

Light charged Higgs boson in $H^\pm h$ associated production at the LHC

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Abstract. We investigate the light charged Higgs boson production via $pp \rightarrow H^\pm h$ at the Large Hadron Collider (LHC) in the Two-Higgs Doublet Model (2HDM) type-I. By focusing on a scenario where H is the observed Higgs boson of mass 125 GeV, we study the aforementioned Higgs boson production channel and explore its bosonic decay $H^\pm \rightarrow W^\pm h$. The latter can have a sizable rate that possibly dominates, over the fermionic decay channels, in several regions of the viable parameter space. We demonstrate that the production process $pp \rightarrow H^\pm h$ followed by $H^\pm \rightarrow W^\pm h$ could be the most promising experimental avenue to search for light H^\pm at the LHC.

1. Introduction

The Standard Model (SM) is the most successful framework that describes the physics of elementary particles. In 2012, a Higgs boson was discovered at the Large Hadron Collider (LHC) [1, 2], which is the only required puzzle piece to confirm, in particular, the mechanism of ElectroWeak Symmetry Breaking (EWSB) and thereby the SM. However, the origin of such a mechanism, which explains the dynamic behind the masses of fermions and gauge bosons, is still a mystery. There is, moreover, no theoretical reason that the Higgs sector is composed of only one Higgs doublet field. A possible non-minimal Higgs sector with more than one scalar doublet, e.g. the SM with an extra singlet, doublet, and/or triplet, might take place. One of the

most important features in models with an extra doublet or triplet is the apparition of charged Higgs bosons, which their discovery would be a clear hint of new physics beyond the SM.

One of the simplest higher Higgs representations beyond the SM, containing a charged Higgs boson, which merits specific attention, is the Two-Higgs Doublet Model (2HDM). The latter is extended by an additional Higgs doublet in order to generate masses for fermions and gauge bosons. The scalar sector of the 2HDM predicts in their spectrum three neutral Higgs states (h , H and A) and a pair of charged Higgs states (H^\pm). One of the two scalars h or H is required to mimic the SM Higgs boson in the so-called *alignment limit* [3, 4, 5, 6]. Such a requirement, indeed, puts rather stringent limits on the 2HDM parameter space. Further bounds arise from direct searches at collider experiments and indirect searches from EW precision measurement as well as flavor physics set, moreover, additional bounds on 2HDM.

At the LHC, two conventional ways have been adopted to search for charged Higgs boson, in which both ATLAS and CMS collaborations almost target the fermionic decay channels in their programs to look for H^\pm . When $M_{H^\pm} < m_t - m_b$, a charged Higgs boson has been searching for through the top pair (anti)quark production and decay, $pp \rightarrow t\bar{t} \rightarrow W^\mp H^\pm b\bar{b}$, with H^\pm decaying into a pair of fermions ($\tau\nu$ and cs). In case the mass of H^\pm exceeds the mass of top and bottom quarks, the dominant production channel is predicted to be the one associated with t and b (H^+tb or the equivalent anti-top mode), with $H^+ \rightarrow tb$ or $H^+ \rightarrow \tau^+\nu$. Nevertheless, bosonic decay channels are expected to be naturally dominant over fermionic decays in 2HDM type-I (with branching ratios almost above 99%) [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20], i.e. the decay of H^\pm into a W^\pm and a neutral Higgs boson. Our study is dedicated to light charged Higgs boson produced via $pp \rightarrow H^\pm h$ followed by $H^\pm \rightarrow W^\pm h$, where h decays into a pair of bottom quarks or tau leptons. The $h \rightarrow \gamma\gamma$ channel will also be investigated here when the h state becomes fermiophobic, in which the coupling of h to fermions is suppressed.

The paper is organized as follows. In Section 2, we introduce the theoretical framework. In Section 3, we present the adopted parameter space scans and applied constraints. In section 4, we discuss our numerical result. We conclude in Section 5.

2. The 2HDM

The most popular and motivated extension of the SM, which merits special attention, is the Two-Higgs Doublet Model (2HDM). The latter contains two Higgs doublet fields $\Phi_{1,2}$ with hypercharge $Y_{\Phi_{1,2}} = 1$. The 2HDM scalar potential invariant under $SU(2)_L \otimes U(1)_Y$ has the following form [21]:

$$\begin{aligned}
V(\Phi_1, \Phi_2) &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\
&+ \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
&+ \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\
&+ \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}, \quad (1)
\end{aligned}$$

where m_{11}^2 , m_{22}^2 and $\lambda_{1,2,3,4}$ are, in general, real. While m_{12}^2 and $\lambda_{5,6,7}$ could be complex to enable CP-violation in the Higgs sector. The natural flavor conservation requirement in the Yukawa sector enforces a Z_2 symmetry to the scalar potential. Such a requirement would lead to $m_{12}^2 = \lambda_{6,7} = 0$. However, one can allow for a soft violation of the discrete symmetry by keeping the m_{12}^2 term. In the present study, we shall consider the CP-conserving 2HDM with a softly broken Z_2 symmetry, in which $\lambda_{6,7} = 0$ and $m_{12}^2 \neq 0$.

In the 2HDM, there exist height degrees of freedom. Three of them are absorbed by W^\pm and Z bosons when EWSB occurs. The rest of the degrees of freedom are the five physical Higgs states mentioned above, i.e. two CP-even h and H , a CP-odd A and a pair of charged Higgs H^\pm .

Under the two minimization conditions, m_{11}^2 and m_{22}^2 can be substituted by $v_{1,2}$ (which are the vacuum expectation values (vevs) of $\Phi_{1,2}$). Furthermore, $\lambda_{1,2,3,4,5}$ can be traded for M_{h,H,A,H^\pm} and $\sin(\beta - \alpha)$, where β and α are the mixing angles. Thus, only seven independent parameters are left: $M_h, M_H, M_A, M_{H^\pm}, \sin(\beta - \alpha), \tan\beta$ and m_{12}^2 .

In the Yukawa sector, if we enable EWSB similar to the SM (both Higgs doublets couple to fermions) we will end up with FCNCs in such a sector at tree level. The latter can be avoided by forcing the Z_2 symmetry such that each fermion type interacts only with one of the Higgs doublets. Thus, there are four possible types of Yukawa textures [21]: type-I, type-II, type-X (or lepton-specific) and type-Y (or flipped). In the present study, we shall focus on type-I 2HDM, which Φ_2 doublet couples to all fermions in order to generate their masses.

The couplings of neutral and charged scalars to fermions can be described by the Yukawa Lagrangian [21],

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

where $v^2 = v_1^2 + v_2^2 \simeq (246 \text{ GeV})^2$ and V_{ud} is the CKM matrix element. $P_{L,R}$ refer to left- and right-handed projection operators. κ_f^S are the Yukawa couplings, which are given in Table 1 for the four types of 2HDM.

Table 1: Higgs couplings to fermions for the four types of 2HDM.

	κ_u^h	κ_d^h	κ_l^h	κ_u^H	κ_d^H	κ_l^H	κ_u^A	κ_d^A	κ_l^A
type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	c_β/s_β	$-c_\beta/s_\beta$	$-c_\beta/s_\beta$
type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	c_β/s_β	s_β/c_β	s_β/c_β
type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	c_β/s_β	$-c_\beta/s_\beta$	s_β/c_β
type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	c_β/s_β	s_β/c_β	$-c_\beta/s_\beta$

3. 2HDM scans and constraints

We perform a random scan over the 2HDM parameter space using the program 2HDMC-1.8.0 [22]. While we assume that H is the observed SM-like Higgs fixing its mass to 125.09 GeV, we demand M_h to lie in the 15 and 120 GeV range. We further scan M_A within the range between 15 and 200 GeV, M_{H^\pm} between 80 and 170, $\sin(\beta - \alpha)$ between -0.5 and 0.5 , $\tan\beta$ between 2 and 50, and m_{12}^2 between 0 and $m_h^2 \sin\beta \cos\beta$. During the scan, we require that each parameter point complies with the following theoretical and experimental constraints:

- Unitarity, perturbativity and vacuum stability using the program 2HDMC.
- The parameters S, T and U , which constrain the mass splitting between the physical scalars, using the result ($U = 0$) of Ref. [23].
- Limits from searches for additional Higgs bosons using the program HiggsBounds-5.9.0 [24].
- Compliance with SM-like Higgs boson measurements using the program HiggsSignals-2.6.0 [25].
- Compliance with the Z width measurement from LEP, $\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$ [26], in which $\Gamma(Z \rightarrow hA)$ is taken to be within the 2σ experimental uncertainty of such a measurement.

- Flavor physics constraints using the program **SuperIso v4.1** [27]. The experimental results of relevant observables are taken from Ref. [23].

In order to satisfy the above constraints, especially those from electroweak oblique parameters S and T , the Higgs states should be relatively close in mass. Note that, after considering the new CDF W boson mass measurement [28], it is found recently that the charged Higgs boson is always heavier than the neutral Higgs states in 2HDM with inverted hierarchy ($H \equiv H_{\text{SM}}$) [20].

4. Results and discussion

As mentioned above, we focus on light charged Higgs boson in $H^\pm h$ associated production channel. We calculate the cross section at the leading order with $\sqrt{s} = 14$ TeV using the code **MadGraph5_aMC@NLO-2.7.3** [29]. In the calculation, we have used the MMHT2014 pdf set [30]. Note that the NNLO-QCD corrections increase the tree-level cross section by a factor of approximately 1.35 [14]. In our study, we shall present the tree-level results only.

In Figure 1a, we show the values of $\sigma(pp \rightarrow H^\pm h)$ as a function of M_h , with the color code indicates M_{H^\pm} , for the parameter points that survive all constraints. It is clearly visible that the production cross section could reach the pb level for small Higgs masses. The results can be, indeed, interpreted by the two factors: the $H^\pm W^\mp h$ vertex, which is proportional to $\cos(\beta - \alpha)$ and is maximized in the *alignment limit*; the phase space attributable to relatively small values of M_h and M_{H^\pm} . The cross section for $pp \rightarrow H^\pm h$ can, in certain scenarios, exceed the light charged Higgs production through top quark decay channel, i.e. $pp \rightarrow \bar{t}t \rightarrow \bar{t}bH^+$, especially when $\tan\beta$ is large in which the H^\pm couplings to fermions is suppressed in 2HDM type-I.

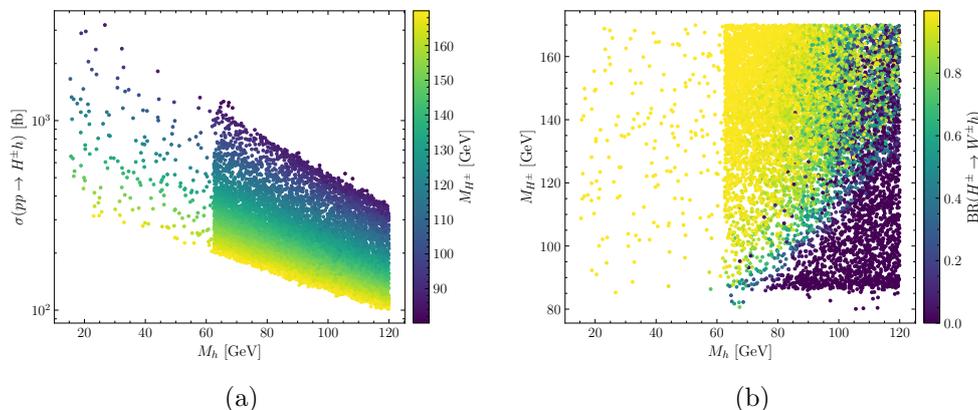


Figure 1: (a) Cross section for $pp \rightarrow H^\pm h$ at $\sqrt{s} = 14$ TeV as a function of M_h , with the color bar indicates M_{H^\pm} . (b) Branching ratio $\text{BR}(H^\pm \rightarrow W^\pm h)$ in the (M_h, M_{H^\pm}) plane.

Let us now turn to the charged Higgs decaying into a W^\pm boson and an h boson, $H^\pm \rightarrow W^\pm h$. Analogous to the $pp \rightarrow H^\pm h$ production cross section, the decay $H^\pm \rightarrow W^\pm h$ is governed by the same vertex and also is maximized in the *alignment limit*. Figure 1b clearly demonstrates that the branching ratio $\text{BR}(H^\pm \rightarrow W^\pm h)$ can reach 100% for light h . Note that $\text{BR}(H^\pm \rightarrow W^\pm A)$ is only relevant when $M_A \lesssim 100$ GeV. $\text{BR}(H^\pm \rightarrow W^\pm H)$ is suppressed in our scenario by the factor $\sin^2(\beta - \alpha)$.

Under these observations, combining the $H^\pm h$ production and the $H^\pm \rightarrow W^\pm h$ decay, one can expect significant signatures, which might be alternative discovery channels for light charged Higgs boson at the LHC [15, 16, 18]. For the neutral Higgs boson, h , we mainly consider bb , $\tau\tau$ and $\gamma\gamma$ decays. These channels would lead to $W + 4b$, $W + 2b2\tau$ and $W + 4\gamma$ final

states, which are depicted in Figure 2. One can see (Figure 2a) that the signal cross section $\sigma(pp \rightarrow H^\pm h \rightarrow W^\pm hh \rightarrow W^\pm + 4b)$ can reach the pb level for very light h . Similar to the $W + 4b$ final state, in figure 2b one sees that $\sigma(pp \rightarrow H^\pm h \rightarrow W^\pm hh \rightarrow W^\pm + 2b2\tau)$ can reach up to 200 fb for low M_h . Besides $W + 4b$ and $W + 2b2\tau$ final states, and since the $h \rightarrow \gamma\gamma$ decay is experimentally the cleanest decay channel (also WW and ZZ decays), which is dominant (close to the *fermiophobic limit*) before the WW^* threshold, the $W + 4\gamma$ signature could be an excellent experimental avenue to identify a light charged Higgs boson at the LHC (Figure 2c). Furthermore, it is found that the signal $pp \rightarrow H^\pm h \rightarrow W^\pm hh \rightarrow W^\pm + 4\gamma$ (assuming $W^\pm \rightarrow \ell^\pm\nu$) is essentially background free, yielding to a large significance [16].

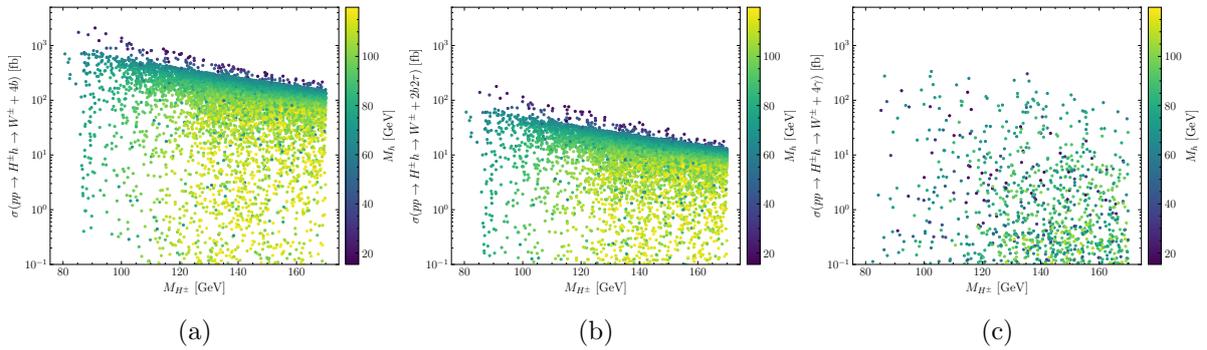


Figure 2: (a) Signal cross sections $\sigma(pp \rightarrow H^\pm h \rightarrow W^\pm hh \rightarrow W^\pm + 4b)$, (b) $\sigma(pp \rightarrow H^\pm h \rightarrow W^\pm hh \rightarrow W^\pm + 2b2\tau)$ and (c) $\sigma(pp \rightarrow H^\pm h \rightarrow W^\pm hh \rightarrow W^\pm + 4\gamma)$ as a function of M_{H^\pm} , with the color map showing M_h .

5. Conclusion

In this study, we have investigated the light charged Higgs boson (H^\pm) production in association with a neutral Higgs boson (h) in a scenario where H is identified to be the SM-like state of mass 125 GeV, and the parameter space consistent with theoretical and experimental constraints. Under these conditions, we have mainly focused on the $W^\pm h$ decay channel of H^\pm , which is naturally dominant close to the *alignment limit*. We have demonstrated that such production and decay channels would lead to significant cross sections for $W^\pm + 4b$, $W^\pm + 2b2\tau$ and $W^\pm + 4\gamma$ final states, which might be alternative signatures to target the light charged Higgs boson at the LHC.

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