Single production of charged gauge bosons from little Higgs models in association with top quark at the LHC

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March 26, 2022

Abstract

In the context of the little Higgs models, we discuss single production of the new charged gauge bosons in association with top quark at the CERN Large Hadron Collider (LHC). We find that the new charged gauge bosons $W_H^-$ and $X^-$, which are predicted by the littlest Higgs model and the $SU(3)$ simple model, respectively, can be abundantly produced at the LHC. However, since the main backgrounds coming from the processes $pp \to t\bar{t} + X$ and $pp \to tW^- + X$ are very large, the values of the ratios $N_W$ and $N_X$ are very small in most of the parameter space. It is only possible to detect the signal of the gauge boson $W_H^-$ via the process $pp \to gb + X \to tW_H^- + X$ at the LHC in a small region of the parameter space.

PACS number(s): 12.60.Cn, 14.65.Ha, 12.15.-y

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I. Introduction

Most of the new physics models predict the existence of the new gauge bosons, generally called $Z'$ or $W'$ with masses in the $\text{TeV}$ range. If these new particles are discovered, they would represent irrefutable proof of new physics, most likely that the gauge group of the standard model ($\text{SM}$) must be extended. Thus, search for extra gauge bosons provides a common tool in quest for new physics at the next generation collider experiments[1]. The discovery and study of extra gauge bosons is one of the important goals of the CERN Large Hadron Collider ($\text{LHC}$).

The little Higgs models[2] propose a new approach to electroweak symmetry breaking ($\text{EWSB}$) accomplished by a naturally light Higgs sector. These models predict new gauge bosons, fermions, and scalars at or below the $\text{TeV}$ scale, which might generate characteristic signatures at the next generation collider experiments, especially at the $\text{LHC}$[3,4]. The little Higgs models generally predict the existence of the pure left-handed charged gauge boson $W'$, which has the $\text{SM}$-like couplings to ordinary particles and might generate significant corrections to single top quark production at the $\text{LHC}$[5]. It has been shown that the charged gauge bosons from little Higgs models should be either seen or excluded in the first year of running at the $\text{LHC}$[6]. Thus, it is very interesting to study production of these new charged gauge bosons at the $\text{LHC}$.

In the $\text{SM}$ framework, single production of the charged gauge bosons $W^\pm$ associated with a top quark is one of the important process for single top quark production. Its cross section is negligible at the $\text{Tevatron}$ but of considerable size at the $\text{LHC}$, where it is larger than that of the $s$-channel process for single top quark production. There is an extensive work on $tW$ associated production at the $\text{LHC}$ in the literature[7,8,9]. The production cross section for this process has been calculated at leading order, with a subset of the next-to-leading order ($\text{NLO}$) corrections included[7]. Including both the subsequent leptonic decays $W \rightarrow l\nu$ and $t \rightarrow l\nu b$, as well as the emission of real radiation in the top decay, a \text{NLO} calculation of this process has been given in Ref.[8]. Recently, Ref.[9] gives a complete calculation of electroweak supersymmetric effects at one loop to $tW$ associated production at the $\text{LHC}$. In this letter, we will study single production
of the charged gauge bosons predicted by the little Higgs models in association with top quark and see whether the possible signals of these new particles can be detected via this process at the LHC.

II. The relevant formulas

Based on the structure of the extended electroweak gauge group, the little Higgs models can be generally divided into two classes[3,10]: the product group models in which the $SU(2)_L$ gauge group arises from the diagonal breaking of two or more gauge groups, and the simple gauge group models in which the $SU(2)_L$ gauge group arises from the breaking of a single larger gauge group down to an $SU(2)$ subgroup. The littlest Higgs models ($LH$)[11] and the $SU(3)$ simple group model[10,12] are the simplest examples of the product group models and the simple group models, respectively. All of these little Higgs models predict the pure left-handed charged gauge boson $W'$. The couplings of the new particle $W'$ to fermions can be unitive written as:

$$\mathcal{L}_{W'q_iq_j} = \frac{eA}{\sqrt{2}S_W} V_{ij} W'_{\mu} \bar{q}_i r^\mu P_L q_j,$$

where $P_L = (1 - \gamma_5)/2$, $V_{ij}$ is the CKM matrix element, and $S_W = \sin \theta_W$ ($\theta_W$ is the Weinberg angle). For the charged gauge boson $W_H$ predicted by the $LH$ model, the constant $A$ equals to $c/s$ for $(q_i, q_j) = (u, d), (c, s)$, and $(t, b)$, in which $c(s = \sqrt{1 - c^2})$ is the mixing parameter between $SU(2)_1$ and $SU(2)_2$ gauge bosons[13]. For the charged gauge boson $X^-$ predicted by the $SU(3)$ simple group model, the constant $A$ equals to $\delta_t$ and $\delta_\nu$ for $(q_i, q_j) = (t, b)$ and $(u, d)[or (c, s)]$, respectively. The factors $\delta_t$ and $\delta_\nu$ can be written as[3]:

$$\delta_t = \frac{\nu}{\sqrt{2}f} \frac{x_\lambda^2 - 1}{x_\lambda^2 + t_\beta^2}, \quad \delta_\nu = -\frac{\nu}{2ft_\beta}.$$  

Where $\nu = 246 GeV$, $f = \sqrt{f_1^2 + f_2^2}$, $t_\beta = \tan \beta = f_2/f_1$, and $x_\lambda = \lambda_1/\lambda_2$, in which $f_1$ and $f_2$ are the vacuum condensate values of the two sigma-model fields $\Phi_1$ and $\Phi_2$, respectively. $\lambda_1$ and $\lambda_2$ are the Yukawa coupling parameters.

It has been shown that the collinear $\bar{b}$ component of the inclusive process $gg \rightarrow t\bar{b}W^-$ can be attached as a QCD NLO correction to bottom quark distribution function of the
exclusive process $bg \rightarrow tW^-$ at the partonic level[7,8,9]. The LO contributions to $tW^-$ associated production is best considered to arise from the process $bg \rightarrow tW^-$. Thus, in this paper, we only consider single production of the heavy charged gauge boson $W^-_i$ in association with a top quark via the two body final state process $bg \rightarrow tW^-_i$ at the LHC as shown in Fig.1 in which $i = 1$ and 2 represent the gauge bosons $W^-_H$ and $X^-$, respectively. Our numerical results are easy transferred to those for single production of the heavy gauge boson $W^+_i$ at the LHC by replacing $\bar{b}$ as $b$ and $\bar{t}$ as $t$.

![Feynman diagrams for the partonic process $bg \rightarrow tW^-_i$](image)

Figure 1: Feynman diagrams for the partonic process $bg \rightarrow tW^-_i$

At the leading order, the scattering amplitude of the partonic process $bg \rightarrow tW^-_i$ can be written as:

$$M = \frac{eg_s A}{\sqrt{2}S_W}\bar{u}(t)[\frac{\varepsilon_2 P_L (P_g + P_b + m_b)}{s' - m_b^2} + \frac{\varepsilon_1 (P_t - P_g + m_t) \varepsilon_2 P_L}{\hat{u} - m_t^2}]u(b),$$

(3)

where $s' = (P_g + P_b)^2 = (P_{W_i} + P_t)^2$, $\hat{u} = (P_t - P_g)^2 = (P_b - P_{W_i})^2$. $\varepsilon_1$ and $\varepsilon_2$ are the gluon and $W^-_i$ polarization vectors, respectively.

The cross section for single production of the heavy gauge boson $W^-_i = W^-_H$ or $X^-$ associated with a top quark at the LHC with the center-of-mass $\sqrt{S} = 14$ TeV can be obtained by convoluting the production cross section $\hat{\sigma}(tW^-_i)$ of the partonic process $gb \rightarrow tW^-_i$ with the parton distribution functions (PDF’s):

$$\sigma_i(S) = \int_{x_1}^{x_1} dx_1 \int_{x_1/\tau}^{1} dx_2 [f_{g/p}(x_1, \mu)f_{b/p}(x_2, \mu)\hat{\sigma}(tW^-_i) + f_{b/p}(x_1, \mu)f_{g/p}(x_2, \mu)\hat{\sigma}(tW^-_i)]$$

where $\tau = (M^2_{W_i} + m_t^2)/S$ and $s' = x_1 x_2 S$. Through out this paper, we will use CTEQ6L PDF’s[14] for the bottom quark and gluon PDF’s. Following the suggestions given by
Refs. [7, 8, 9], we assume that the factorization scale $\mu$ for the bottom quark $PDF$ is of order $(M_{W_t} + m_t)/4$.

III. Numerical results and conclusions

Except for the $SM$ input parameter $m_t = 171.4 GeV$ [15], $\alpha_e = 1/128.8$, $\alpha_s = 0.118$, and $S^2_W = 0.2315$ [16], the production cross sections of the new charged gauge bosons $W_{H^-}$ and $X^-$ coming from the $LH$ model and the $SU(3)$ simple group model are dependent on the free parameters $(M_{W_H}, c)$ and $(M_X, x_\lambda, t_\beta)$, respectively. Considering the constraints of the electroweak precision data on these free parameters, we will assume $1 TeV \leq M_{W_H} \leq 2 TeV$ and $0 < c \leq 0.6$ for the $LH$ model [17] and $1 TeV \leq M_X \leq 2 TeV$, $x_\lambda > 1$, and $t_\beta > 1$ for the $SU(3)$ simple group model [3, 10, 12] in our numerical calculation.

Figure 2: The cross section $\sigma_{W^-}$ as a function of the mass parameter $M_{W_H}$ for the mixing parameter $c = 0.2$ (solid line), 0.4 (dashed line), and 0.6 (dashed-dotted line).

The cross sections $\sigma_{W^-}$ and $\sigma_X$ for single production of the new gauge bosons $W_{H^-}$ and $X^-$ associated with top quark at the $LHC$ with $\sqrt{S} = 14 TeV$ are plotted as functions of the mass parameters $M_{W_H}$ and $M_X$ in Fig. 2 and Fig. 3, respectively, in which we have taken different values of the free parameters $c, x_\lambda$, and $t_\beta$. One can see from these figures that the single production cross section for the gauge boson $W_{H^-}$ is larger than that for the gauge boson $X^-$, which is because compared to the coupling $W_{H^-} t \bar{b}$, the coupling $X^- t \bar{b}$ is suppressed by the factor $\nu/f$. For $0.2 \leq c \leq 0.6$, $1 TeV \leq M_{W_H} \leq 2 TeV$, the value of
the production cross section $\sigma_W$ is in the range of $0.7 fb \sim 286.7 fb$. The production cross section $\sigma_X$ increase as the free parameter $x_\lambda$ increasing. For $x_\lambda = 5$, $1 \leq t_\beta \leq 3$, and $1 TeV \leq M_X \leq 2 TeV$, the value of $\sigma_X$ is in the range of $0.16 fb \sim 15.3 fb$.

![Graphs showing $\sigma_X$ vs $M_X$ for different $x_\lambda$ and $t_\beta$.](image)

Figure 3: The cross section $\sigma_X$ as a function of the mass parameter $M_X$ for different values of the free parameters $x_\lambda$ and $t_\beta$.

To see whether the heavy gauge bosons $W^-_H$ and $X^-$ can be observed at the LHC via the processes $pp \to gb + X \to tW^-_H + X$ and $pp \to gb + X \to tX^- + X$, we discuss the possible decay modes of the heavy gauge bosons $W^-_H$ and $X^-$. For $W^-_H$, the main decay modes are $W^-H$, $\bar{q}q'$, and $l^-\nu$, in which $q(q')$ and $l^-$ present all three generation quarks and leptons, respectively. If we neglect the final state masses, then we have $\Gamma(W^-_H \to \bar{q}q') = 3\Gamma(l^-\nu)$. At leading order, the total decay width $\Gamma_{W^-_H}$ can be approximately written
as\cite{17}:

\[
\Gamma_{W^+H^-} = \frac{\alpha_s}{96s_W^2} \left[\frac{96c^2}{s^2} + \frac{C_W^2 (c^2 - s^2)^2}{s^2 c^2}\right] M_{W^+H^-}. \quad (5)
\]

For the heavy gauge boson $X^-$, the main decay modes are $\bar{q}q'$ and $l^-\nu$. The total decay width $\Gamma_{X^-}$ can be approximately written as\cite{3}:

\[
\Gamma_{X^-} = \frac{\alpha_s M_X}{4S_W^2} (\delta_t^2 + 5\delta_r^2). \quad (6)
\]

In general, to reject backgrounds in hadronic collider environment, the heavy gauge bosons may be most likely to be observed via their pure leptonic decays. In this case, single production of the heavy gauge boson $W_H^-$ or $X^-$ associated with a top quark gives the possible observable five fermion final states with at least one $b$ quark $\nu l^+ l^- b$ with $W_H^-(X^-) \rightarrow l^- \nu$ and $t \rightarrow W^+ b \rightarrow \nu l^+ b$. The backgrounds of this kind signals mainly come from the SM processes $pp \rightarrow tt + X$ and $pp \rightarrow tW^- + X$, in which for the $tt$ production process, one of the bottom quarks from a top decay is assumed missing detection\cite{7}. Under narrow width approximation, the number of this kind signal events can be written as $S_W = \mathcal{L}_{int} \sigma_W Br(W_H^- \rightarrow l^- \nu) Br(t \rightarrow \nu l^+ b)$ and $S_X = \mathcal{L}_{int} \sigma_X Br(X^- \rightarrow l^- \nu) Br(t \rightarrow \nu l^+ b)$, in which $\mathcal{L}_{int}$ is the yearly integrated luminosity of the LHC with $\sqrt{s} = 14 TeV$. In our numerical estimation, we will take $\mathcal{L}_{int} = 100 fb^{-1}$.

![Figure 4: The ratio of signal over square root of the background ($S_W/\sqrt{B}$) for the $W_H^-$ production associated with top quark at the LHC.](image-url)
To see the signals against the backgrounds for the heavy gauge bosons $W^-_H$ and $X^-$, we introduce the ratio of signal over square root of the backgrounds: $N_W = S_W/\sqrt{B}$ and $N_X = S_X/\sqrt{B}$, in which $B$ includes the contributions of $t\bar{t}$ production process and $tW^-$ production process. To simple our calculation, we assume that all charged gauge bosons $W^-_H, X^-$ and $W^+$ decay to $e\nu_e$. Similar to Ref.[8], we take the appropriate cuts on the transverse momentum $P_T(e)$ and rapidly $\eta(e)$ for the final electron as: $P_T(e) > 20\text{GeV}$ and $|\eta(e)| \leq 2.5$. For the $b$ quark, which comes from top quark decay, we take the cuts as: $P_T(b) > 30\text{GeV}$ and $|\eta(b)| \leq 3$. Our numerical result are shown in Fig.4, in which we plot the ratio $N_W$ as a function of the mass $M_{W_H}$ for three values of the free parameter $c$. Our numerical results show that the value of the ratio $N_X$ is smaller than 0.1 in most of the parameter space of the $SU(3)$ simple model. So we do not give our numerical results for the heavy gauge boson $X^-$ in Fig.4. One can see from Fig.4 that for $c \geq 0.5$ and $M_{W_H} \leq 1.5\text{TeV}$, the value of the ratio $N_W$ is larger than 1, which might be detected at the $LHC$[1].

Little Higgs models can be generally divided in two classes: product group models and simple group models. All of the little Higgs models predict the existence of the new charged gauge boson $W'$ with mass in TeV range, which has the $SM$-like couplings to the ordinary fermions. In this letter, we investigate single production of these new gauge bosons associated with a top quark at the $LHC$. We find that the new charged gauge bosons $W^-_H$ and $X^-$, which are predicted by the $LH$ model and the $SU(3)$ simple model, respectively, can be abundantly produced at the $LHC$. However, since the main backgrounds coming from the processes $pp \to t\bar{t} + X$ and $pp \to tW^- + X$ are very large, the values of the ratios $N_W$ and $N_X$ are very small in most of the parameter space. The possible signals of the gauge bosons $X^-$ can not be observed via the process $pp \to gb + X \to tX^- + X$ at the $LHC$. For the gauge boson $W^-_H$, it might be possible to detect its signal via the process $pp \to gb + X \to tW^-_H + X$ at the $LHC$ only for the mixing parameter $c \geq 0.5$ and the mass parameter $M_{W_H} \leq 1.5\text{TeV}$.
Acknowledgments

C. X. Yue would like to thank the Abdus Salam International Centre for Theoretical Physics (ICTP) for partial support. This work was supported in part by Program for New Century Excellent Talents in University (NCET-04-0290), the National Natural Science Foundation of China under the Grants No.10475037.

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