Probing the charged Higgs quantum numbers through the decay $H^+ \rightarrow W^+ h^0_\beta$

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Abstract. The vertex $H^+ W^- h^0_\beta$, involving the gauge boson $W^\pm$ and the charged ($H^\pm_\alpha$) and neutral Higgs bosons ($h^0_\beta$), arises within the context of many extensions of the SM, and it can be used to probe the quantum numbers of the Higgs multiplet. After presenting a general discussion for the expected form of this vertex for arbitrary Higgs representations, we discuss its strength for an extended MSSM with one complex triplet. We find that in this model, there are regions of parameters where the decay $H^+ \rightarrow W^+ h^0_\beta$, is kinematically allowed, and reaches Branching Ratios (BR) that may be detectable, thus allowing to test the properties of the Higgs sector.

1. Introduction

The Higgs spectrum of many well motivated extensions of the Standard Model (SM) often includes a charged Higgs, whose detection at future colliders would constitute a clear evidence of a Higgs sector beyond the minimal SM [1]. Charged Higgs production at hadron colliders was studied long ago [3], and recently more systematic calculations of production process at LHC have been presented [4]. Current bounds on charged Higgs mass can be obtained at Tevatron, by studying the top decay $t \rightarrow bH^+$, which already eliminates some region of parameter space [5], whereas LEP bounds give approximately $m_{H^+} > 100$ GeV [6]. On the other hand, the vertex $H^+_\alpha W^- h^0_\beta$, deserves special attention because it can give valuable information about the underlying structure of the gauge and scalar sectors. In the first place, the decay mode $H^+ \rightarrow W^+ h^0$ could be detected at the future Large Hadron Collider (LHC) as it was claimed in [7] within the context of the MSSM. Furthermore, the vertex $H^+_\alpha W^- h^0_\beta$, can also induce the associated production of $H^+_\alpha + h^0_\beta$ at hadron collider, through a virtual $W^{*+}$ in the s-channel, which could become a relevant production mechanism for heavy charged Higgs boson.

2. The vertex $H^+_\alpha W^- h^0$

In order to obtain the coupling $W^- H^+ h^0$ it is necessary to determine the physical Higgs states of the charged sector and neutral sector (CP-even). Since we have assumed that the Higgs
potential is CP-invariant, the imaginary and real parts of the neutral scalar fields decouple. Thus, the physical neutral Higgs bosons (CP-even) are determined from \( \text{Re} \phi_0^0 = \varphi_0^0 \). For the charged Higgs, we define a unitary rotation that gives the physical mass eigenstates \( H_\alpha^+ \) as:

\[
H_\alpha^+ = \sum_\beta U_{\alpha\beta} \phi_\beta^+.
\]

Thus, using these rotations \( U \) and \( V \), as well as the previous conventions, we find that the vertex \( W^+ H^-_\alpha H^0_\beta \) is given by

\[
(\mathcal{L}_K)_{W^+ H^-_\alpha H^0_\beta} = \frac{i g}{2} \left[ \sum_{\alpha \geq 2, \beta} \eta_{\alpha, \beta} H^0_\beta \partial^\mu \, H^+_\alpha \right] W^-_\mu.
\]

where \( \eta_{\alpha, \beta} = \sqrt{2} \sum_\gamma T^{\alpha, 0}_\gamma V^{\beta \gamma}_\mu U^{\alpha, 0}_\nu \); it depends on the quantum number \( T_\alpha \), but not on the vev’s.

3. The vertex \( H^+ W^- h^0 \) in a SUSY models with a Higgs triplet

One of the simplest models that predicts a charged Higgs is the THDM, which includes two scalar doublets of equal hypercharge, namely \( \Phi_1 = (\phi_1^+, \phi_1^0) \) and \( \Phi_2 = (\phi_2^+, \phi_2^0) \). This is indeed the Higgs content used in the minimal SUSY extension of the SM (MSSM). In this model, the factor \( \eta \) that appears in the vertex \( H^+ W^- h^0 \) is given by \( \eta_{1,0} = \cos(\beta - \alpha) \), which it is consistent with the literature[2].

The supersymmetric model with two doublets and a complex triplet is one of the simplest extension of the minimal supersymmetric model, that allows to study phenomenological consequences of an explicit breaking of the custodial symmetry SU(2) [8]. As the large number of parameters appearing in the model, which include \( \tan \beta, R, \lambda, \mu_D, \mu_T, A_B, B_T \), one has to consider some simplified cases, for which we shall try to identify useful relations or trends for the behaviour of Higgs masses and couplings of the model. For our numerical analysis of the allowed region and Higgs masses, we shall consider: a) \( \tan \beta \) as an independent-variable; b) \( R \) will take the representative value 0.01; c) the parameter \( \lambda \) will take the value 0.5; and d) the remaining parameters will cover the ranges allowed by SUSY, namely masses in the range between 0 and 1000 GeV. Furthermore, we shall analyze the following specific scenario:

**Scenario I:** \( B_D = \mu_D = 0 \), which represent the scenario when SSB is dominated by the effects of the Higgs triplets, and we shall also consider the following cases (A) \( B_T = \mu_T = A \); (B) \( B_T = \mu_T = -A \); (C) \( B_T = -\mu_T = A \); (D) \( -B_T = \mu_T = A \). Then, for each point in parameter space, within this scenario, we shall determine the allowed regions, by requiring the scalar squared mass eigenvalues to be positive, and the Higgs potential laying in a global minimum. In these allowed regions the masses of the physical Higgs states of the model are computed numerically.

4. Branching ratios for the modes \( H^+_\alpha \to W^+ Z \) and \( H^+_\alpha \to W^+ h^0 \)

We now discuss the BR for the \( H^+_\alpha \to W^+ Z \) and \( H^+_\alpha \to W^+ h^0 \) modes, including also the decay widths of the dominant modes of \( H^+_\alpha \), which turn out to be the following four modes: 1) \( H^+_\alpha \to W^+ Z \); 2) \( H^+_\alpha \to W^+ h^0 \); 3) \( H^+_\alpha \to \tau \nu_\tau \); and 4) \( H^+_\alpha \to t \bar{b} \). We have then evaluated numerically the BR for these four modes, using the previous expressions. For the numerical analyses, we considered the scenarios listed above, which have fixed values of \( \lambda \) and \( \tan \beta \). In scenario I, the calculation are performed for \( \lambda = 0.5, 1 \) and \( \tan \beta = 5, 10, 15 \). We considered the cases A and D within this scenario, for each of the charged Higgs bosons \( H^+_\alpha \). In Figs. 1 we present the BR for case A, with \( \lambda = 0.5 \). In this scenario, the decay \( H^+_\alpha \to W^+ h^0 \) is not allowed for the lightest charged Higgs boson, thus and we only show the results for \( H^+_3 \) and \( H^+_4 \). For \( H^+_2 \), the second lighter charged Higgs boson, we can see that \( W Z \) is the dominant mode, which would be a clear signature of the Higgs triplet. The mode \( W^+ H^0_3 \) reaches an important BR, although it is smaller than the BR for \( t \bar{b} \). For the state \( H^+_3 \), \( W^+ Z \) has a BR of the \( 10^{-1} \) order;
Figure 1. Branching Ratios of the charged Higgs bosons $H^+_\alpha$ in the principal modes for the scenario I, case A, considering $\lambda = 0.5$. The kind of lines correspond to the different modes as: a) dashed: $H^+_\alpha \rightarrow tb$; b) dotted: $H^+_\alpha \rightarrow W^+Z$; c) solid: $H^+_\alpha \rightarrow \tau \bar{\nu}_\tau$; and dot-dashed: $H^+_\alpha \rightarrow W^+ h^0$. The figure show this modes for each charged Higgs boson, the first row correspond to the $H^+_2$ and the second row to $H^+_3$. In the columns is shown the different results to $\tan \beta = 5, 10$ y $15$.

here the mode $W^+ h^0$ is dominant, while the mode $tb$ becomes dominant when $\tan \beta$ increases. In turn, the mode $\tau \nu_\tau$ is the most supressed one, and it reaches a maximum BR of order $10^{-3}$ when $\lambda = 0.5$ and large $\tan \beta$. 
5. Conclusions

We have studied the charged Higgs vertex $H^+_α W^+ φ^0_β$, within the context of several extensions of the $SM$ that predict this vertex. For a Higgs sector that includes arbitrary Higgs representations, we were able to derive the form of this vertex, i.e. its dependence on the isospin and hypercharge of the Higgs multiplet. Then, we evaluated the strength of this vertex for several specific models, which include: i) the THDM, both generic and the MSSM version, and ii) models with additional Higgs triplets, for both SUSY and non-SUSY cases. When the decay $H^+_α → W^+ h^0$ is allowed, it reaches a BR of order $10^{-1} – \cdots$, which could be detected at LHC, and would permit to test the charged Higgs quantum numbers.

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