Article

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

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Abstract: A light charged Higgs boson has been searched for at the Large Hadron Collider (LHC) via top (anti)quark decay, i.e., $t \to bH^+$, if kinematically allowed. In this contribution, we propose new channels for light charged Higgs boson searches via the pair productions $pp \to H^\pm h/A$ and $pp \to H^+H^-$ 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, $H^\pm \to W^\pm h$ and/or $H^\pm \to W^\pm A$. 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, $pp \to t\bar{t}$, times the decay one, $\bar{t} \to \bar{b}H^-$, 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 $pp \to t\bar{b}H^-$ 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 $pp \to H^\pm h/A$ and $pp \to H^+H^-$ 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 organized 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 Sections 4 and 5, and we finally conclude in Section 6.

2. The 2HDM

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

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

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

$$
M_h, M_H, M_A, M_{H^{\pm}}, \alpha, \tan\beta \text{ and } m_{12}^2.
\tag{2}
$$

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 2HDM Type-I, the fermions acquire mass via the interaction with the doublet ϕ_2 as in the SM. In 2HDM Type-X (or lepton-specific), the charged leptons acquire mass from ϕ_1 while all quarks receive mass from ϕ_2. In 2HDM Type-II, up-type quarks acquire mass through their interactions with ϕ_2, and down-type quarks and charged leptons acquire mass through their interactions with ϕ_1. Finally, in 2HDM Type-Y (or flipped), the up-type quarks and charged leptons receive mass from ϕ_2, and down-type quarks receive mass from ϕ_1. Here, though, we only consider 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]:

$$
\begin{aligned}
-\mathcal{L}_{\text{Yukawa}} = {} & \sum_{f=u,d,l} \left(\frac{m_f}{v}\kappa_f^h \bar{f}fh + \frac{m_f}{v}\kappa_f^H \bar{f}fH - i\frac{m_f}{v}\kappa_f^A \bar{f}\gamma_5 fA \right) + \\
& \left(\frac{V_{ud}}{\sqrt{2}v}\bar{u}(m_u\kappa_u^A P_L + m_d\kappa_d^A P_R)dH^+ + \frac{m_l\kappa_l^A}{\sqrt{2}v}\bar{v}_L l_R H^+ + H.c. \right),
\end{aligned}
\tag{3}
$$

where m_f $(f = u, d, l)$ are the masses of the fermions and κ_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-handed and right-handed projection operators.

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

	κ_u^S	κ_d^S	κ_ℓ^S
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	$\cot\beta$	$-\cot\beta$	$-\cot\beta$

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:

$$M_h = 10\text{–}120\,\text{GeV};\quad M_H = 125\,\text{GeV};\quad M_A = 10\text{–}120\,\text{GeV};\quad M_{H^\pm} = 80\text{–}170\,\text{GeV}$$

$$\tan\beta = 2\text{–}60;\quad \sin(\beta-\alpha) = (-0.3)\text{–}(-0.05);\quad m_{12}^2 = 0 - M_H^2\sin\beta\cos\beta. \tag{4}$$

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 the 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., $gg, q\bar{q} \to t\bar{t} \to t\bar{b}H^-$ + c.c. (NWA), $gg, q\bar{q} \to t\bar{b}H^-$ + c.c., $q\bar{q} \to H^+H^-$ plus $q\bar{q}' \to H^+h/A$ + c.c. taking into account their either $W^\pm h$ or $W^\pm A$ decays, where h and A decay into a pair of bottom quarks. (We are only interested here in the $4b$ final states; see [9] for the $2b2\tau$ and 4τ final states.) Relevant LHC signatures are summarized in Table 2.

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

	Higgs Production and Decay Process
$\sigma_{2t}^{h_i}(2W+4b)$	$2\,\sigma_{t\bar{t}} \times \text{BR}(t \to bH^+) \times \text{BR}(\bar{t} \to \bar{b}W^-) \times \text{BR}(H^\pm \to W^\pm h_i) \times \text{BR}(h_i \to b\bar{b})$
$\sigma_t^{h_i}(2W+4b)$	$\sigma(pp \to t\bar{b}H^-) \times \text{BR}(t \to bW^+) \times \text{BR}(H^\pm \to W^\pm h_i) \times \text{BR}(h_i \to b\bar{b})$
$\sigma_{h_i}^{h_i}(2W+4b)$	$\sigma(pp \to H^+H^-) \times \text{BR}(H^\pm \to W^\pm h_i)^2 \times \text{BR}(h_i \to b\bar{b})^2$
$\sigma_{h_i}^{h_i}(W+4b)$	$\sigma(pp \to H^\pm h_i) \times \text{BR}(H^\pm \to W^\pm h_i) \times \text{BR}(h_i \to b\bar{b})^2$

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 $pp \to H^\pm h \to W^\pm hh$ and $pp \to H^+H^- \to W^+W^-hh$ with $\sigma_{2t}(2W+4b)$ (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 $pp \to H^\pm A \to W^\pm AA$ and $pp \to H^+H^- \to W^+W^-AA$ 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.
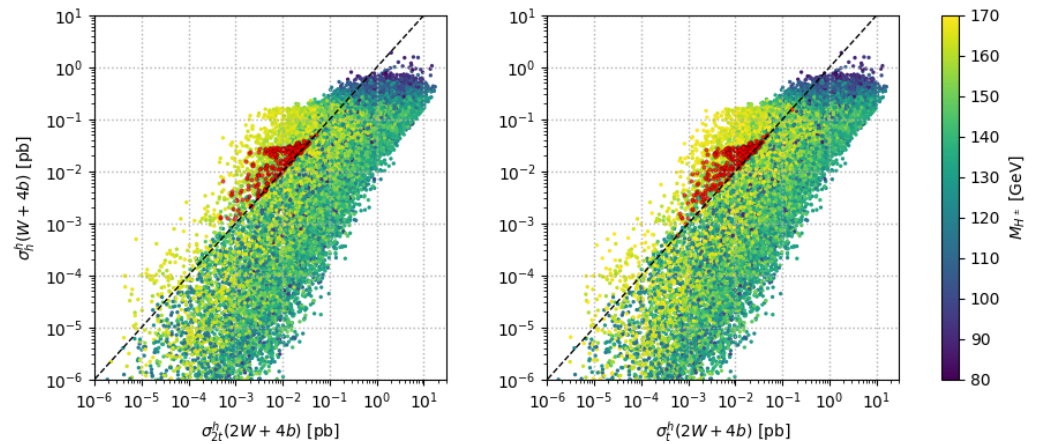
Figure 1. Total cross-sections $\sigma(pp \to H^{\pm}h) \times \mathrm{BR}(H^{\pm} \to W^{\pm}h) \times \mathrm{BR}(h \to b\bar{b})^2$ are shown against those of $2\,\sigma_{t\bar{t}} \times \mathrm{BR}(t \to bH^+) \times \mathrm{BR}(\bar{t} \to \bar{b}W^-) \times \mathrm{BR}(H^{\pm} \to W^{\pm}h) \times \mathrm{BR}(h \to b\bar{b})$ **(left)** and $\sigma(pp \to t\bar{b}H^-) \times \mathrm{BR}(t \to bW^+) \times \mathrm{BR}(H^{\pm} \to W^{\pm}h) \times \mathrm{BR}(h \to b\bar{b})$ **(right)**. The red points refer to the total cross-sections $\sigma(pp \to H^+H^-) \times \mathrm{BR}(H^{\pm} \to W^{\pm}h)^2 \times \mathrm{BR}(h \to b\bar{b})^2$, which are also large compared to the two top production processes. The mass of the charged Higgs boson, $M_{H^{\pm}}$, is indicated by the color map.
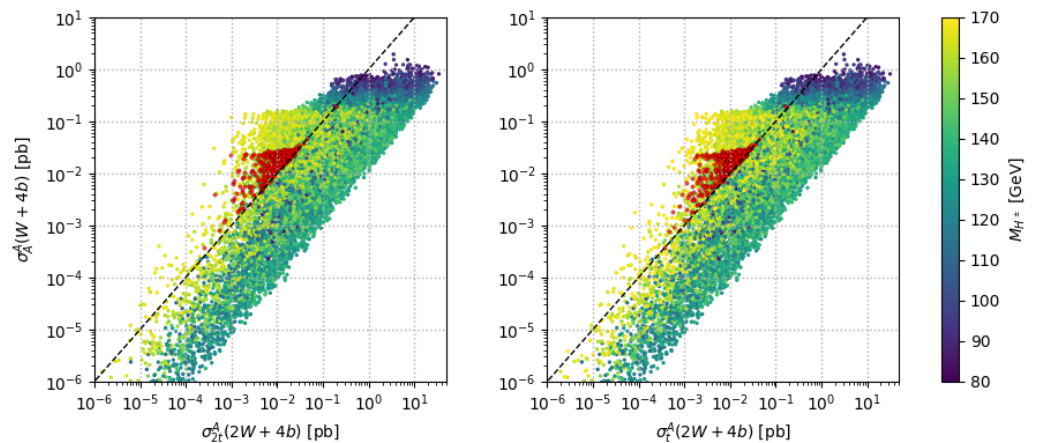
Figure 2. Total cross-sections of $\sigma(pp \to H^{\pm}A) \times \mathrm{BR}(H^{\pm} \to W^{\pm}A) \times \mathrm{BR}(A \to b\bar{b})^2$ are shown against those of $2\,\sigma_{t\bar{t}} \times \mathrm{BR}(t \to bH^+) \times \mathrm{BR}(\bar{t} \to \bar{b}W^-) \times \mathrm{BR}(H^{\pm} \to W^{\pm}A) \times \mathrm{BR}(A \to b\bar{b})$ **(left)** and $\sigma(pp \to t\bar{b}H^-) \times \mathrm{BR}(t \to bW^+) \times \mathrm{BR}(H^{\pm} \to W^{\pm}A) \times \mathrm{BR}(A \to b\bar{b})$ **(right)**. The red points refer to the total cross-sections $\sigma(pp \to H^+H^-) \times \mathrm{BR}(H^{\pm} \to W^{\pm}A)^2 \times \mathrm{BR}(A \to b\bar{b})^2$ which are also large compared to the two top production processes. The mass of the charged Higgs boson, $M_{H^{\pm}}$, is indicated by the color map.

5. Benchmark Points

In order to encourage future searches for light charged Higgs boson via such new channels, we propose eight BPs for 2HDM Type-I. These 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 that of the top one. The total cross-sections 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 fb (we refer here to the $pp \to t\bar{b}H^-$ + c.c. rates), whereas the cross-section rate of the $2W + 4b$ signature from the pair production of $H^{\pm}$ bosons is $\approx$23.1 fb. Moreover, the cross-section rate $\sigma(W + 4b)$ from the h/A-associated $H^{\pm}$ production can reach values of around 174 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.

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).

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_{12}^2	204.22	161.85	196.73	252.94	277.81	294.00	294.00	294.00
$\sigma_{2t}^h(2W + 4b)$	2.30	1.65	2.06	—	2.42	—	—	—
$\sigma_t^h(2W + 4b)$	3.85	2.35	2.26	0.85	3.84	5.03	4.68	3.52
$\sigma_{2t}^A(2W + 4b)$	0.70	0.25	4.63	—	2.47	—	—	—
$\sigma_t^A(2W + 4b)$	1.17	0.36	5.07	3.03	3.92	0.83	0.44	1.08
$\sigma_h^h(2W + 4b)$	13.58	15.99	2.29	0.97	5.38	14.08	13.27	7.35
$\sigma_A^h(2W + 4b)$	4.13	2.44	5.14	3.46	5.50	2.32	1.25	2.24
$\sigma_A^A(2W + 4b)$	1.26	0.37	11.55	12.35	5.62	0.38	0.12	0.68
$\sigma_h^A(2W + 4b)$	4.13	2.44	5.14	3.46	5.50	2.32	1.25	2.24
$\sigma_h^h(W + 4b)$	75.88	77.61	26.47	17.68	46.00	73.25	68.00	48.81
$\sigma_A^h(W + 4b)$	23.07	11.86	59.44	63.04	47.00	12.07	6.42	14.90
$\sigma_A^A(W + 4b)$	17.48	6.12	64.39	69.22	43.51	9.16	4.91	11.45
$\sigma_h^A(W + 4b)$	57.51	40.06	28.68	19.41	42.59	55.59	52.02	37.51
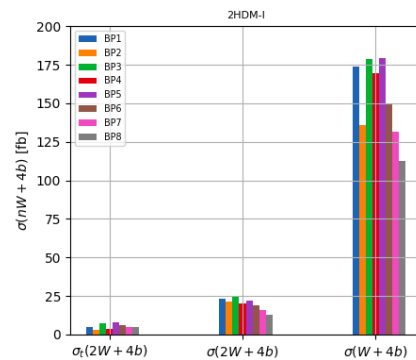
Figure 3. Cross-section rates of $2W + 4b$ and $W + 4b$ signatures for the selected BPs.

6. Conclusions

In this contribution, we have investigated the production of charged Higgs bosons through $pp \rightarrow H^\pm h/A$ and $pp \rightarrow H^+ H^-$ at the LHC with $\sqrt{s} = 14$ TeV in 2HDM Type-I, after satisfying all theoretical and experimental constraints. By focusing on $H^\pm \rightarrow W^\pm h/A$ 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 eight BPs amenable to experimental investigation.

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