Search for charged Higgs boson via $H^{\pm}bj$ at the LHC

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Abstract

In the current study, we concentrate on the associated production of the charged Higgs boson with the bottom quark and the jet in Two-Higgs Doublet Model (2HDM) type-I as promising mode for a light $H^{\pm}$, i.e. $m_{H^{\pm}} < m_t$. For this we consider the two situations where h or H is the SM-type Higgs boson discovered with a mass close to 125 GeV and investigate its bosonic decays, namely $H^{\pm} \to W^{\pm}h_i(h_i = h, H, A)$. The potential signals at the LHC are then discussed, under both theoretical and experimental constraints. Over a substantial region of the 2HDM type-I parameter space, a promising alternative signals that could be used for the discovery of $H^{\pm}$ states at the LHC are identified as $qbW + 2b/2\tau/2\gamma/WW$ and ZZ.

Introduction

The charged Higgs phenomenology has been extensively examined at collider experiments(LHC), it's most common production modes includes[1]:

- $pp \to t\bar{t}$, $t \to bH^+(\bar{t} \to \bar{b}H^-)$,competing with the SM decay of $\bar{t} \to W^-H^-$
- Single production: $gb \to tH^- + c.c.$ and $gg \to t\bar{b}H^-$
- Associated production with a $W^{\pm}$ gauge boson:$bb \to H^{\pm}W^{\mp}$ and $gg \to H^{\pm}W^{\mp}$
- Resonant production via $c\bar{s}, c\bar{b} \to H^+$.
- Associate production with a neutral Higgs: $q\acute{q} \to H^{\pm}h_i(hi = h, H, A)$.
- Pair production: $gg \to H^+H^- and q\bar{q} \to H^+H^-$.
- Associate production with a bottom quark and a light jet, $pp \to H^{\pm}bj$

The goal of our study is to look at the generation of singly-charged Higgs bosons in conjunction with a bottom quark and a jet j using the subprocess $pp(qb) \to H^+bj$ in the 2HDM type-I[2].

2HDM framework

The most simple extension of the SM that leads to charged Higgs bosons is the Two-Higgs Doublet Model (2HDM), where an additional complex doublet Φ_2 of the groupe $SU(2)$ was added to the standard Model Higgs sector. Under the soft broken Z_2 symmetry, the fourth-dimension most widespread scalar potential that is $SU(2)_L \otimes U(1)_Y$ invariant and CP-conserving is given by[3]:

$$\begin{aligned} V_{2\mathrm{HDM}}(\Phi_1,\Phi_2) = & \\ & m_{11}^2(\Phi_1^+\Phi_1) + m_{22}^2(\Phi_2^+\Phi_2) - m_{12}^2(\Phi_1^+\Phi_2 + h.c.) \\ & +\lambda_1(\Phi_1^+\Phi_1)^2 + \lambda_2(\Phi_2^+\Phi_2)^2 + \lambda_3(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2) \\ & +\lambda_4(\Phi_1^+\Phi_2)(\Phi_2^+\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^+\Phi_2)^2 + \mathrm{h.c.}], \end{aligned} \tag{1}$$

- the doublets $\Phi_{1,2}$ has 8 degree of freedom.
- 3 absorbed by the Z and $W^{\pm}$.
- 5 physical Higgses : 2 CP-even h and H, 1 CP-odd A and 2 Charged Higgs $H^{\pm}$.
- Avoid FCNCs lead to $\mathcal{Z}_2$ Symmetry ($\lambda_6 = \lambda_7 = 0$).
- Two minimization conditions and the combination $v_1^2 + v_2^2 \Longrightarrow 7$ free parameters :v^2 $m_h < m_H, m_A, m_{H^{\pm}}, \sin(\beta-\alpha), \tan\beta = v_2/v_1$ and m_{12}^2.

Depending on the $\mathcal{Z}_2$ charged assignment, there are four different version of interaction carrying the name of 2HDM type I, type II, type X or lepton-specific and, type Y or flipped. The Yukawa Lagrangian, which describes the interactions between the Higgs sector and the fermion sector, is given as follows

$$-\mathcal{L}_{\mathrm{Yukawa}} = \tag{2}$$

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

the coefficients κ_f^{hi} are understood as the ratio of the Higgs boson couplings to the fermions with respect to the SM ones, which are defined according to the definition of the alignment limit for type I as following:

$$\kappa_u^h = \kappa_d^h = \kappa_l^h = c_\alpha/s_\beta \tag{3}$$
$$\kappa_u^H = \kappa_d^H = \kappa_l^H = s_\alpha/s_\beta \tag{4}$$
$$\kappa_u^A = cot\beta, \kappa_d^A = \kappa_l^A = -cot\beta \tag{5}$$

Constraints

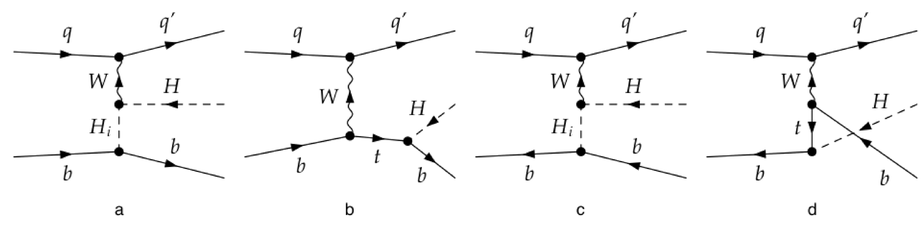
During our study,we have implement all the available theoretical and experimental constraint:

- Theoretical Constraints
  - Vacuum stability: demand that the potential of the field ϕ_i to be confined from below and positive in all directions[4]; $\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2}, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$
  - Perturbativity constraint: limite the quartic couplings of the scalar potential to be below 4π[5].
  - Unitarity pertubative: The gauge boson and Higgs state scattering processes must continue to be unitary at high energies; $e_i = f(\lambda_i) < 8\pi$.[6, 7]
- Experimental Constraints:
  - EWPOs through the parameter S, T and U[8]:
    $$\text{PDG: } S = 0.05 \pm 0.08, \quad T = 0.09 \pm 0.07. \tag{6}$$
  - compatibility of the SM-like scalar with the experimentally discovered Higgs boson using HiggsSignals[9]
  - limits from direct searches for BSM scalars using HiggsBounds[10]
  - B physics observable are calculated using the public code SuperIso v4.1[11]:

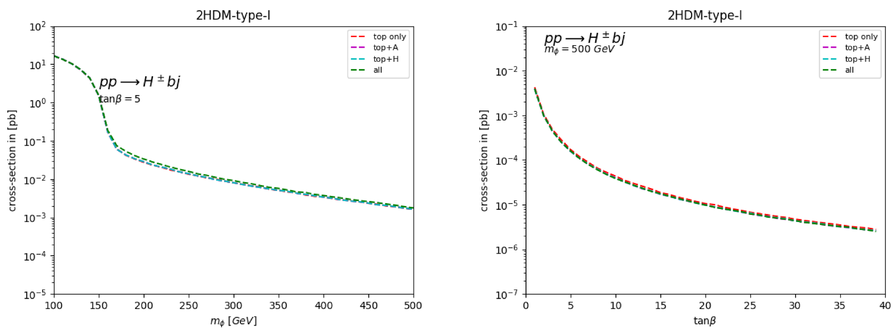
$$BR(B \to X_s\gamma)_{E_\gamma \geq 1.6\ \mathrm{GeV}} = (3.32 \pm 0.15) \times 10^{-4} \tag{7}$$
$$BR(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6_{\mathrm{stat}}{}^{+0.3}_{-0.2}{}_{\mathrm{sys}}) \times 10^{-9} \tag{8}$$
$$BR(B_d \to \mu^+\mu^-)(1.5^{+1.2}_{-1.0}{}_{\mathrm{stat}}{}^{+0.2}_{-0.1}{}_{\mathrm{sys}}) \times 10^{-10} \tag{9}$$
$$BR(B_\mu \to \tau\nu) = (1.06 \pm 0.19) \times 10^{-4}. \tag{10}$$

$H^{\pm}bj$ production

- $pp(qb) \to H^{\pm}bj$ in the 2HDM type-I.



- a-b): $qb \to \acute{q}H^+b$, c-d): $q\bar{b} \to \acute{q}H^+\bar{b}$
- $(q,\acute{q}) = (u,d),(c,s)$, $(\bar{q},\bar{\acute{q}}) = (\bar{d},\bar{u}),(\bar{s},\bar{c})$, $H_i = h, H, A$



Space parameter and Results

parameter	m_h [GeV]	m_H [GeV]	m_A [GeV]	$m_{H^{\pm}}$ [GeV]	$s_{\beta-\alpha}$	$\tan\beta$	m_{12}^2
h Scenario	125.09	[126; 200]	[60; 200]	[80; 170]	[0.95; 1]	[2; 15]	[0; $m_H^2\cos\beta\sin\beta$]
H Scenario	[10; 120]	125.09	[60; 200]	[80; 170]	[−1; 1]	[2; 15]	[0; $m_h^2\cos\beta\sin\beta$]

Table 1:2HDM input parameters for both scenarios.

Standard Hierarchy; $H^{\pm} \to WA$

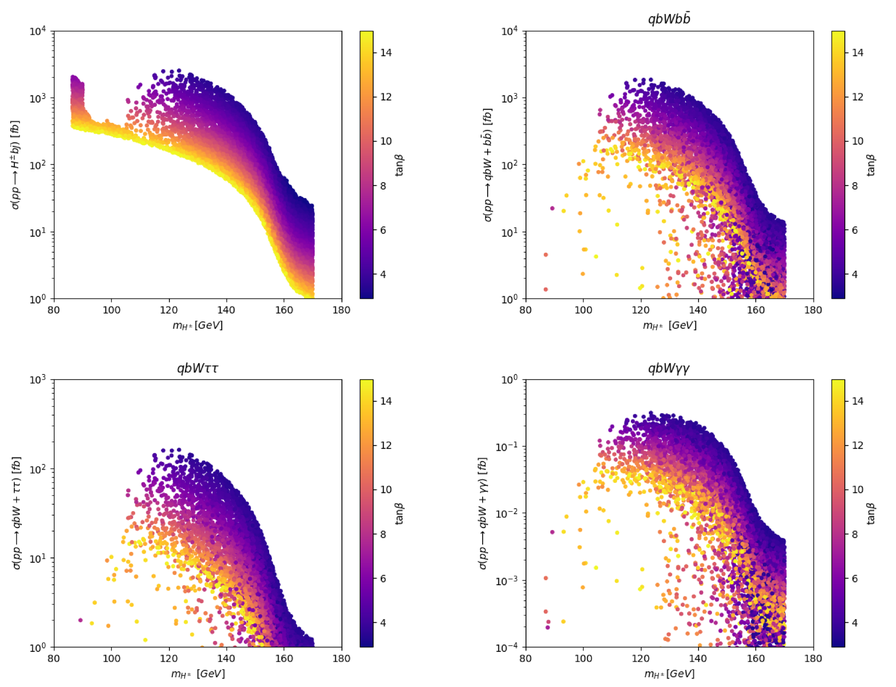


Figure 1:$\sigma(pp \to H^{\pm}bj)$(upper left), at $\sqrt{s} = 14$ TeV and $qbW + bb$(upper right), $qbW + \tau\tau$(lower left) and $qbW + \gamma\gamma$(lower right) as a function of $m_{H^{\pm}}$, with $\tan\beta$ indicated by the colour map.

Inverted Hierarchy; $H^{\pm} \to W^{\pm}h/A$

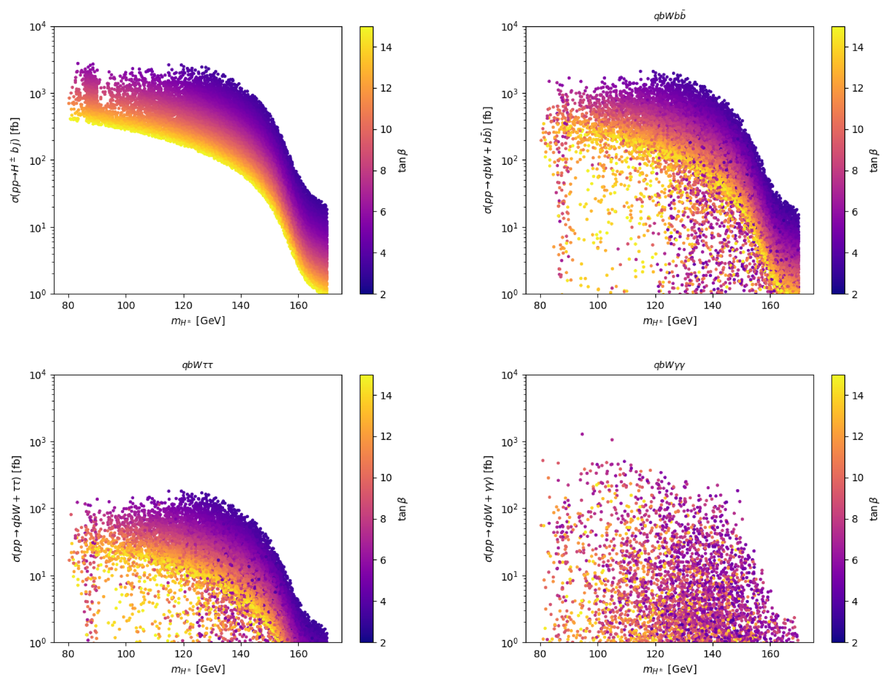


Figure 2:$\sigma(pp \to H^{\pm}bj)$ at 14 TeV, $\sigma(pp \to qbW + b\bar{b})$ (upper left), $\sigma(pp \to qbW + \tau\tau)$ (lower left) and $\sigma(pp \to qbW + \gamma\gamma)$ (lower left) showed against the charged Higgs mass. The color code indicates the parameter $\tan\beta$.

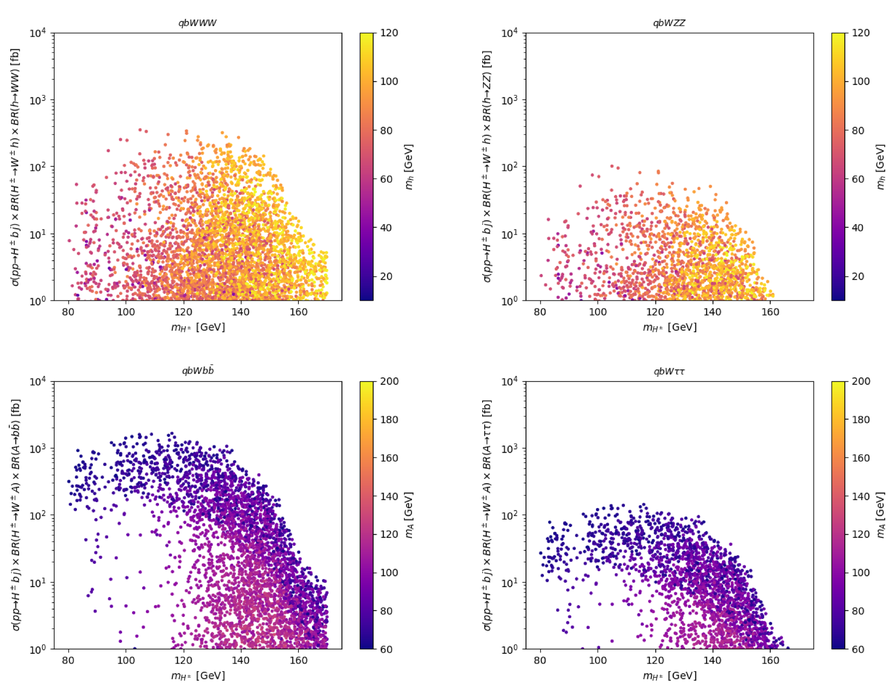


Figure 3:$\sigma(pp \to qbW + WW)$ (upper left), $\sigma(pp \to qbW + ZZ)$ (upper right),$\sigma(pp \to qbW + b\bar{b})$ (lower left) and $\sigma(pp \to qbW + \tau\tau)$ (lwer right) showed against the charged Higgs mass. The color code indicates m_h.

Benchmarking

We propose a set of the Benchmark Points (BPs) in the 2HDM typeI for both the LHC and future colliders to help experimentalists look for such novel discovery channels and to analyze the key characteristics of the recommended parameter space.
The table2, show eight BPs in the case of h-scenario, we concentrate to the rgion where $m_{H^{\pm}} + m_b < m_t$.

Selected BPs in h−scenario

Parameters	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8
m_h(GeV)	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09
m_H(GeV)	139.0	137.15	133.7	129.2	142.0	136.8	138.03	131.8
m_A(GeV)	68.45	64.65	65.45	63.05	64.6	66.8	63.65	71.2
$m_{H^{\pm}}$(GeV)	123.55	121.0	118.0	115.0	128.0	127.12	126.04	124.2
$s_{\beta-\alpha}$	0.96	0.98	0.99	0.95	0.98	0.99	0.99	0.98
$\tan\beta$	3.55	3.78	3.95	4.44	3.54	3.69	3.96	4.03
m_{12}^2(GeV^2)	2895.9	4367.0	703.6	1197.9	2801.6	421.6	3046.9	2240.3
BR($H^{\pm} \to XY$) in %								
$BR(H^{\pm} \to W^{\pm}A)$	91.97	93.83	92.56	93.92	95.37	94.68	96.16	92.30
BR($A \to XY$) in %								
$BR(A \to b\bar{b})$	79.69	80.46	80.30	80.78	80.45	80.02	80.66	79.10
$BR(A \to \tau\tau)$	6.96	6.95	6.95	6.94	6.95	6.95	6.94	6.97
$BR(A \to \gamma\gamma)$	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}
$\sigma \times$ BR in fb								
$\sigma^A(\acute{q}bW + b\bar{b})$	1839.9	1825.5	1825.6	1631.8	1607.7	1512.5	1428.1	1371.6
$\sigma^A(\acute{q}bW + \tau\tau)$	160.8	157.6	158.1	140.2	138.9	131.5	122.9	120.87
$\sigma^A(\acute{q}bW + \gamma\gamma)$	0.15	0.13	0.13	0.11	0.11	0.12	0.10	0,12

Table 2:Mass spectra, mixing angles, branching ratios and cross section (in fb) selected as BPs in h-scenario.

In the tabe3, we show eight Benchmark points (BPs) for the Inverted Scenario. all the the selected points are fulfilled the condition $m_{H^{\pm}} + m_b < m_t$.

Parameters	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8
m_h (GeV)	62.72	63.89	64.26	65.76	107.63	102.58	117.26	92.92
m_H (GeV)	125.09	125.09	125.09	125.09	125.09	125.09	125.09	125.09
m_A (GeV)	139.65	116.98	125.49	180.11	66.52	65.93	64.61	60.65
$m_{H^{\pm}}$ (GeV)	114.96	120.19	119.36	109.35	116.08	108.96	104.74	102.14
$s_{\beta-\alpha}$	−0.003	0.037	0.085	−0.186	−0.078	−0.187	0.015	−0.197
$\tan\beta$	4.07	3.86	3.78	5.45	4.32	4.76	5.02	5.50
m_{12}^2 (GeV^2)	529.84	609.85	943.67	175.08	1698.99	1119.51	2444.95	1077.66
BR($H^{\pm} \to XY$) in %								
BR($H^{\pm} \to W^{\pm}h$)	92.969	94.093	93.267	91.173	0.0196	0.0093	–	0.0706
BR($H^{\pm} \to W^{\pm}A$)	–	–	–	–	91.987	88.509	86.424	89.953
BR($h \to XY$) in %								
BR($h \to b\bar{b}$)	85.904	85.820	85.793	49.183	52.407	3.7663	43.522	6.1552
BR($h \to \tau\tau$)	7.3468	7.3623	7.3671	4.2398	4.9326	0.3514	4.1609	0.5640
BR($h \to \gamma\gamma$)	0.0028	0.0005	0.0001	32.414	0.0515	0.5740	0.0017	0.9951
BR($A \to XY$) in %								
BR($A \to b\bar{b}$)	14.223	45.246	34.384	0.0547	80.088	80.208	80.476	81.267
BR($A \to \tau\tau$)	1.4309	4.4003	3.3896	0.0058	6.9588	6.9565	6.9509	6.9289
BR($A \to \gamma\gamma$)	0.0120	0.0252	0.0225	0.0001	0.0127	0.0125	0.0120	0.0106
$\sigma \times$ BR in fb								
$\sigma^h(qbW b\bar{b})$	2105.88	2000.24	2100.43	760.232	0.2294	0.0079	–	0.0874
$\sigma^h(qbW\tau\tau)$	180.102	171.595	180.366	65.5355	0.0216	0.0007	–	0.0080
$\sigma^h(qbW\gamma\gamma)$	0.06864	0.01165	0.00245	501.033	0.0002	0.0012	–	0.0141
$\sigma^A(qbW b\bar{b})$	–	–	–	–	1645.44	1594.58	1580.73	1469.54
$\sigma^A(qbW\tau\tau)$	–	–	–	–	142.971	138.299	136.532	125.294
$\sigma^A(qbW\gamma\gamma)$	–	–	–	–	0.26093	0.24851	0.23571	0.19168

Table 3:2HDM Type-I paramters, branching rations and total cross sections corresponding to the selected BPs. All cross sections are in fb.

Conclusion

In this study, we have looked for light charged Higgs signatures via the process $pp \to H^{\pm}bj$ at LHC with $\sqrt{s} = 14$ TeV in the 2HDM type I, taking into account the theoretical and available experimental constraints. We mainly focused on the bosonic decays of $H^{\pm}$ and investigated the final states $qbW + b\bar{b}, \tau\tau, \gamma\gamma$, ZZ and WW in both h and H scenarios. We have demonstrated that such signatures can be exploited as possible discovery modes for light $H^{\pm}$ states, even when the signals are contaminated by the QCD background.

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