New Light $H^\pm$ Discovery Channels at the LHC

Abdesslam Arhrib 1, Rachid Benbrik 2, Mohamed Krab 3,* Bouzid Manaut 3, Stefano Moretti 4, Yan Wang 5 and Qi-Shu Yan 6,7

Abstract: A light charged Higgs boson has been searched for at the Large Hadron Collider (LHC) via top (anti)quark decay, i.e., $t \rightarrow bH^-$, if kinematically allowed. In this contribution, we propose new channels for light charged Higgs boson searches via the pair productions $pp \rightarrow H^\pm h/A$ and $pp \rightarrow H^++H^-$ at the LHC in the context of the Two-Higgs Doublet Model (2HDM) Type-I. By focusing on a case where the heavy H state is the Standard Model (SM)-like one already observed, we investigate the production of the aforementioned charged Higgs bosons and their bosonic decay channels, namely, $H^\pm \rightarrow W^\mp h$ and/or $H^\pm \rightarrow W^\mp A$. We demonstrate that such production and decay channels can yield substantial alternative discovery channels for $H^\pm$ bosons at the LHC. Finally, we propose eight benchmark points (BPs) to motivate the search for such signatures.

Keywords: physics beyond the Standard Model, charged Higgs boson, Large Hadron Collider

1. Introduction

With the discovery of a 125 GeV Higgs boson at the Large Hadron Collider LHC [1,2] in 2012, the verification of the Standard Model (SM) of particle physics was completed. However, despite its agreement with the experiment, the SM is certainly not an ultimate theory. Thus, any extension of the SM is well motivated. One of the simplest and most straightforward extensions of the SM, which deserves particular attention, is the Two-Higgs Doublet Model (2HDM). The model contains two Higgs doublet fields that can generate masses for all (massive) fermions and gauge bosons. The scalar sector of 2HDM contains two Charge-Parity (CP)-even Higgs bosons, $h$ and $H$ (conventionally the mass of $h$ is less than the mass of $H$, $M_h < M_H$), one CP-odd Higgs boson, $A$, and a pair of charged Higgs bosons, $H^\pm$ (in addition to the fermions and gauge bosons of the SM).

At the LHC, a light $H^\pm$ boson has been searched for via the decay of a top (anti)quark ($t\bar{t}$) if kinematically allowed. Typically, this process can be calculated using the usual method of factorizing the production process of proton–proton collisions, $pp \rightarrow t\bar{t}$, times the decay one, $t \rightarrow bH^-$, in the Narrow-Width Approximation (NWA). However, if the mass of the charged Higgs boson approaches the maximum, this approximation becomes invalid, and
thus it is quite appropriate to target the process $pp \rightarrow t\bar{b}H^-$ to search instead [3]. This contribution revisits these two $H^\pm$ production channels for the upcoming LHC Run 3 and compares them to the pair productions $pp \rightarrow H^\pm h/A$ and $pp \rightarrow H^+H^-$ in the 2HDM Type-I. We show that signatures from such pair productions followed by $H^\pm \rightarrow W^\pm h$ and/or $H^\pm \rightarrow W^\pm A$ decays may lead to new discovery channels for light charged Higgs bosons searches at the LHC.

The contribution is organised as follows. First, we briefly describe the 2HDM and its Yukawa scenarios in Section 2. In Section 3 we explain the scan of the parameter space and the applied constraints. We discuss the numerical results and the selected Benchmark Points (BPs) in both Sections 4 and 5, and we finally conclude in Section 6.

2. The 2HDM

The $CP$-conserving 2HDM scalar potential, which is renormalisable and invariant under $SU(2)_L \otimes U(1)_Y$ with a softly broken $Z_2$ symmetry, can be written as

$$V(\phi_1, \phi_2) = m_{11}^2(\phi_1^\dagger \phi_1) + m_{22}^2(\phi_2^\dagger \phi_2) - |m_{12}^2(\Phi_1^\dagger \phi_2) + h.c.| + \frac{1}{2} \lambda_1(\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2} \lambda_5[(\phi_1^\dagger \phi_2)^2 + h.c.]$$

where $m_{11}^2$, $m_{22}^2$ and $m_{12}^2$ are squared mass parameters, and $\lambda_{1-5}$ are dimensionless coupling parameters. $\phi_{1,2}$ are the Higgs doublet fields with $v_{1,2}$ their respective Vacuum Expectation Values (VEVs) such that $v_1^2 + v_2^2 = v^2 \approx (246 \text{ GeV})^2$ (where $v$ is the SM Higgs VEV). Using the two minimization conditions of the potential, $m_{11}^2$, $m_{22}^2$, and $\lambda_{1-5}$ can be substituted by $v_{1,2}$, the physical mass eigenstates and $\sin(\beta - \alpha)$, where $\alpha$ and $\beta$ are the mixing angles. Thus, we are left with only 7 independent parameters:

$$M_h, M_H, M_A, M_{H^\pm}, \alpha, \tan \beta \text{ and } m_{12}^2.$$  \hspace{1cm} (2)

In the Yukawa sector, though, the Flavor Changing Neutral Currents (FCNCs) can be induced at the tree level if both the Higgs doublets of the general 2HDM couple to all fermions. To avoid FCNCs, which would be inconsistent with the experiment, a $Z_2$ symmetry can be enforced in such a way that each fermion type ($u, d, l$) acquires mass from one of the Higgs doublets. Thus, there are four possible Types of 2HDM [4]. In the 2HDM Type-I, the fermions acquire mass via the interaction with the doublet $\phi_2$ as in the SM. In the 2HDM Type-X (or lepton-specific), the charged leptons acquire mass from $\phi_1$ while all quarks receive mass from $\phi_2$. In the 2HDM Type-II, up-type quarks acquire mass through their interaction with $\phi_1$ while down-type quarks and charged leptons acquire mass through their interaction with $\phi_2$. Finally, in the 2HDM Type-Y (or flipped), the up-type quarks and charged leptons receive mass from $\phi_2$ while down-type quarks receive mass from $\phi_1$. Here, though, we will only consider the 2HDM Type-I.

The Yukawa Lagrangian which describes the coupling of the neutral and charged Higgs bosons to quarks and leptons can be written as [4]:

$$-\mathcal{L}_{\text{Yukawa}} = \sum_{f=u,d,l} \left( \frac{mf}{\sqrt{2}v} \kappa^h_f \bar{f}fh + \frac{mf}{\sqrt{2}v} \kappa^H_f \bar{f}fh \right) + \left( \frac{V_{ud}^L}{\sqrt{2}v}(u_d \kappa^A_d P_L + m_d \kappa^A_d P_R) dH^+ + \frac{m_l \kappa^A_l}{\sqrt{2}v} \bar{\nu}_l l_R h^+ + H.c. \right),$$

(3)
Table 1: Yukawa couplings of the neutral Higgs bosons $h$, $H$ and $A$ to quarks and leptons in 2HDM Type-I.

|   | $\kappa_u^2$ | $\kappa_d^2$ | $\kappa_l^2$ |
|---|---|---|---|
| $h$ | $\cos \alpha / \sin \beta$ | $\cos \alpha / \sin \beta$ | $\cos \alpha / \sin \beta$ |
| $H$ | $\sin \alpha / \sin \beta$ | $\sin \alpha / \sin \beta$ | $\sin \alpha / \sin \beta$ |
| $A$ | $\cot \beta$ | $- \cot \beta$ | $- \cot \beta$ |

where $m_f$ ($f = u, d, l$) are the masses of the fermions and $\kappa_f^S$ are the Yukawa couplings, which are given in Table 1 for Type-I. $V_{ud}$ denotes the Cabibbo-Kobayashi-Maskawa (CKM) matrix element, and $m_u$ and $m_d$ are the masses of up and down quarks, respectively. $P_{L,R}$ represent the left- and right-handed projection operators.

3. Parameter Space Scans

In what follows, we perform a broad scan of the following 2HDM Type-I parameter space, where the H state is assumed to be the observed SM-like Higgs at the LHC in 2012 with mass fixed to 125 GeV,

$$M_H = 10 - 120 \text{ GeV}; \quad M_{H^\pm} = 80 - 170 \text{ GeV}$$

$$\tan \beta = 2 - 60; \quad \sin(\beta - \alpha) = (-0.3) - (-0.05); \quad m_{t2}^2 = 0 - M_{H^\pm}^2 \sin \beta \cos \beta.$$ (4)

In the scan, the theoretical and experimental constraints are taken into account. 2HDMC [5] is used to check unitarity, perturbativity, vacuum stability and the electroweak oblique parameters ($S$, $T$ and $U$). HiggsBounds-5.9.0 [6] and HiggsSignals-2.6.0 [7] are both used to enforce the exclusion bounds at 95% Confidence Level (CL) from Higgs boson searches at LEP, Tevatron and LHC, and to check agreement with SM-like Higgs boson measurements, respectively. Constraints from flavour physics are tested using the public code SuperIso v4.1 [8].

4. Results

In the present contribution, we target the signatures of light charged Higgs bosons from processes involving top quarks and di-Higgs processes, i.e., $gg, q\bar{q} \to t\bar{t} \to tbH^- + \text{c.c.}$ (NWA), $gg, q\bar{q} \to t\bar{t}bH^- + \text{c.c.}, q\bar{q} \to H^+H^- + \text{c.c.}, q\bar{q} \to H^+H^- + \text{c.c.}$. Taking into account their either $W^\pm h$ or $W^\pm A$ decays, where the $h$ and $A$ decay into a pair of bottom quarks. Relevant LHC signatures are summarised in Table 2.

| | Higgs production and decay process |
|---|---|
| $\sigma_{ht}(2W + 4b)$ | $2 \sigma_{tt} \times \text{BR}(t \to bH^+) \times \text{BR}(\bar{t} \to bW^-) \times \text{BR}(H^\pm \to W^\pm h_1) \times \text{BR}(h_1 \to bb)$ |
| $\sigma_{ht}(2W + 4b)$ | $\sigma(pp \to tbH^-) \times \text{BR}(t \to bW^+) \times \text{BR}(H^\pm \to W^\pm h_1) \times \text{BR}(h_1 \to bb)$ |
| $\sigma_{ht}(2W + 4b)$ | $\sigma(pp \to H^+H^-) \times \text{BR}(H^\pm \to W^\pm h_1)^2 \times \text{BR}(h_1 \to bb)^2$ |
| $\sigma_{ht}(W + 4b)$ | $\sigma(pp \to H^+h_1) \times \text{BR}(H^\pm \to W^\pm h_1) \times \text{BR}(h_1 \to bb)^2$ |

Table 2: Charged Higgs bosons production modes and their final states. $\sigma_{tt}$ denotes the production process of proton-proton collisions, $pp \to t\bar{t}$, and BR refers to the branching ratio. Here, $h_1$ ($i = 1,2$) refers to $h_1 = h$ and $h_2 = A$.  

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1 We are only interested here in the 4l final states. See Ref. [9] for the 2l2τ and 4τ final states.
Figure 1. Total cross section $\sigma(pp \rightarrow H^{\pm}h) \times \text{BR}(H^{\pm} \rightarrow W^{\pm}h) \times \text{BR}(h \rightarrow b\bar{b})^2$ are showed against those $2 \sigma_{t\bar{t}} \times \text{BR}(t \rightarrow bH^+) \times \text{BR}(\bar{t} \rightarrow \bar{b}W^-) \times \text{BR}(H^{\pm} \rightarrow W^{\pm}h) \times \text{BR}(h \rightarrow b\bar{b})$ (left) and $\sigma(pp \rightarrow t\bar{b}H^-) \times \text{BR}(t \rightarrow bW^+) \times \text{BR}(H^{\pm} \rightarrow W^{\pm}h) \times \text{BR}(h \rightarrow b\bar{b})$ (right). The red points refer to the total cross section $\sigma(pp \rightarrow H^+H^-) \times \text{BR}(H^\pm \rightarrow W^{\pm}h)^2 \times \text{BR}(h \rightarrow b\bar{b})^2$ which are also large compared to the two top production processes. With the mass of charged Higgs boson, $M_{H^\pm}$, indicated by the colour map.

Figure 2. Total cross section $\sigma(pp \rightarrow H^{\pm}A) \times \text{BR}(H^{\pm} \rightarrow W^{\pm}A) \times \text{BR}(A \rightarrow b\bar{b})^2$ are showed against those $2 \sigma_{t\bar{t}} \times \text{BR}(t \rightarrow bH^+) \times \text{BR}(\bar{t} \rightarrow \bar{b}W^-) \times \text{BR}(H^{\pm} \rightarrow W^{\pm}A) \times \text{BR}(A \rightarrow b\bar{b})$ (left) and $\sigma(pp \rightarrow t\bar{b}H^-) \times \text{BR}(t \rightarrow bW^+) \times \text{BR}(H^{\pm} \rightarrow W^{\pm}A) \times \text{BR}(A \rightarrow b\bar{b})$ (right). The red points refer to the total cross section $\sigma(pp \rightarrow H^+H^-) \times \text{BR}(H^\pm \rightarrow W^{\pm}A)^2 \times \text{BR}(A \rightarrow b\bar{b})^2$ which are also large compared to the two top production processes. With the mass of charged Higgs boson, $M_{H^\pm}$, indicated by the colour map.

In what follows, we show the production rates of relevant final states from different scenarios. In Figure 1, we compare $W + 4b$ and $2W + 4b$ signatures from $pp \rightarrow H^\pm h \rightarrow W^\pm hh$ and $pp \rightarrow H^+H^- \rightarrow W^+W^- hh$ with $\sigma_{t\bar{t}}(2W + 4b)$ (left panel) and $\sigma_{t}(2W + 4b)$ (right panel) ones from the two top (anti)quark processes. Analogously to Figure 1, the same signatures from $pp \rightarrow H^{\pm}A \rightarrow W^{\pm}AA$ and $pp \rightarrow H^+H^- \rightarrow W^+W^- AA$ are compared with those from processes involving the top (anti)quark in Figure 2. From these plots, it is therefore clear that signatures from di-Higgs processes can yield substantial alternative discovery modes for charged Higgs bosons at the LHC in the context of the 2HDM Type I.
5. Benchmark Points

In order to encourage future searches for light charged Higgs boson via such new channels, we propose 8 BPs for the 2HDM Type-I. Such BPs are presented in Table 3. In our selected BPs, notice that we take also into account the case where the mass of the charged Higgs is larger than the top one. The total cross section of the final states $2W + 4b$ and $W + 4b$ from both di-Higgs and the two top (anti)quarks are given herein.

In BP1, for instance, the cross-section rate of the $2W + 4b$ signature from the top (anti)quark processes can only reach $5\text{ fb}^2$, whereas the cross-section rate of the $2W + 4b$ signature from the pair production of $H^\pm$ bosons is $\approx 23.1\text{ fb}$. Moreover, the cross-section rate $\sigma(W + 4b)$ from the $h/A$-associated $H^\pm$ production can reach values of around $174\text{ fb}$, which are much larger than the rates of $\sigma(2W + 4b)$ from charged Higgs pair production. This behavior is well illustrated in Figure 3. For other BPs, the cross-section rates of the $2W + 4b$ and $W + 4b$ signatures from different production processes are also shown in Figure 3.

| Parameters | BP1 | BP2 | BP3 | BP4 | BP5 | BP6 | BP7 | BP8 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| $M_{h}$   | 91.00 | 96.84 | 103.34 | 99.61 | 95.57 | 94.00 | 94.00 | 94.00 |
| $M_{H}$   | 125.00 | 125.00 | 125.00 | 125.00 | 125.00 | 125.00 | 125.00 | 125.00 |
| $M_{A}$   | 102.04 | 112.35 | 93.80 | 88.98 | 94.41 | 105.00 | 105.00 | 105.00 |
| $M_{H^\pm}$ | 167.02 | 166.34 | 161.02 | 169.46 | 167.02 | 176.00 | 186.00 | 196.00 |
| $\sin(\beta - \alpha)$ | $-0.18$ | $-0.11$ | $-0.19$ | $-0.06$ | $-0.09$ | $-0.09$ | $-0.09$ | $-0.09$ |
| $\tan \beta$ | 40.87 | 58.17 | 54.79 | 39.10 | 32.44 | 30.00 | 30.00 | 30.00 |
| $m_{t_2}^2$ | 204.22 | 161.85 | 196.73 | 252.94 | 277.81 | 294.00 | 294.00 | 294.00 |
| $\sigma_{2t}^2(2W + 4b)$ | 2.30 | 1.65 | 2.06 | $-$ | 2.42 | $-$ | $-$ | $-$ |
| $\sigma_{2t}^t(2W + 4b)$ | 3.85 | 2.35 | 2.26 | 0.85 | 3.84 | 5.03 | 4.68 | 3.52 |
| $\sigma_{2A}^2(2W + 4b)$ | 0.70 | 0.25 | 4.63 | $-$ | 2.47 | $-$ | $-$ | $-$ |
| $\sigma_{2t}^t(2W + 4b)$ | 1.17 | 0.36 | 5.07 | 3.03 | 3.92 | 0.83 | 0.44 | 1.08 |
| $\sigma_{2b}^2(2W + 4b)$ | 13.58 | 15.99 | 2.29 | 0.97 | 5.38 | 14.08 | 13.27 | 7.35 |
| $\sigma_{2b}^t(2W + 4b)$ | 4.13 | 2.44 | 5.14 | 3.46 | 5.50 | 2.32 | 1.25 | 2.24 |
| $\sigma_{2A}^2(2W + 4b)$ | 1.26 | 0.37 | 11.55 | 12.35 | 5.62 | 0.38 | 0.12 | 0.68 |
| $\sigma_{2b}^t(2W + 4b)$ | 4.13 | 2.44 | 5.14 | 3.46 | 5.50 | 2.32 | 1.25 | 2.24 |
| $\sigma_{2h}^2(W + 4b)$ | 75.88 | 77.61 | 26.47 | 17.68 | 46.00 | 73.25 | 68.00 | 48.81 |
| $\sigma_{2h}^t(W + 4b)$ | 23.07 | 11.86 | 59.44 | 63.04 | 47.00 | 12.07 | 6.42 | 14.90 |
| $\sigma_{2A}^2(W + 4b)$ | 17.48 | 6.12 | 64.39 | 69.22 | 43.51 | 9.16 | 4.91 | 11.45 |
| $\sigma_{2h}^t(W + 4b)$ | 57.51 | 40.06 | 28.68 | 19.41 | 42.59 | 55.59 | 52.02 | 37.51 |

Table 3: Mass spectra (in GeV), mixing angles and cross sections (in fb) for the selected BPs. (Notice that all these parameters have been discussed above.)

6. Conclusions

In this contribution, we have investigated the production of charged Higgs bosons through $pp \to H^\pm h/A$ and $pp \to H^+ H^-$ at the LHC with $\sqrt{s} = 14\text{ TeV}$ in the 2HDM Type-I, after satisfying all theoretical and experimental constraints. By focusing on $H^\pm \to W^\pm h/A$ decays, we have suggested the $2W + 4b$ and $W + 4b$ signatures as possible alternative discovery modes. We have demonstrated that such signatures could well be the most promising discovery for light $H^\pm$ states. Thus, to motivate experimentalists to search for these, we have proposed 8 BPs amenable to experimental investigation.

\footnote{we refer here to the $pp \to t\bar{t}H^- + c.c.$ rates}
Figure 3. Cross section rates of $2W + 4b$ and $W + 4b$ signatures for the selected BPs.

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