^{\pm}b$. Hence, $H^{\pm} \to cs$ gives two (non-b quark) jets. Candidate signal events are therefore $b\bar{b}e\nu$ plus two non-b jets. A peak at $m_{H^{\pm}}$ in the invariant mass distribution of non-b jets is the hallmark signal. The main background comes from $t/\bar{t} \to Wb$ and $W \to ud/cs$, which would give a peak at $m_{W^{\pm}}$.

The above procedure (implying two b-tags) is also sensitive to $H^{\pm} \to cb$ decays, with identical efficiency. We simply remark here that applying a third b-tag would improve sensitivity to $H^{\pm} \to cb$ greatly, as the main background from $W \to cb$ has a very small rate. This is made explicit by choosing a b-tagging efficiency $\varepsilon_b = 0.5$, a c-quark mistagging rate $\varepsilon_c = 0.1$ and a light quark (u, d, s) mistagging rate $\varepsilon_j = 0.01$. It follows that the estimated gain in sensitivity is then:

$$\frac{[S/\sqrt{B}]_{\text{btag}}}{[S/\sqrt{B}]_{\not{\text{b}}\text{tag}}} \sim \frac{\varepsilon_b\sqrt{2}}{\sqrt{(\varepsilon_j + \varepsilon_c)}} \sim 2.13. \tag{3.1}$$

Clearly, experimentally, the presence of an additional (tagged) b-quark in the final state makes the analysis more complicated. However, one could perform a kinematical fit to m_t for the two '$bl\nu$'

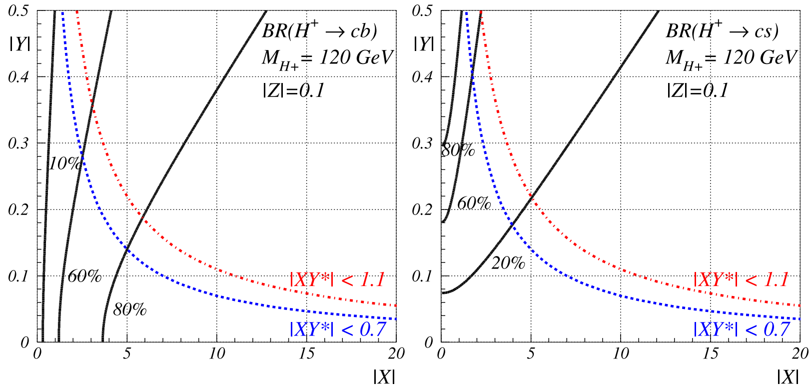

Figure 1: Left: BR($H^{\pm} \to cb$) in the plane $[|X|, |Y|]$. Right: BR($H^{\pm} \to cs$) over the same plane.

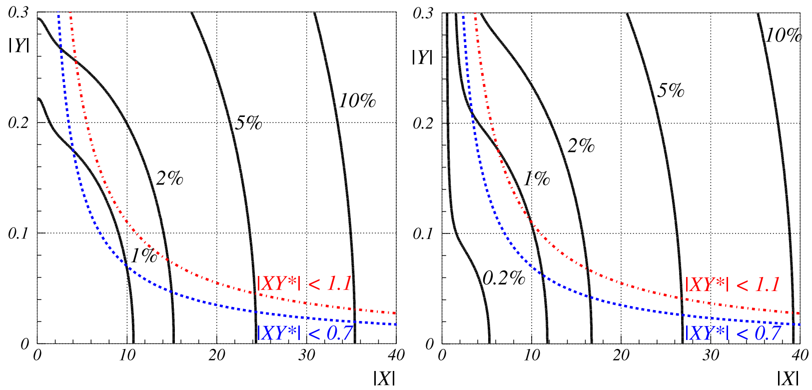

Figure 2: Left: BR($t \to H^{\pm}b$)×BR($H^{\pm} \to cb + cs$) (no b-tag). Right: BR($t \to H^{\pm}b$)×BR($H^{\pm} \to cb$) (b-tag).

($l = e, \mu$) and 'bb jet' systems, where in the latter combinatorics imposes to plot the mass of both 'b jet' subsystems, one of which will yield the $H^{\pm}$ peak.

Current ATLAS and CMS limits for $m_{H^{\pm}} = 120$ GeV are of order BR($t \to H^{\pm}b$) < 0.02 (assuming BR($H^{\pm} \to cs$) $= 100\%$). In the plane of $[|X|, |Y|]$ we now show contours of: 1) BR($t \to H^{\pm}b$)×BR($H^{\pm} \to cb + cs$); 2) BR($t \to H^{\pm}b$)×BR($H^{\pm} \to cb$). This is done in Fig. 2, from where it is clearly visible that constraints from $t \to H^{\pm}b$ are competitive with those from $b \to s\gamma$. In fact, BR($t \to H^{\pm}b$) $< 2\%$ rules out two regions which cannot be excluded via $b \to s\gamma$: 1) $15 < |X| < 40$ and $0 < |Y| < 0.04$; 2) $0 < |X| < 4$ and $0.3 > |Y| > 0.8$. Further, tagging the b-quark from $H^{\pm} \to cb$ would possibly allow sensitivity to BR($t \to H^{\pm}b$) $< 0.5\%$ or less so that $t \to H^{\pm}b$ combined with $H^{\pm} \to cb$ could provide even stronger constraints on the $[|X|, |Y|]$ plane (or perhaps enable discovering $H^{\pm} \to cb$).

4. Conclusions

A Higgs particle has been discovered, maybe there are more such states to be found, including a $H^{\pm}$. We have emphasied here that a light (with mass below m_t) $H^{\pm}$ is possible in a 3HDM wherein $H^{\pm} \to cb$ can be dominant. Based on ongoing analyses by ATLAS and CMS searching for $t \to H^{\pm}b$, $H^{\pm} \to cs$, which are already sensitive to $H^{\pm} \to cb$, we proposed tagging the b-quark from $H^{\pm} \to cb$, procedure that could further improve sensitivity to the fermionic couplings of $H^{\pm}$ (X and Y). This is a straightforward extension of ongoing searches for $t \to H^{\pm}b$ and $H^{\pm} \to cs$ that would enable one to make rather definitive statements regarding the viability of a 3HDM (and also a A2HDM).

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