Light charged Higgs at LHC

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Abstract

The LHC program for discovery of light charged Higgs with mass 135-180 GeV has to take into account decay $H^+ \rightarrow h t^* \rightarrow W^+ b \bar{b}$. The distribution of decay products in effective mass of $t^* = Wb$ is obtained.

The discovery of a charged Higgs boson $H^\pm$ will be a clear indication of non-minimal realization of Higgs mechanism. Below we consider the Two-Higgs-Doublet Model (2HDM) with two basic scalar doublets $\phi_1$ and $\phi_2$, in which vacuum state is characterized by two v.e.v.'s $\langle \phi_1 \rangle = v \cos \beta / \sqrt{2}$ and $\langle \phi_2 \rangle = v \sin \beta / \sqrt{2}$ with $v = 246$ GeV. The observable particles in this model are two neutral scalar Higgs bosons $h$ and $H$ with $M_H \geq M_h$, pseudoscalar $A$ and two charged Higgses $H^\pm$ with mass $M_\pm$. We assume, in accordance with recent LHC data, that $M_h \approx 125$ GeV.

The interaction of charged Higgs with fermions of one generation can be parameterized by Lagrangian

$$L_e = \frac{\sqrt{2}}{v} [\bar{u} (M_d P_R F_D + M_t P_L F_U) d + \bar{\nu} M_\ell P_R F_\ell \ell] H^+ + h.c. \quad (1)$$

The 2HDM allows different variants of the Yukawa interaction. The most popular models for this interaction and coefficients $F_{U,D}$ for them are summarized in the Table 1. The Yukawa sector in 2HDM-II is the same as in MSSM, here right down-type quarks and charged leptons are coupled to $\phi_1$, while right up-type quarks are coupled to $\phi_2$.

| Model | $d$ | $u$ | $\ell$ |
|-------|-----|-----|-------|
| I     | $\phi_2 \cot \beta$ | $\phi_2 \cot \beta$ | $\phi_2 \cot \beta$ |
| II    | $\phi_1 \tan \beta$ | $\phi_2 \cot \beta$ | $\phi_1 \tan \beta$ |
| X     | $\phi_2 \cot \beta$ | $\phi_2 \cot \beta$ | $\phi_1 \tan \beta$ |
| Y     | $\phi_1 \tan \beta$ | $\phi_2 \cot \beta$ | $\phi_2 \cot \beta$ |

Table 1: The most popular models of the Yukawa interactions in the 2HDM and Yukawa couplings $F_A$. The symbols $u, d, \ell$ refer to right up- and down-type quarks and charged leptons of any generation.
coupling constant. In the 2HDM-I all right quarks and leptons are coupled to \( \phi_2 \) only. In the 2HDM-X (lepton-specific model) all right quarks are coupled to \( \phi_2 \) while right leptons are coupled to \( \phi_1 \) (for quark sector 2HDM-X coincides with 2HDM-I). In the 2HDM-Y (flipped model) right down-type quarks are coupled to \( \phi_1 \), while right up-type quarks and leptons are coupled to \( \phi_2 \) (for quark sector 2HDM-Y coincides with 2HDM-II). The table does not include 2HDM-III. This title combines models in which individual fermions interact with both scalars.

In the 2HDM-II the well-measured \( B \to X_s \gamma \) decay rate excludes \( M_+ < 300 \) GeV \(^2\). For other models \( H^\pm \) can be lighter, up to 90 GeV (limitation from LEP).

The strategy of hunting for charged Higgs depends on its mass. At \( M_+ > 180 \) GeV main decay channels of \( H^+ \) are \( H^+ \to t\bar{b} \) and \( H^+ \to hW^+ \). At \( M_+ < 180 \) GeV these decay channels are kinematically forbidden and for the first glance main decay channels are \( H^+ \to c\bar{s}, \ H^+ \to \tau^+ \nu \). This statement is, generally speaking, incorrect since the coupling constant \( g(H^+t\bar{b}) \) is \( \sim 135 \) times larger than \( g(H^+c\bar{s}) \). Because of this huge strengthening, the probabilities of three-body decay \( H^+ \to t^*\bar{b} \to Wb\bar{b} \) and two-particle decay \( H^+ \to c\bar{s} \) are comparable (here \( t^* = W + b \) is off-shell \( t \)).

This fact was noticed while studying small \( \tan \beta \) region of MSSM (where Higgs sector is a special case of 2HDM-II) \(^1\). Later the same phenomenon was found in the 2HDM with another forms of Yukawa interaction (see e.g. \(^3\)). Unfortunately, while discussing the discovery of the light charged Higgs at the LHC some modern papers do not pay attention to this fact \(^4\), \(^5\).

All mentioned calculations were performed using a package HDECAY \(^6\). We find useful to present simple analytical equations, which allow to perform rapid analysis with reasonable accuracy. Besides, we demonstrate that the effect takes place even at large \( \tan \beta \).

First of all, for 2-body decays we have

\[
\Gamma(H^+ \to c\bar{s}) = 3M_+ \frac{M_0^2 F_U^2 + M_W^2 F_D^2}{8\pi v^2}, \quad \Gamma(H^+ \to \tau^+ \nu) = M_+ \frac{M_0^2 F_U^2}{8\pi v^2}. \tag{2}
\]

We denote the effective mass of \( t^* = W + b \) by \( M^* \) and

\[
y = M_0^2 / M_W^2, \quad x = M^2 / M_W^2 \quad \text{with} \quad y > x > 1. \tag{3}
\]

In the calculation of the width \( \Gamma(H^+ \to t^*\bar{b} \to Wb\bar{b}) \) we neglect \( M_b \) in the kinematical relations and traces. The distribution in effective mass \( M^* \) has form

\[
\frac{d\Gamma(H^+ \to t^*\bar{b} \to Wb\bar{b})}{dx} = M_+ \frac{3\alpha}{(8\pi)^2 s_W^2 v^2} \frac{M_0^2}{M_W^2} \times \frac{(y-x)^2(x-1)^2(2+x)}{y^2x(T-x)^2} \left( F_U^2 + F_D^2 \frac{y}{x} + 4F_U F_D \frac{y}{y-x} \right); \tag{4}
\]

\[
T = \frac{M_0^2}{M_W^2} = 4.58, \quad \gamma = \frac{M_b^2}{M_W^2} = 2.7 \times 10^{-3}, \quad s_W = \sin \theta_W.
\]

All parameters were taken from ref. \(^7\). The range of parameters, describing light charged Higgs \( M_+ < M_t \) is \( y < T \).

Let us consider hadronic widths in different cases.
For 2HDM-I and 2HDM-X the coupling $F_U$ dominates at all $\tan\beta$. Hence, the ratio of hadronic widths is independent on $\tan\beta$. The ratio of partial widths of $H^+$ decay is

$$\frac{\Gamma(H^+ \rightarrow \bar{b}t^* \rightarrow \bar{b}bW^+)}{\Gamma(H^+ \rightarrow cs)} = \left(\frac{M_t}{M_c}\right)^2 \frac{\alpha}{8\pi s_W^2} \int_1^\infty \frac{(y-x)^2(x-1)^2(2+x)}{y^2x(T-x)^2} \, dx = 23.05 \left(\frac{y-x}{y-x-1}\right)^2 \frac{2+x}{y^2x(T-x)^2} \, dx. \tag{5}$$

This ratio is shown in Fig. 1-A. One can see that at $M^+ > 130$ GeV the discussed channel reduces strongly BR’s for channels $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow \tau^+\nu$, at $M^+ > 145$ GeV the channel with off-shell $t$ becomes the dominant hadronic channel.

For 2HDM-Y the ratio of hadronic widths depends on $\tan\beta$. At $\tan\beta < 6$, the term $F_D^2$ dominates as in previous case, and ratio of widths is given by eq. (5), Fig. 1-A. With the growth of $\tan\beta$ relative role of $F_D$ term increases, at $\tan\beta > 8$ the term $F_D^2$ becomes dominant and we have (see Fig. 1-B)

$$\frac{\Gamma(H^+ \rightarrow \bar{b}t^* \rightarrow \bar{b}bW^+)}{\Gamma(H^+ \rightarrow cs)} = \left(\frac{M_b}{M_c}\right)^2 \frac{T\alpha}{8\pi s_W^2} \int_1^\infty \frac{(y-x)^2(x-1)^2(2+x)}{y^2x(T-x)^2} \, dx. \tag{6}$$

The ratio of main couplings is reduced from 135 at $\tan\beta < 6$ to $M_b/M_c \sim 40$ at $\tan\beta \geq 9$. Due to this reduction, the area, where 3-body channel is essential, narrows. Note that the narrowing of the range of dominance of 3-body decay occurs in relatively narrow interval of $6 < \tan\beta < 9$. In this interval contribution of the interference term $F_U F_D$ is also essential.

The comparison with leptonic decay channel ($H^+ \rightarrow \tau^+\nu$) can be made in the same manner.

Summary. At $M^+ < 135$ GeV, only 2-body decays of $H^+$ can be observed. At $180$ GeV $> M^+ > 135$ GeV, one should try to observe 3-body decay as well. The BR’s
for different decay channels ($cs, \tau\nu, Wbb$) depend on the model of Yukawa sector and value of $\tan\beta$. Therefore, even rough measuring of BR’s for these decay channels will give important information about mentioned properties of the model.

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