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Bosonic decays of charged Higgs bosons in a 2HDM type-I

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Abstract In this study, we focus on the bosonic decays of light charged Higgs bosons in the 2-Higgs Doublet Model (2HDM) Type-I. We quantify the Branching Ratios (BRs) of the $H^\pm \to W^\pm h$ and $H^\pm \to W^\pm A$ channels and show that they could be substantial over several areas of the parameter space of the 2HDM Type-I that are still allowed by Large Hadron Collider (LHC) and other experimental data as well as theoretical constraints. We suggest that $H^\pm \to W^\pm h$ and/or $H^\pm \to W^\pm A$ could be used as a feasible discovery channel alternative to $H^\pm \to \tau\nu$.

1 Introduction

Following the discovery of a 125 GeV Higgs boson in the first run of the LHC [1,2], several studies of its properties were performed. The current situation is that the measured Higgs signal rates in all channels agree with the Standard Model (SM) predictions at the $\sim 2\sigma$ level [3]. Although the current LHC Higgs data are consistent with the SM, there is still the possibility that the observed Higgs state could be part of a model with an extended Higgs sector including, e.g., an extra doublet, singlet and/or triplet. As the discovered Higgs state belongs to a doublet, we concern ourselves here with such a scenario. Most of the higher Higgs representations with an extra doublet predict in their spectrum one or more charged Higgs bosons. Discovery of such a state would therefore be an indisputable signal of an extended Higgs sector and clear evidence for a departure from the SM.

One of the main goals of the 13 TeV LHC (eventually to be upgraded to 14 TeV) is to improve the precision of the measurements of the Higgs couplings, thus to access potential new physics indirectly. However, in parallel, direct searches for new Higgs states will also take place in the quest to find evidence of physics Beyond the SM (BSM).

One of the simplest extensions of the SM is the 2HDM, which contains two Higgs doublets, H_1 and H_2, used to give mass to all fermions. The particle spectrum of the 2HDM is as follows: two CP-even (h and H, with $m_h < m_H$), one CP-odd (A) and a pair of charged ($H^\pm$) Higgs bosons. At hadron colliders, a charged Higgs boson can be produced through several channels. Light charged Higgs states, i.e., with $m_{H^\pm} \leq m_t - m_b$, are copiously induced by $t\bar{t}$ production followed by the top decay $t \to bH^+$ (or the equivalent antitop mode). When kinematically allowed, $pp \to t\bar{t} \to b\bar{b}H^-W^+$ + c.c. provides the most important source of light charged Higgs bosons, above and beyond the yield of various direct production modes: $gb \to tH^-$ and $gg \to t\bar{b}H^-$ [4–8], $gg \to W^\pm H^\mp$ and $b\bar{b} \to W^\pm H^\mp$ [9–13], $q\bar{q}' \to \phi H^\pm$ where ϕ denotes one of the three neutral Higgs bosons [14], $gg \to H^+H^-$ and $q\bar{q} \to H^+H^-$ [15–17], $qb \to q'H^+b$ [18,19] and $c\bar{s}, c\bar{b} \to H^+$ [20] (see also Refs. [21,22] for a review of all available $H^\pm$ hadro-production modes in 2HDMs).

At the Tevatron and LHC, light charged Higgs bosons can be detected through $pp \to t\bar{t} \to b\bar{b}H^-W^+$ followed by $\tau\nu$ decay. In fact, for a light charged Higgs state, the $\tau\nu$ decay is the dominant mode. The ATLAS and CMS experiments have already drawn an exclusion on BR$(t \to bH^+) \times$ BR$(H^\pm \to \tau\nu)$ based on the search for the corresponding decay chain [23–26]. Other channels, such as $H^+ \to c\bar{s}$, have also been searched for by ATLAS and CMS [27,28]. Assuming that BR$(H^+ \to c\bar{s}) = 100\%$, one can set a limit on BR$(t \to bH^+)$ to be in the range 5–1% for a charged Higgs mass between 90 and 150 GeV. We recall here in passing that charged Higgs bosons have been also searched for at LEP-II using charged Higgs pair production followed by either $H^\pm \to \tau\nu$, $H^\pm \to cs$ or $H^\pm \to W^\pm A$ [29]. If the charged Higgs boson decays dominantly to $\tau\nu$ or cs, the LEP-II lower

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bound on the mass is of the order of 80 GeV while in the case where charged Higgs decay is dominated by $W^{\pm *}A$, via a light CP-odd Higgs state ($m_A \approx 12$ GeV), the lower bound on the charged Higgs mass is about 72 GeV [29].

The aim of this letter is to show that the bosonic decays of a *light* charged Higgs boson, such as $H^\pm \to W^{\pm(*)}h$ and/or $H^\pm \to W^{\pm(*)}A$, could be substantial and may compete with $H^\pm \to \tau\nu$ and cs.[1] In particular, $H^\pm \to W^{\pm(*)}h$ with leptonic decay of $W^\pm$ could be an alternative channel to $H^\pm \to \tau\nu$ in order to discover a light charged Higgs boson at the LHC owing to the handle offered by the SM-like Higgs mass reconstruction, now possible after discovery [32–34]. We also discuss the case of a light CP-odd Higgs $m_A \le 120$ GeV where $H^\pm \to W^{\pm(*)}A$ could be substantial and reach a 100% branching fraction while being consistent with LHC and LEP data. This possibility may suggest that a light charged Higgs state could have escaped detection during previous LHC searches. Therefore, the bosonic decays of a 2HDM charged Higgs boson might be complementary to the usual search channels $H^\pm \to \tau\nu$ and $H^\pm \to cs$. We also point out that $H^\pm \to W^{\pm(*)}h/A$ would lead to the same final state as $H^\pm \to t^*b \to W^*b\bar{b}$ in the case where h and A decay to $b\bar{b}$. Clearly, there are kinematic differences between these three channels, so that one can eventually separate them, e.g., by reconstructing the $b\bar{b}$ pair around a Higgs resonance (125 GeV or others) and/or the $bW^\pm$ pair around the (anti)top pole, yet it may pay off to devise an inclusive approach that maximizes the signal yield across the three decay patterns [35].

2 A review of the 2HDM

The most general renormalizable potential for a model of exactly two scalar Electro-Weak (EW) doublets with the quantum numbers which are invariant under $SU(2) \otimes U(1)$ can be written as

$$\begin{aligned} V(\Phi_1,\Phi_2) &= m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) \\ &\quad + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &\quad + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &\quad + \frac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + (\lambda_6\Phi_1^\dagger\Phi_1 \\ &\quad + \lambda_7\Phi_2^\dagger\Phi_2)\Phi_1^\dagger\Phi_2 + \text{h.c.}], \end{aligned} \tag{1}$$

where Φ_i, $i = 1, 2$, are complex $SU(2)$ doublets with four degrees of freedom each while m_i^2 and $\lambda_{1,2,3,4}$ are real, which follows from the hermiticity of the potential. Further, m_{12}^2 and $\lambda_{5,6,7}$ could be complex to allow for CP-violation. In what follows, in order to avoid Flavor Changing Neutral Currents (FCNCs), we impose a Z_2 symmetry. Furthermore, we tolerate that such a symmetry is broken by the dimension-2 term m_{12}^2 and we will set $\lambda_{6,7} = 0$. We then assume that our potential is CP-conserving and hence m_{12}^2 and λ_5 are assumed to be real.

From the initial eight degrees of freedom, if the $SU(2)$ symmetry is broken, we end up with the aforementioned five physical Higgs states, upon the absorption of three Goldstone bosons by the $W^\pm$ and Z states.

The potential in Eq. (1) has a total of 10 parameters if one includes the vacuum expectation values. In a CP-conserving minimum there are two minimization conditions that can be used to fix the tree-level value of the parameters m_1^2 and m_2^2. The combination $v^2 = v_1^2 + v_2^2$ is fixed as usual by the EW breaking scale through $v^2 = (2\sqrt{2}G_F)^{-1}$. We are thus left with 7 independent parameters, namely $(\lambda_i)_{i=1,\ldots,5}$, m_{12}^2, and $\tan\beta \equiv v_2/v_1$. Equivalently, we can take instead the set m_h, $m_H, m_A, m_{H^\pm}, \tan\beta, \sin(\alpha-\beta)$ and m_{12}^2 as the 7 independent parameters. The angle β is the rotation angle from the group eigenstates to the mass eigenstates in the CP-odd and charged sector. The angle α is the corresponding rotation angle for the CP-even sector. The parameter m_{12} is a measure of how the discrete symmetry is broken. The potential with $m_{12} = 0$ has an exact Z_2 symmetry and is always CP-conserving.

3 Theoretical and experimental bounds

The parameter space of the scalar potential of the 2HDM is reduced both by theoretical constraints and by the results of experimental searches. Amongst the theoretical constraints which the 2HDM is subjected to, we start by requiring vacuum stability of the theory. We also force the potential to be perturbative by requiring that all quartic couplings of the scalar potential, Eq. (1), obey $|\lambda_i| \le 8\pi$ for all i. For the vacuum stability conditions, which ensure that the potential is bounded from below, we use those from [36], which are given by

$$\lambda_1 > 0, \lambda_2 > 0, \sqrt{\lambda_1\lambda_2} + \lambda_3 + \min(0, \lambda_4 - |\lambda_5|) > 0.$$

However, the most restrictive theoretical bounds come from the full set of unitarity constraints [37–40] established using the high energy approximation as well as the equivalence theorem and which can be written as

$$|a_\pm|, |b_\pm|, |c_\pm|, |d_\pm|, |e_{1,2}|, |f_\pm|, |g_{1,2}| < 8\pi \tag{2}$$

with

$$a_\pm = \frac{3}{2}\left\{(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + \frac{4}{9}(2\lambda_3+\lambda_4)^2}\right\}, \tag{3}$$

$$b_\pm = \frac{1}{2}\left\{(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2}\right\}, \tag{4}$$

[1] These channels have been studied previously in [30,31]. We show here that this possibility is consistent with LHC data.

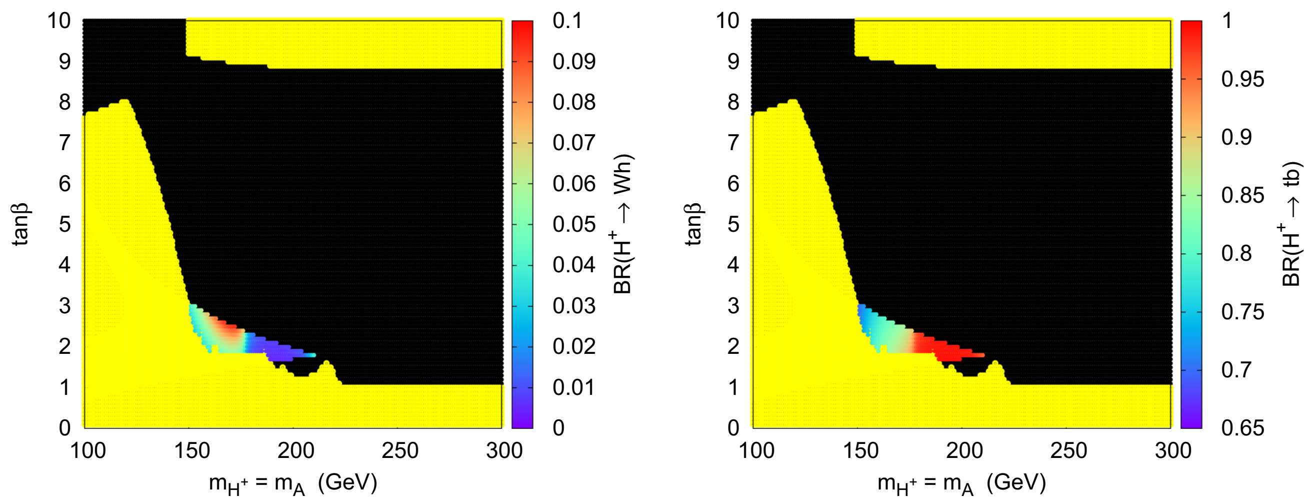

Fig. 1 The $\mathrm{BR}(H^\pm \to W^{\pm(*)}h)$ (left) and $\mathrm{BR}(H^\pm \to t^*b)$ (right) in the 2HDM Type-I mapped over the $(m_{H^\pm}, \tan\beta)$ plane with $m_{H^\pm} = m_A, m_H = 300$ GeV and $\sin(\beta-\alpha) = 0.85$. We set $m_{12}^2 = m_{H^\pm}^2 s_\beta c_\beta$. Yellow color areas are excluded from LHC Higgs data at 95% Confidence Level (CL) while black/gray ones are excluded from theoretical constraints

$$c_\pm = d_\pm = \frac{1}{2}\left\{(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2}\right\}, \quad (5)$$

$$e_1 = (\lambda_3 + 2\lambda_4 - 3\lambda_5), \qquad e_2 = (\lambda_3 - \lambda_5), \quad (6)$$

$$f_+ = (\lambda_3 + 2\lambda_4 + 3\lambda_5), \qquad f_- = (\lambda_3 + \lambda_5), \quad (7)$$

$$g_1 = g_2 = (\lambda_3 + \lambda_4). \quad (8)$$

The 2HDM parameters are also constrained by direct experimental searches and by precision experimental data. First, the extra contributions to the $\delta\rho$ parameter from the extra Higgs scalars [41] should not exceed the current limits from precision measurements [42]: $|\delta\rho| \lesssim 10^{-3}$. Values of $\tan\beta$ smaller than ≈ 1 are disallowed both by the constraints coming from $Z \to b\bar{b}$ and from $B_q\bar{B}_q$ mixing [43,44] for all Yukawa versions of the model. Conversely, $\tan\beta$ cannot be too large due to the aforementioned theoretical constraints. We also require agreement with the null-searches from the LEP, Tevatron and LHC experiments. Finally, we require agreement within 2σ for the 125 GeV Higgs signal strength measurements.

4 Discussion

It is well known that, in the framework of a 2HDM Type-II, the $b \to s\gamma$ constraints force the charged Higgs mass to be heavier than 580 GeV [45,46] for any value of $\tan\beta \geq 1$. Therefore, in the present study, we will deal only with a 2HDM Type-I, where a light charged Higgs state is still allowed by all B-physics constraints [47] so long that $\tan\beta \geq 1.5$.

In this study, h is taken to be the SM-like Higgs boson and will be fixed at 125 GeV. The other parameters are varied within a specific range in order to satisfy theoretical as well as experimental constraints. We have used the public code 2HDMC-1.7.0 [48] to perform the scan over the 2HDM parameter space. The program is also linked to HiggsBounds-4.3.1 and HiggSignals-1.4.0 [49] to check against available collider constraints. A systematic scan is performed over m_A, $m_{H^\pm}$, $\tan\beta$ and $\sin(\beta-\alpha)$. The mixing angle α is fixed from $\sin(\beta-\alpha)$. The mass of the heavy CP-even Higgs boson was fixed at $m_H = 300$ GeV. Since we are interested in light charged Higgs states, in order to satisfy EWPT constraints the other Higgses should not be too heavy. With $m_H = 300$ GeV and $m_A \leq 90$ GeV, to allow for the decay $H^\pm \to W^\pm A$, all the 2HDM quartic couplings $\lambda_{1,\ldots,5}$ are not too large and they are in the range [0, 2.2]. Therefore, one would expect the radiative corrections to the Higgs boson masses not to be very large.

In Fig. 1, we scan over the $(m_{H^\pm}, \tan\beta)$ plane and set $m_{H^\pm} = m_A$ with $\sin(\beta-\alpha) = 0.85$ while m_{12}^2 is fixed to m_A^2. The black/gray regions are excluded from theoretical constraints, while the yellow region is excluded by experimental constraints at 95% CL. It is clear that a light charged Higgs state with mass ≤ 150 GeV is excluded from $H^\pm \to \tau\nu$ and $H^\pm \to cs$ searches [23–28]. We are left with a small region with $m_{H^\pm} \in [150, 210]$ GeV in which we have evaluated $\mathrm{BR}(H^\pm \to W^\pm h)$ and $\mathrm{BR}(H^\pm \to t^*b)$. The two BRs are quantitatively shown in the vertical palette: left panel is for $\mathrm{BR}(H^\pm \to W^{\pm(*)}h)$ and right panel is for $\mathrm{BR}(H^\pm \to t^*b)$. One can see that, in this scenario, before the top–bottom threshold, $\mathrm{BR}(H^\pm \to W^{\pm(*)}h)$ can reach 10% for a charged Higgs mass around 160 GeV and $2 \leq \tan\beta \leq 3$. After crossing the top–bottom threshold, $\mathrm{BR}(H^\pm \to W^{\pm(*)}h)$ becomes suppressed and $\mathrm{BR}(H^\pm \to t^*b)$ gets enhanced so as to dominate over all other decays.

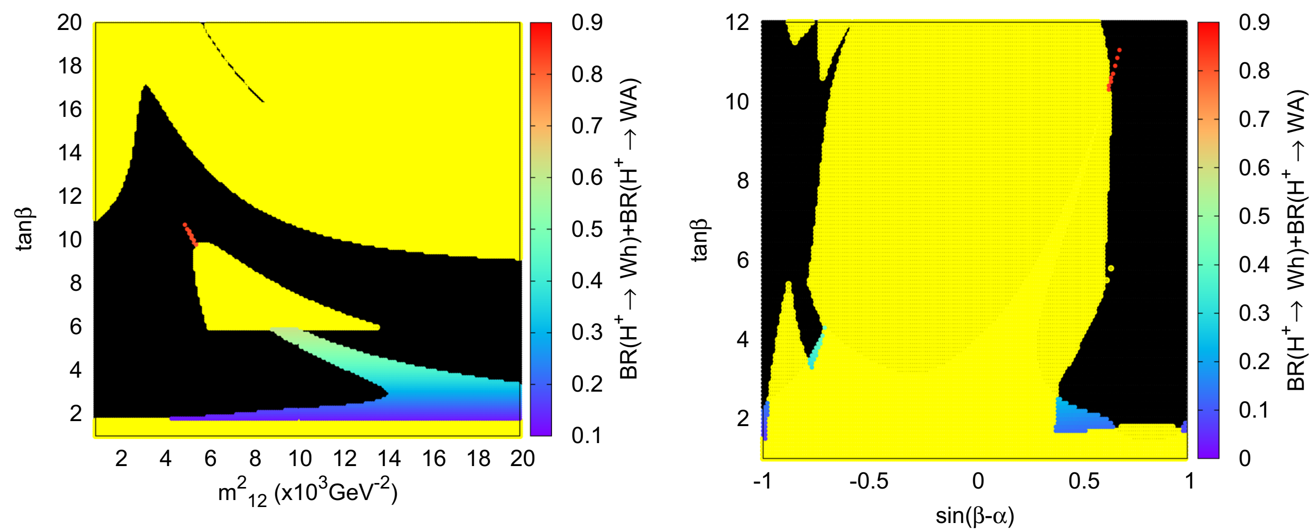

Fig. 2 The BR($H^{\pm} \to W^{\pm(*)}h + W^{\pm(*)}A$) in the 2HDM Type-I mapped over the (m_{12}^2, $\tan\beta$) (left) and ($\sin(\beta-\alpha)$, $\tan\beta$) (right) planes with $m_A = m_h = 125$ GeV, $m_{H^{\pm}} = 170$ GeV and $m_H = 300$ GeV. The other parameters are $\sin(\beta-\alpha) = 0.65$ (left) and $m_{12}^2 = 5000$ GeV^{-2} (right). Color coding is the same as in Fig. 1

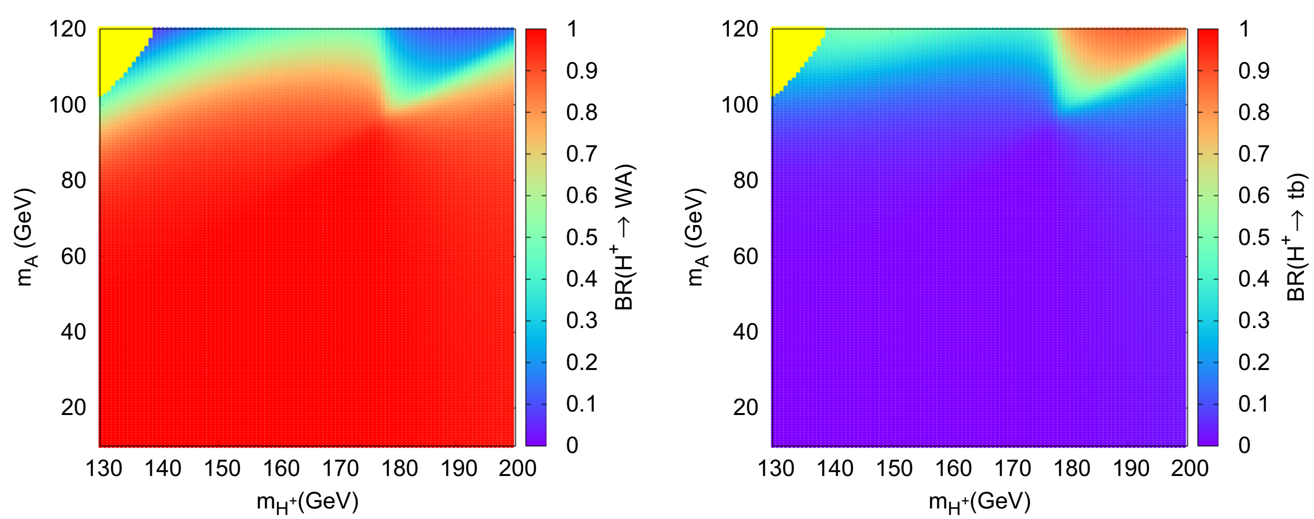

Fig. 3 The BR($H^{\pm} \to W^{\pm(*)}A$) (left) and BR($H^{\pm} \to t^{*}b$) (right) rates in the 2HDM Type-I mapped over ($m_{H^{\pm}}$, m_A) plane for the following parameter choice: $m_h = 125$ GeV, $\sin(\beta-\alpha) = 0.85$, $\tan\beta = 5$, $m_H = 300$ GeV and $m_{12}^2 = 16 \times 10^3$ GeV^2. The yellow region is excluded by LHC data at 95% CL

In Fig. 2 we illustrate the size of BR($H^{\pm} \to W^{\pm(*)}h + W^{\pm(*)}A$) over the ($m_{12}^2$, $\tan\beta$) plane (left) and ($\sin(\beta-\alpha)$, $\tan\beta$) plane (right) for $m_{H^{\pm}} = 170$ GeV, $m_H = 300$ GeV, $m_h = m_A = 125$ GeV. In the left panel we show the effect of the soft Z_2 breaking term m_{12}. It is clear that, for some special m_{12}^2 and $\tan\beta$ choices, the BR($H^{\pm} \to W^{\pm(*)}h + W^{\pm(*)}A$) could reach 90%. In the right panel, one can see that LHC data favor $\sin(\beta-\alpha)$ to be rather close to the decoupling limit: $\sin(\beta-\alpha) \approx 1$, which implies $\cos(\beta-\alpha) \approx 0$. Therefore, the coupling $W^{\pm}H^{\mp}h$, which is proportional to $\cos(\beta-\alpha)$, is suppressed for $\sin(\beta-\alpha) \approx 1$ while the $W^{\pm}H^{\mp}A$ one, which is a gauge coupling, has no suppression factor. This fact will make BR($H^{\pm} \to W^{\pm(*)}A$) larger than BR($H^{\pm} \to W^{\pm(*)}h$) in the special case of $m_h = m_A$. In this scenario where $m_h = m_A$, BR($H^{\pm} \to t^{*}b$) and BR($H^{\pm} \to W^{\pm(*)}h + W^{\pm(*)}A$) are anti-correlated, i.e., when BR($H^{\pm} \to W^{\pm(*)}h + W^{\pm(*)}A$) is maximal BR($H^{\pm} \to t^{*}b$) is suppressed and vice versa.

We now turn to the case of a light CP-odd Higgs state, with $m_A \leq 125$ GeV. Such a Higgs state is still allowed by LEP-II and LHC data. In Fig. 3 we scan over both the CP-odd and the charged Higgs boson masses over the following

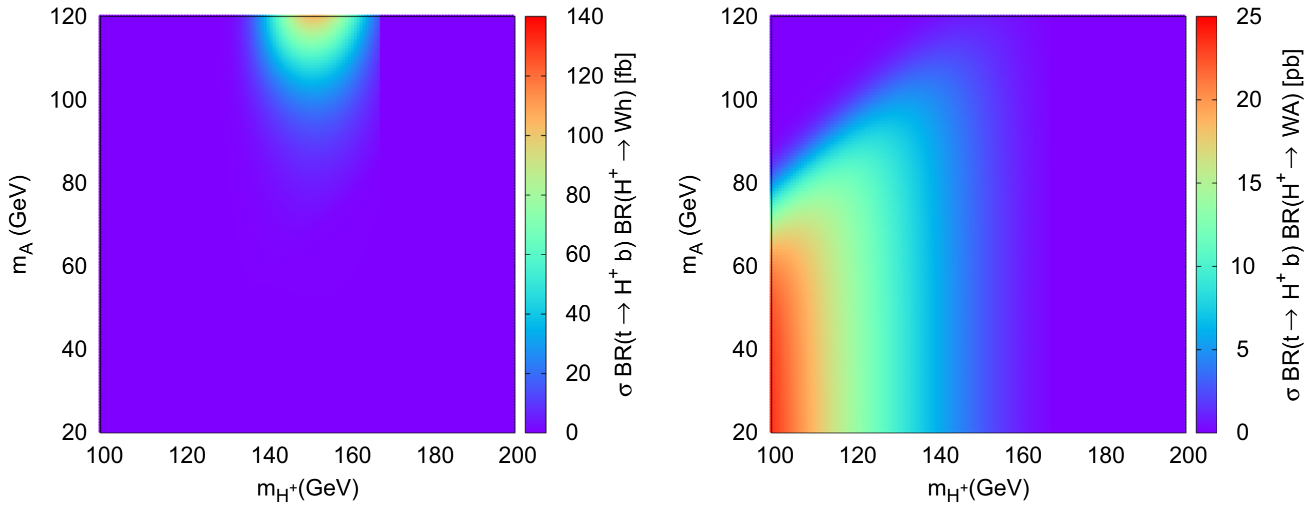

Fig. 4 The rates for $\sigma(pp \to t\bar{t}) \times \mathrm{BR}(t \to H^{\pm}b) \times \mathrm{BR}(H^{\pm} \to W^{\pm(*)}\phi)$ with $\phi = h$ (left) and A (right) in the 2HDM Type-I with the same parameters as in Fig. 3 where the $t\bar{t}$ cross section central value is computed at Next-to-Next-to-Leading Order (NNLO) at LHC with $\sqrt{s} = 14$ TeV

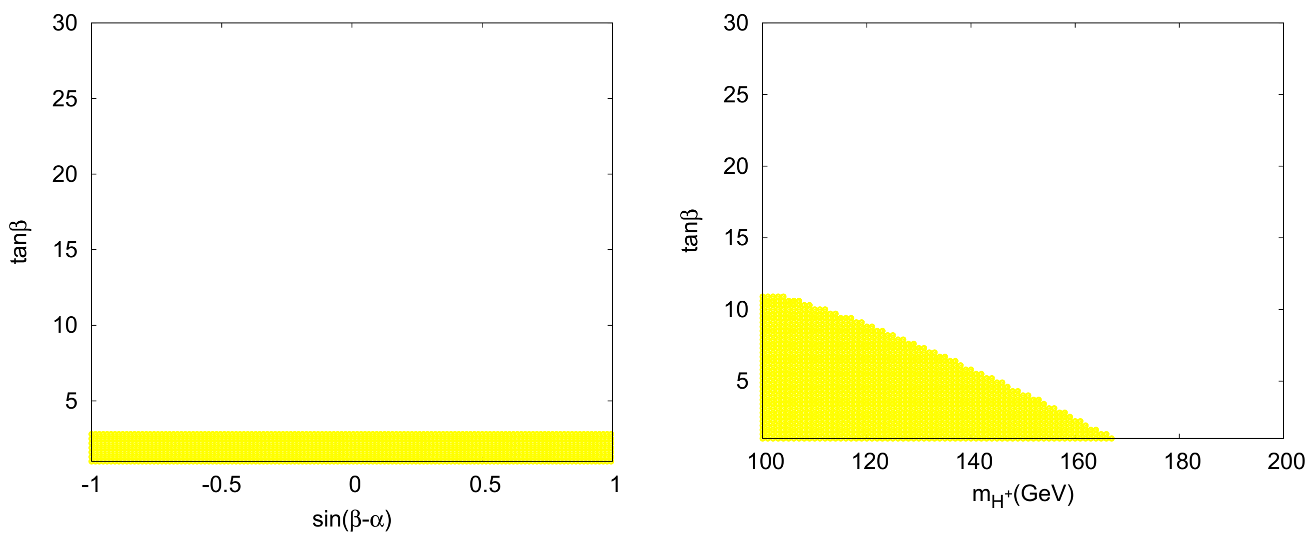

Fig. 5 The excluded regions of the 2HDM Type-I parameter space at 95% CL using the channel $pp \to t\bar{t} \to H^{\pm}W^{\pm}b\bar{b} \to AW^{\pm}W^{\mp}b\bar{b}$, with $A \to \tau^{+}\tau^{-}$, at the LHC with $\sqrt{s} = 14$ GeV and 100 fb^{-1} of luminosity. In the left (right) plot we set $m_{H^{\pm}} = 160$ GeV($\sin(\beta - \alpha) = 0.85$), the remaining parameters being the same as in Fig. 3

region: 10 GeV $\leq m_A \leq$ 120 GeV, 100 GeV $\leq m_{H^{\pm}} \leq$ 200 GeV with $m_h = 125$ GeV, $\sin(\beta - \alpha) = 0.85$, $\tan\beta = 5$ and $m_H = 300$ GeV. In this scan, the yellow region is where $H^{\pm} \to W^{\pm(*)}A$ is kinematically not allowed and therefore the charged Higgs boson will decay dominantly to $\tau\nu$ and/or cs pairs and is excluded by LHC data. However, over a substantial area of the $(m_{H^{\pm}}, m_A)$ plane, it is clear that $\mathrm{BR}(H^{\pm} \to W^{\pm(*)}A)$ can be the dominant decay channel, i.e., for $m_A \leq 100$ GeV for any value of the charged Higgs mass and in such a case $\mathrm{BR}(H^{\pm} \to t^{*}b)$ becomes a subleading channel.

We show in Fig. 4 the single charged Higgs production cross section where the $H^{\pm}$ state comes from (anti)top decays following $t\bar{t}$ hadro-production: $\sigma(tbW^{\pm(*)}\phi) = \sigma(pp \to t\bar{t}) \times \mathrm{BR}(t \to H^{\pm}b) \times \mathrm{BR}(H^{\pm} \to W^{\pm(*)}\phi)$, where $\phi = h$ or A. We plot the cross section in the $(m_{H^{\pm}}, m_A)$ plane for $m_h = 125$ GeV, $\tan\beta = 5$, $\sin(\beta - \alpha) = 0.85$, $m_H = 300$ GeV and $m_{12}^2 = 16 \times 10^3$ GeV^2. The left panel is for $\phi = h$ while the right panel is for $\phi = A$. Both cross sections reach their maximum values when kinematically possible. At the LHC with 14 TeV of energy and for $m_{H^{\pm}} \approx 150$ GeV, $\sigma(tbW^{\pm(*)}A)$, which can be of order 400–450 fb, is significantly larger than $\sigma(tbW^{\pm(*)}h)$. Notice that the former is larger than the latter mainly because $\mathrm{BR}(H^{\pm} \to W^{\pm(*)}A)$ can be about 4 times larger than $\mathrm{BR}(H^{\pm} \to W^{\pm(*)}h)$.

Therefore, starting from $t\bar{t}$ production at LHC followed by one top decay via $t \to bH^+$ with $H^\pm \to W^{\pm(*)}A$ and the other via $t \to bW$, we get a copious production of $t\bar{t} \to H^\pm W^\pm b\bar{b} \to AW^{\pm(*)}W^\mp b\bar{b}$ events. Depending on how A would decay, $\tau^+\tau^-$ or to $b\bar{b}$, the final state could be $2\tau 2b 2W^\pm$ or $4b2W^\pm$, where $W^\pm(*)$ leptonic decays would offer a useful lepton trigger. As an example, we illustrate in Fig. 5 the exclusion region in the parameter space of our 2HDM Type-I using $pp \to t\bar{t} \to \tau^+\tau^- W^{\pm(*)}W^\mp b\bar{b}$ at the LHC with 14 TeV of energy and 100 fb^{-1} of luminosity; see [31]. We use a CP-odd mass of 60 GeV, which makes BR($H^\pm \to W^\pm A$) almost 100%, and assume that the A decays to $\tau^+\tau^-$. For $m_{H^\pm} = 160$ GeV, as an illustration, one can conclude that $\tan\beta < 2.8$ is excluded at 95% CL (yellow region in the left plots of Fig. 5). We also draw the exclusion in the plane ($\tan\beta$, $m_{H^\pm}$), from where we can see, for example, that $\tan\beta \leq 12$ is excluded for $m_{H^\pm} = 100$ GeV.

In conclusion, we have proven the existence within the 2HDM Type-I of sizable regions of the parameter space compliant with all available theoretical and experimental constraints yielding substantial BRs for $H^\pm$ decays into $W^{\pm(*)}h$ (with h being the SM-like Higgs state) and/or, especially, $W^{\pm(*)}A$ in which the $H^\pm$ mass is less than $m_t - m_b$. Under the circumstances, $H^\pm$ production in single mode from the decay of a(n) (anti)top quark is possible with high rates, which are indeed potentially accessible during the present Run 2 of the LHC. These regions of parameter space within the 2HDM Type-I are amenable to immediate experimental investigation by the ATLAS and CMS collaborations, which have so far concentrated their attention almost exclusively onto $\tau\nu$ and/or cs decays of a light charged Higgs state emerging from $t\bar{t}$ production and decay.

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