Research Article

Possible Impact of the Fourth-Generation Quarks on Production of a Charged Higgs Boson at the LHC

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Received 26 August 2011; Accepted 9 October 2011

Academic Editors: K. Cho and H. Hayashii

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We investigate the impact of the fourth-generation quarks on production and decays of the charged Higgs boson at CERN Large Hadron Collider (LHC) with 14 TeV center of mass energy. The signal is the process $gg \rightarrow \bar{u}_4 u_4$, followed by $\bar{u}_4 \rightarrow W^- \bar{b}$ and $u_4 \rightarrow h^+ b$ decays with subsequent $h^+ \rightarrow t \bar{b}$ and corresponding hermitic conjugates. It is shown that if $m_{u_4} = 400$ GeV, then considered process will provide unique opportunity to discover charged Higgs boson with mass range of 200 to 350 GeV at the LHC.

1. Introduction

It is known that two-Higgs doublet model (2HDM), in general, and minimal supersymmetric extension of the standard model (MSSM), in particular, predict the existence of a charged scalar particle as well as two neutral scalar particles in addition to the standard model (SM) Higgs boson [1]. Experimental observations of these particles could be indirect indication of SUSY. Experiments at LEP II limit the mass of a charged Higgs boson from below as 79.2 GeV [2]. The Tevatron CDF excludes masses of a charged Higgs boson below 105 and 130 GeV for $\tan \beta = 1$ and $\tan \beta = 40$, respectively, by searching $t \rightarrow h^\pm b$ decays [3]. Obviously, higher energy reach of the Large Hadron Collider (LHC) will give opportunity to search charged

Higgs boson in wider mass region. The production of the charged Higgs boson at the LHC for three SM generation case is considered in a number of papers [4–9].

On the other hand, flavor democracy, which is quite natural in the SM framework, predicts the existence of the fourth-generation (see review [10] and references therein). The masses of the fourth-generation quarks and charged leptons are expected to be almost degenerate with preferable range of $m_4 = 300\text{--}500\text{ GeV}$. Obviously, the fourth-generation quarks in this mass region will be observed at the first few years of the LHC data taking [11–16]. Meanwhile, data collected at Tevatron experiments set limits on m_{u_4} and m_{d_4} as 358 GeV and 372 GeV, respectively [17]. Naturally, as the Tevatron searches $h^\pm$ in t -quark decays, the LHC may do the same in u_4 -quark decays.

In this paper, we investigate the impact of the fourth-generation quarks on production and decays of the charged Higgs boson of 2HDM at the LHC with 14 TeV center of mass energy. In Section 2, the lagrangian describing decays of the charged Higgs is presented and the branching ratios of decays of the fourth SM generation up quark and charged Higgs boson are evaluated. The production of the charged Higgs boson at the LHC via gluon-gluon fusion process $gg \rightarrow \bar{u}_4 u_4$, followed by $\bar{u}_4 \rightarrow W^- \bar{b}$ and $u_4 \rightarrow h^+ b$ decays with subsequent $h^+ \rightarrow t \bar{b}$, as well as the SM background, is studied in Section 3. The statistical significance of the charged Higgs boson signal at the LHC is estimated assuming three b -quark jets to be tagged. Finally, concluding remarks are made in Section 4.

2. Charged Higgs Boson Decays

Interactions involved charged Higgs boson can be described as below [6]:

$$\mathcal{L} = \frac{g}{\sqrt{2}} h^+ (\cot \beta m_{u_i} \bar{u}_i d_{iL} + \tan \beta m_{d_i} \bar{u}_i d_{iR} + \tan \beta m_{l_i} \bar{\nu}_i l_{iR}) + h.c., \quad (2.1)$$

where $i = 1, 2, 3, 4$ denotes the generation index and $\tan \beta$ is defined as ratio of the two Higgs doublets vacuum expectation values. Applying the flavor democracy to three-generation MSSM results in $\tan \beta = m_t / m_b \approx 40$ [10], whereas $\tan \beta = m_{u_4} / m_{d_4} \approx 1$ is preferable in four-generation case. The Cabibbo-Kobayashi-Maskawa (CKM) matrix elements are not shown in (2.1). In numerical calculations, we use CKM mixings given in [18].

In order to compute decay widths of the charged Higgs boson, above lagrangian has been implemented into the CompHEP [19]. The decay branching ratios of the fourth-generation up quark with mass of 400 GeV (used at the rest of the paper), which is the mid-point of preferable range of u_4 mass mentioned at the Section 1, are plotted in Figure 1(a) for $m_{h^\pm} = 200\text{ GeV}$. These plots show that the dominant decay channels of u_4 are bh^+ and sh^+ at low $\tan \beta$ values; bW and sW decays are dominant at $\tan \beta > 1$ region.

Obtained results for branching ratios of decays of the charged Higgs boson into SM fermions are given in Figure 1(b) as a function of $\tan \beta$. The charged Higgs boson dominantly decays to $t\bar{b}$ for almost all $\tan \beta$ values. Furthermore, Figures 2(a) and 2(b) present the branching ratios of the charged Higgs boson decays as a function of its mass for two different values of $\tan \beta$, 1 and 40, respectively.

Figure 1: Branching ratios for different decay channels of the (a) fourth-generation up quark and (b) charged Higgs boson as a function of the $\tan\beta$ in the 2HDM. Following mass values are used: $m_{u_4} = 400$ GeV, $m_{h^\pm} = 200$ GeV, and $m_{h^0} = 115$ GeV.

3. Charged Higgs Boson Production at the LHC

We study the $gg \rightarrow \bar{u}_4 u_4 \rightarrow W^- \bar{b} b h^+ \rightarrow W^- \bar{b} b t \bar{b} \rightarrow W^- \bar{b} \bar{b} b W^+$ (and its hermitic conjugate) production process at the LHC, followed by leptonic decay of one W and hadronic decay of the other. The calculated production cross-sections with $m_{u_4} = 400$ GeV are plotted in Figure 3 for charged Higgs boson mass values of 200 and 300 GeV. CTEQ6L1 parton distribution functions [20] are used in numerical calculations. The SM background (6 jet + 1 lepton + missing energy) cross-sections are computed using MadGraph package [21]. This background is potentially much larger than the signal. However, in order to extract the charged Higgs boson signal and to suppress the SM background, we impose some kinematic cuts. In addition, we assume that three b -quark jets are tagged.

Figure 2: Branching ratios for decays of the charged Higgs boson as a function of its mass for different values of $\tan\beta$: (a) $\tan\beta = 1$ and (b) $\tan\beta = 40$.

We choose the following set of selection cuts: $P_T > 80$ GeV cut for at least one of b -jets and $P_T > 20$ GeV for the rest of the jets and the lepton $|\eta| < 2.5$, where η denotes pseudorapidity, a minimum separation of $\Delta R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} > 0.4$ (ϕ is the azimuthal angle) between the lepton and the jets as well as each pair of jets. The signal and background cross-sections are given in Figure 4 as a function of the reconstructed tb invariant mass. It is drawn for sample values of the charged Higgs boson masses of 200, 250, 300, and 350 GeV for $\tan\beta = 1$. Here, we have included a b -tagging efficiency of 50%. The signal and SM background cross-sections are shown separately in Figure 4(a), while their sum is presented in Figure 4(b). The signal peaks are clearly visible at all selected mass values. The similar plots for $\tan\beta = 40$ are presented in Figures 5(a) and 5(b).

Figure 3: $\sigma \times BR$ of the process $gg \rightarrow \bar{u}_4 u_4 \rightarrow W^- \bar{b} b h^+ \rightarrow W^- \bar{b} b t \bar{b} \rightarrow W^- \bar{b} b \bar{b} b W^+ \rightarrow \bar{b} \bar{b} \bar{b} b l \nu \bar{q} q'$ for a charged Higgs boson with 200 and 300 GeV masses as a function of $\tan \beta$.

Table 1: The number of charged Higgs boson signal and SM background events and the statistical significance of the signal for $\tan \beta = 1$.

$m_{h^\pm} \pm 20 \text{ GeV}$	S		B		$S/\sqrt{B}$	
	100 fb ⁻¹	10 fb ⁻¹	100 fb ⁻¹	10 fb ⁻¹	100 fb ⁻¹	10 fb ⁻¹
200	1710	171	105	10.5	166.9	52.8
250	1540	154	134	13.4	133.0	42.1
300	833	83.3	75	7.5	96.3	30.4
350	215	21.5	47	4.7	31.3	9.9

Table 2: The same as Table 1 but for $\tan \beta = 40$.

$m_{h^\pm} \pm 20 \text{ GeV}$	S		B		$S/\sqrt{B}$	
	100 fb ⁻¹	10 fb ⁻¹	100 fb ⁻¹	10 fb ⁻¹	100 fb ⁻¹	10 fb ⁻¹
200	630	63.0	105	10.5	61.5	19.4
250	599	59.9	134	13.4	51.8	16.4
300	263	26.3	75	7.5	30.4	9.6
350	57	5.7	47	4.7	8.2	2.6

The number of events—in a window of 40 GeV around selected $m_{h^\pm}$ values—for signal (S), and SM background (B), along with the statistical significance ($S/\sqrt{B}$) for 100 fb⁻¹ and 10 fb⁻¹ of integrated luminosity is presented in Tables 1 and 2 for $\tan \beta = 1$ and $\tan \beta = 40$, respectively. It is seen that the mass regions $m_{h^\pm} = 200\text{--}350$ GeV for $\tan \beta = 1$ and $m_{h^\pm} = 200\text{--}300$ GeV for $\tan \beta = 40$ are covered with more than 5σ even with low integrated luminosity

Figure 4: The signal cross-section distributions of the reconstructed charged Higgs boson mass for four selected mass values at $\tan\beta = 1$ and corresponding SM background: (a) separated and (b) summed.

of 10 fb^{-1} . To compare with three SM generation case, for example, we obtain the signal significance 9.6σ with 10 fb^{-1} for the four-family case at $\tan\beta = 40$ and $m_{H^\pm} = 300 \text{ GeV}$, whereas $S/\sqrt{B}$ is 6.2 with 100 fb^{-1} in three SM generation case as given in [7]. The signal significance discussed here assumes perfect detector. More realistic detector future such as the effect of the realistic jet-mass resolutions as well as the method of how to choose the best combination is discussed in [9].

Figure 5: The same as Figure 4 but for $\tan\beta = 40$.

4. Conclusion

Our study shows that the existence of the fourth SM generation provides new channel for charged Higgs boson search at the LHC. If the fourth-generation quarks and charged Higgs boson have appropriate masses, then this channel will be a discovery mode. More detailed study including higher m_{u_4} mass values, as well as further optimizations of cuts, detector features, and so forth, is ongoing.

Acknowledgments

R. Çiftçi would like to acknowledge for support from the Scientific and Technical Research Council (TUBITAK) BİDEB-2218 Grant. This work was also supported in part by the State Planning Organization (DPT) under Grant no. DPT-2006K-120470 and in part by the Turkish Atomic Energy Authority (TAEA) under Grant no. VII-B.04.DPT.1.05.

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