Associated production of the charged Higgs boson and single top quark at the LHC

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Abstract

The left-right twin Higgs(LRTH) model predicts the existence of the charged Higgs $\phi^{\pm}$. In this paper, we study the production of the charged Higgs boson $\phi^{-}$ with single top quark via the process $bg \to t\phi^{-}$ at the CERN Large Hadron Collider(LHC). The numerical results show that the production cross section can reach the level of 10pb in the reasonable parameter space of the LRTH model. We expect that, as long as it is not too heavy, the possible signatures of the heavy charged Higgs boson $\phi^{-}$ might be detected via the decay mode $\phi^{-} \to t\bar{b}$ at the LHC experiments.

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1 Introduction

Most extensions of the standard model (SM) require the introduction of extended Higgs sector to the theory. Generically, charged Higgs boson arises in the extended Higgs sector, which does not exist in the SM. It implies that the observation of a charged Higgs boson is a clear evidence for existence of the new physics beyond the SM. Many alternative new physics theories, such as supersymmetry, topcolor, and little Higgs, predict the existence of new scalar or pseudo-scalar particles. These new particles may have cross sections and branching fractions that differ from those of the SM Higgs boson. Thus, studying the production and decays of the new scalars at hadron colliders will be of special interest. The CERN Large Hadron Collider (LHC) is expected to directly probe possible new physical beyond the SM up to few TeV and provide some striking evidence of new physics [1].

Recently, the twin Higgs mechanism has been proposed as a solution to the little hierarchy problem [2, 3, 4, 5]. The Higgs is a pseudo-Goldstone boson of a spontaneously broken global symmetry. Gauge and Yukawa interactions that explicitly break the global symmetry give mass to the Higgs. Once a discrete symmetry is imposed, the leading quadratic divergent term respects the global symmetry, thus does not contribute to the Higgs model. The twin Higgs mechanism can be implemented in left-right models with the discrete symmetry being identified with left-right symmetry [4]. The left-right twin Higgs (LRTH) model contains $U(4)_1 \times U(4)_2$ global symmetry as well as $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetry. The left-right symmetry acts on only the two $SU(2)_L$ gauge symmetry. The leading quadratically divergent SM gauge boson contributions to the Higgs masses are canceled by the loop involving the heavy gauge bosons. A vector top singlet pair is introduced to generate an $O(1)$ top Yukawa coupling. The quadratically divergent SM top contributions to the Higgs potential are canceled by the contributions from a heavy top partner. The LRTH model predicted the existence of the new heavy particles, such as heavy gauge boson, fermions, and scalars at or below the TeV scale, which might generate characteristic signatures at the present and future collider experiments, especially at the LHC [6, 7, 8, 9].

This paper is organized as follows, In section two, we first briefly introduce the LRTH model, and then give the production amplitude of the process. The numerical results and discussions are presented in section three. The conclusions are given in section four.
2 The Left-Right twin Higgs model and the production amplitude of $bg \to t\phi^-$

The LRTH model is based on the global $U(4)_1 \times U(4)_2$ symmetry, with a locally gauged subgroup $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The two Higgs fields, $H$ and $\hat{H}$, are introduced and each transforms as $(4, 1)$ and $(1, 4)$ respectively. The introduction of the extra Higgs field $\hat{H}$ enlarge the global symmetry to $U(4)_1 \times U(4)_2$. The global $U(4)_1(U(4)_2)$ symmetry is spontaneously broken down to its subgroup $U(3)_1(U(3)_2)$ with non-zero vacuum expectation values as $\langle H \rangle = (0, 0, 0, f)$ and $\langle \hat{H} \rangle = (0, 0, 0, \hat{f})$. Each spontaneously symmetry breaking results in seven Nambu-Goldstone bosons. Three of six Goldstone bosons that are charged under $SU(2)_R$ are eaten by the heavy gauge bosons, while leaves three physical Higgs: $\phi^0$ and $\phi^\pm$. The remaining Higgses are the SM Higgs doublet $H_L$ and an extra Higgs doublet $\hat{H}_L = (\hat{H}_1^+, \hat{H}_2^0)$ that only couples to the gauge boson sector. A residue matter parity in the model renders the neutral Higgs $\hat{H}_2^0$ stable, and it could be a good dark matter candidate. A pair of vector-like quarks $q_L$ and $q_R$ are introduced in order to give the top quark a mass of the order of electroweak scale, which are singlets under $SU(2)_L \times SU(2)_R$. The masse of the light SM-like top and the heavy top are \[\frac{m_t^2}{y^2 f^2} \sim \left(\frac{y v}{\sqrt{2}}\right)^2,\] \[m_T^2 \sim y^2 f^2 + M^2 - m_t^2, \tag{2}\]

where $x = v/\sqrt{2}f$, the mass parameter $M$ is essential to the mixing between the SM-like top quark and the heavy top quark. The top Yukawa coupling can then be determined by fitting the experimental value of the light top quark mass. At the leading order of $1/f$, the mixing angles for left-handed and right-handed fermions are \[S_L \sim \frac{M}{m_T} \sin x, \quad \tag{3}\] \[S_R \sim \frac{M}{m_T} (1 + \sin^2 x). \quad \tag{4}\]

The value of $M$ is constrained by the requirement that the branching ratio of $Z \to b\bar{b}$ remains consistent with the experiments.

The LRTH model introduces charged Higgs bosons $\phi^\pm$ in addition to the neutral Higgs, the
couplings constant of the charged Higgs boson to the third generation quarks can be written as [6]

\[ \Lambda^{\phi tb} = -i(S_R m_b P_L - y S_L f P_R)/f, \]  

(5)

where \( P_{L(R)} = (1 \mp \gamma_5)/2 \) is the left(right)-handed projection operator.

A future discovery of a charged Higgs boson would be a sure sign of new physics beyond SM. We concentrate on the process \( gb \to tH^\pm \) which is the most promising channels for the charged Higgs boson production at the LHC when \( H^\pm \) is heavier than the top quark [10]. Thus, the associated production of the charged Higgs bosons predicted by the minimal supersymmetric standard model (MSSM) with single top quark has been extensively investigated in Refs. [11, 12, 13, 14, 15, 16, 17]. In the LRTH model, the charged Higgs boson \( \phi^\pm \) have larger Yukawa couplings to the third family quarks. Thus, the charged Higgs boson \( \phi^\pm \) should be abundantly produced via the subprocess \( gb \to t\phi^\pm \) at LHC. The relevant Feynman diagrams are shown in Fig.1.

At the leading order, the scattering amplitude of the partonic process \( bg \to t\phi^- \) can be written as:

\[ M_1 = g_s \bar{u}(t) \left[ \frac{\Lambda^{\phi tb}(P_g + P_b + m_b)z_1}{s' - m_b^2} + \frac{z_1 (P_t - P_g + m_t)\Lambda^{\phi tb}}{\hat{u} - m_t^2} \right] u(b), \]

(6)

where \( s' = (P_g + P_b)^2 = (P_{\phi^-} + P_t)^2 \), \( \hat{u} = (P_t - P_g)^2 = (P_b - P_{\phi^-})^2 \), \( z_1 \) is the gluon polarization vector.

The cross section for single production of the charged gauge boson \( \phi^- \) associated with a top
quark at the LHC with the center-of-mass $\sqrt{s} = 14TeV$ can be obtained by convoluting the production cross section $\hat{\sigma}(t\phi^-)$ of the partonic process $bg \rightarrow t\phi^-$ with the parton distribution functions [18]. In the calculation of the cross section, instead of calculating the square of the production amplitudes analytically, we calculate the amplitudes numerically by using the method of the references [19] which can greatly simplify our calculation.

3 The numerical results and discussions

In the numerical calculation, we take the input parameters as $m_t = 171.4 GeV$ [20], $\alpha_e = 1/128.8$, $\alpha_s = 0.118$ and $s_W^2 = 0.2315$ [21]. Except for these SM input parameters, the production cross sections of the charged Higgs boson from twin Higgs model is dependent on the symmetry breaking scale $f$ and the mass of the charged Higgs boson $\phi^-$. Taking into account the precision electroweak constraints on the parameter space, the symmetry breaking scales $f$ is allowed in the range of $f = 500 \sim 1500 GeV$. It has been shown $M_{\phi^-}$ is allowed to be in the range of a few hundred GeV depending on the model [6]. As numerical estimation, we will assume that $M_{\phi^-}$ is in the range of $150 \sim 500 GeV$.

In Fig.2, we plot the cross section $\sigma(s)$ for single production of the charged Higgs boson $\phi^-$.

![Figure 2: The cross section $\sigma(s)$ as a function of the mass parameter $M_{\phi^-}$ for $M = 150GeV$ and different values of the symmetry breaking scales $f=500, 1000$ and $1500GeV$.](image-url)
associated with top quark at the LHC with $\sqrt{s} = 14 TeV$ are plotted as a function of the mass parameter $M_{\phi^-}$ for three values of the symmetry breaking scales $f$. One can see that the dependence of the cross section $\sigma(s)$ on the parameter $f$ is obvious and the cross section decrease as $f$ increases. In all the parameter space, the cross section increase with $M_{\phi^-}$ decreasing. For $f = 1000 GeV$ and $150 GeV \leq M_{\phi^-} \leq 500 GeV$, the value of the cross section $\sigma(s)$ is in the range of $0.1 \sim 1.6 pb$. If we assume the yearly integrated luminosity of the LHC is $\mathcal{L} = 100 fb^{-1}$, then there will be $1.08 \times 10^4 \sim 1.62 \times 10^5$ events to be generated each year.

The cross section depends sensitively on the parameter $M$, which is the mass mixing between the SM-like top quark and the heavy top quark. In Fig.3, we plot the cross sections as the function of the mass parameter $M_{\phi^-}$ for $f = 1 TeV$ and three different values of the parameter $M$.

![Figure 3: The cross section $\sigma(s)$ of single $\phi^-$ production as a function of the mass parameter $M_{\phi^-}$ for $f = 1 TeV$ and three different values of the parameter $M$.](image)

Furthermore, it yields large log divergence of the SM Higgs mass. To compensate for it the heavy gauge bosons also get large masses, it is natural for us to take a typical nonzero value of the mass mixing parameter $M = 150 GeV$. 
To see the influence of the symmetry breaking scale $f$ on the cross section, in Fig. 4 we

plot $\sigma(s)$ as a function of the symmetry breaking scale $f$ for $M = 150 GeV$ and three values of $M_{\phi^-} = 200, 300, 400 GeV$, respectively. From Fig. 4, one can see that the cross section decreases as the symmetry breaking scale $f$ increases for fixed new gauge boson mass $M_{\phi^-}$. This is because the value of the production section is proportional of the order of $M^2/f^2$, which comes from the flavor changing couplings $\Lambda_{\phi^-tb}$. On the other hand, as long as the symmetry breaking scale $f$ is smaller than $1000 GeV$, the production section of $t\phi^-$ can reach the level of several $pb$ at the LHC. With the yearly luminosity $\mathcal{L} = 100 fb^{-1}$ for the LHC, there will be a promising number of fully reconstructible events to detect at the LHC.

It is known that many new physics model predict similar heavy charged scalars, such as $\Pi^\pm$ in the topcolor-assisted technicolor model (TC2) and $H^\pm$ in the MSSM [22, 23, 24]. The results show that the production rates are larger than those for the charged Higgs boson $H^\pm$ from the MSSM. It has been shown that the heavy Higgs bosons $H^\pm$ can be detected via the decay channels $H^\pm \rightarrow \tau \nu, \, tb$ or $W^\pm h^0$ at LHC [24]. The $tb$ is the main decay mode for both charged Higgs boson, such mode is not suitable to distinguish these particles. To obtain the identified signals of the charged Higgs bosons, we should probe the charged Higgs bosons $H^\pm$ from MSSM.

Figure 4: The cross section $\sigma(s)$ of single $\phi^-$ production as a function of the symmetry breaking scales $f$ for $M = 150 GeV$ and different values of $M_{\phi^-}$. 
via the decay mode $\tau \nu_\tau$ which does not exist for the charged Higgs bosons $\phi^\pm$ in the LRTH model. To distinguish the scalars in the LRTH model from the charged top-pions in the TC2 model, we should probe charged top-pions via the flavor-changing decay mode $\Pi^+ \to c\bar{b}$ to obtain the identified signals, which is not exist for the charged Higgs bosons $\phi^\pm$.

According the analysis results of Ref.\[11, 12, 13, 14\], the 3 b-tags is better for detecting the signals of this process than the 4 b-tags. For 3 b-tags, the background of the subprocess $gb \to t\bar{b} \phi^- \to t\bar{b}b$ comes from the next-to-leading order QCD processes

$$gg \to t\bar{b}b, \quad gb \to t\bar{b} + h.c., \quad gg \to t\bar{b}g,$$  \hspace{1cm} (7)

where the gluon jet in the last case can be mistagged as $b$ (with a typical probability of $\sim 1\%$). One requires leptonic decay of one of the $t\bar{t}$ pair and hadronic decay of the other with a $p_T > 30 GeV$ cut on all the jets \[24\]. For this cut the b-tagging efficiency at LHC is expected to be $\sim 50\%$. Considering the complete next-to-leading order QCD corrections, the production cross section for the process $p\bar{p} \to tH^\pm + X$ is smaller than 1pb in most of the parameter space of MSSM. Reference\[25\] has reviewed the main background processes for the charged Higgs boson production at the LHC. They have shown that, the total background cross section is about $8.5 pb$. Similar to Ref.\[25\], we take the appropriate cuts and the reconstruction of the $\phi^-$ mass, the value of the ratio of signal over square root of the background $S/\sqrt{B}$ is larger than 5 in the suitable parameter space of the LRTH model. We expect that, as long as it is not too heavy, the charged Higgs boson $\phi^\pm$ should be observed in the near future LHC experiments in the favorable parameter spaces(for example, small value of $f$ and large value of $M$) of the LRTH model.

4 Conclusion

The SM predicts the existence of a neutral Higgs boson, while many popular models beyond the SM predict the existence of the neutral or charged scale particles. These new particles might produce the observable signatures in the current or future high energy experiments, which is different from that for the SM Higgs boson. Any visible signal from the new scalar particles will be evidence of new physics beyond the SM. Thus, studying the new scalar particle production at LHC is very interesting.
The twin Higgs mechanism provides an alternative method to solve the little hierarchy problem. The LRTH model is a concrete realization of the twin Higgs mechanism. The model predicts a heavy top quark, new gauge bosons and several scalar bosons. The process $bg \rightarrow tH^-$ offers a promising possibility for discovering a charged Higgs boson. In the context of the LRTH model, we calculate the production cross sections of the process $p\bar{p} \rightarrow t\phi^\pm + X$ at the LHC. Our numerical results show that the new charged Higgs boson $\phi^-$ can be abundantly produced at the LHC. We can detect the possible signals of the charged scalar $\phi^\pm$ at the near future LHC experiments through the process $p\bar{p} \rightarrow t\phi^\pm + X$ in their $tb$ decay channel.

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