Associated production of the $Z$ boson with a pair of top quarks in
the left-right twin Higgs model

Jinzhong Han$^1$, Bingfang Yang$^{2,3}$, and Xiantu Zhang$^1$

$^1$School of Physics and Electromechanical Engineering,
Zhoukou Normal University, Henan, 466001, China
$^2$Basic Teaching Department, Jiaozuo University, Jiaozuo 454000, China
$^3$School of Materials Science and Engineering,
Henan Polytechnic University, Jiaozuo 454000, China

Abstract

In the context of the left-right twin Higgs (LRTH) model, we first examine the effects on the
$Zt\bar{t}$ production at the ILC and LHC. Our results show that the cross-sections can be significantly
deviated from the standard model predictions and thus provide a good probe for the LRTH model.
We also estimate the new production channel, $ZtT$ or $Zt\bar{T}$ production, at the LHC. Compared
with $Zt\bar{t}$ production, we find that the $ZtT$ production can have a sizable production rate when the
scale $f$ is not too high. Considering the dominant decay mode $T \rightarrow \phi^+b \rightarrow t\bar{b}b$, we find that $Zt\bar{T}$
final state has less background than $Zt\bar{t}$ production and may likely be observable at the LHC.

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$^*$Electronic address: hanjinzhongxx@gmail.com
$^†$Electronic address: yangbingfang@gmail.com
I. INTRODUCTION

The direct evidence for the top quark was presented in 1995 by the CDF and D0 collaborations [1]. From that time on, top quark physics has always been one of the central physical topics at the Large Hadron Collider (LHC) and the future International Linear Collider (ILC). The top quark is the heaviest particle in the standard model (SM), so it is widely speculated that the properties of the top quark are sensitive to new physics. Deviations of experimental measurements from the SM predictions would indicate new non-standard top production or decay mechanisms. One of particular interest is the large top quark forward-backward asymmetry observed at the Tevatron may imply the new physics in the top quark sector [2].

The probe of the couplings between the top quark and gauge bosons, such as $\gamma t\bar{t}$, $Zt\bar{t}$ and $Wtb$, is another way to discover new physics. Because of the small cross-section, $Zt\bar{t}$ coupling is not observable at the Tevatron. On the contrary, these couplings can be measured precisely at the LHC [3] and the ILC [4]. And many relevant works focusing on $pp \rightarrow Zt\bar{t}$ at the LHC [3] and $e^+e^- (\gamma\gamma) \rightarrow Zt\bar{t}$ at the ILC [6] in the SM and beyond have been done. Recently, the CMS Collaboration [7] and the ATLAS Collaboration [8] have, respectively, published the first set of results using the $\sqrt{s} = 7$ TeV $pp$ collision data by the trilepton channel, in which the $Z$ boson decays to a pair of leptons and one of the $W$ bosons coming from $t \rightarrow Wb$ decays, gives rise to a lepton after decay. The measured values are compatible within uncertainties with the next-to-leading order (NLO) SM calculations.

To solve the little hierarchy problem of the SM, the left-right twin Higgs (LRTH) model was proposed and regarded as an alternative candidate for new physics [9–11]. The phenomenology of the LRTH model has been widely discussed in Refs. [12, 13]. In this model, a top partner (denoted as $T$-quark) is contained. Due to the mixing between $t$ and $T$, the $Zt\bar{t}$ coupling is modified. Moreover, the $T$-quark can contribute to the $Zt\bar{t}$ production process through its virtual effects. The precision measurements of $Zt\bar{t}$ production at high energy colliders make it possible to unravel the new physics effects or constrain the model parameters. In addition, the new production channel $Zt\bar{T}$ or $ZtT$ productions can be implemented at the LHC. This new production channel has the different final states from the $Zt\bar{t}$ production due to the dominant decay $T \rightarrow \phi^+ b \rightarrow t\bar{b}b$. A search for this new effect will provide a good probe to detect the LRTH model.
This paper is organized as follows. In Sec.II we briefly review the LRTH model related to our calculations. We study the \( Zt\bar{t} \) production at the ILC in Sec.III and the \( Zt\bar{t} \) production at the LHC in Sec.IV, respectively. In Sec.V we study the new production channel \( Zt\bar{T} \) or \( ZT\bar{t} \) at the LHC. Finally, we give our conclusions in Sec.VI.

II. A BRIEF REVIEW OF THE LRTH MODEL

Here we will briefly review the ingredients which are relevant to our calculations, and a detailed description of the LRTH model can be found in Ref. [12].

The LRTH model is based on the global \( U(4)_1 \times U(4)_2 \) symmetry with a locally gauged subgroup \( SU(2)_L \times U(2)_R \times U(1)_{B-L} \). Under the global symmetry, two Higgs fields, \( H = (H_L, H_R) \) and \( \hat{H} = (\hat{H}_L, \hat{H}_R) \), are introduced and each transforms as \((4,1)\) and \((1,4)\), respectively. \( H_L,R \) and \( \hat{H}_L,R \) are two component objects which are charged under \( SU(2)_L \) and \( SU(2)_R \), respectively. The global \( U(4)_1[U(4)_2] \) symmetry is spontaneously broken down to its subgroup \( U(3)[U(3)] \) with non-zero vacuum expectation values (VEVs) as \(< H > = (0,0,0,f) \) and \( H = (0,0,0,\hat{f}) \). Each spontaneously symmetry breaking results in seven Nambu-Goldstone bosons. Three Goldstone bosons are eaten by the massive heavy gauge bosons \( W^\pm_H \) and \( Z_H \), while the remaining Goldstone bosons contain three physical Higgs \( \phi^0 \) and \( \phi^\pm \). The mass of the heavy gauge bosons can be expressed as:

\[
M^2_{W_H} = \frac{1}{2}g^2(\hat{f}^2 + f^2 \cos^2 x),
\]

\[
M^2_{Z_H} = \frac{g^2 + g'^2}{g^2}(M^2_W + M^2_{W_H}) - M^2_Z,
\]

where \( g = e/S_W \), \( g' = e/\sqrt{\cos 2\theta_W} \), \( S_W = \sin \theta_W \), \( \theta_W \) is the Weinberg angle. \( x = v/(\sqrt{2}f) \), and \( v \) is the electroweak scale, the values of \( f \) and \( \hat{f} \) will be bounded by electroweak precision measurements. In addition, \( f \) and \( \hat{f} \) are interconnected once we set \( v = 246 \) GeV.

The mass of the light SM-like top quark and its partner heavy top quark \( T \) are

\[
m^2_t = \frac{1}{2}(M^2 + y^2f^2 - N_t), \quad M^2_T = \frac{1}{2}(M^2 + y^2f^2 + N_t),
\]

where \( N_t = \sqrt{(y^2f^2 + M^2)^2 - y^4f^4\sin^2 2x} \). Provided \( M_T \leq f \) and the parameter \( y \) is of order one, the top Yukawa coupling will also be of order one. The mass parameter \( M \) is essential to the mixing between the SM top quark and its partner \( T \). At the leading order
of $1/f$, the mixing angles can be written as:

$$ S_L = \sin \alpha_L \simeq \frac{M}{M_T} \sin x, \quad S_R = \sin \alpha_R \simeq \frac{M}{M_T} (1 + \sin^2 x), $$

The couplings expression forms which are related to our calculations are given as follows \[12\]:

$$ g_{Zt\bar{t}} = \frac{eC_LS_L}{2C_W S_W}; \quad g_{Zt\bar{t}}^R = \frac{ef^2 x^2 S_W C_R S_R}{2f^2 C_W^3}; \quad (5) $$

$$ g_{Zt\bar{t}} = \frac{e(3C_L^2 - 4S_W^2)}{6C_W S_W}; \quad g_{Zt\bar{t}}^R = -\frac{2eS_W^2}{3C_W S_W}; \quad (6) $$

$$ g_{Ze^+e^-} = \frac{e(-\frac{1}{2} + S_W^2)}{S_W C_W}; \quad g_{Ze^+e^-}^R = \frac{eS_W}{C_W}; \quad (7) $$

$$ g_{ZHt\bar{t}} = \frac{eC_LS_LS_W}{2C_W \sqrt{\cos 2\theta_W}}; \quad g_{ZHt\bar{t}}^R = -\frac{eC_RS_R C_W}{2S_W \sqrt{\cos 2\theta_W}}; \quad (8) $$

$$ g_{ZHt\bar{t}}^e = \frac{eS_W}{2C_W \sqrt{\cos 2\theta_W}}; \quad g_{ZHt\bar{t}}^e = \frac{e(1 - 3 \cos 2\theta_W)}{4S_W C_W \sqrt{\cos 2\theta_W}}; \quad (9) $$

$$ V_{hZ\mu Z\nu} = \frac{em_\mu g_{\mu\nu}}{S_W C_W^2}; \quad V_{hZ\mu Z\nu} = \frac{e^2 f_x g_{\mu\nu}}{\sqrt{2} C_W \sqrt{\cos 2\theta_W}}; \quad (10) $$

$$ V_{ht\bar{t}} = -\frac{em_tC_L C_R}{2m_W S_W}; \quad (11) $$

where $C_L^2 = (1 - S_L^2)$, $C_R^2 = (1 - S_R^2)$.

### III. PRODUCTION OF $Zt\bar{t}$ AT THE ILC

In this section, we study the process $e^+ e^- \rightarrow Zt\bar{t}$ in the LRTH model at the ILC. The relevant Feynman diagrams are shown in fig.1. In comparison with the SM, we can see there are additional diagrams mediated by the $Z_H$ gauge boson and the heavy $T$-quark in the LRTH model.

In our numerical calculations, we take the SM parameters as follows \[14\]:

$$ \alpha(m_Z) = 1/128.8, \sin^2 \theta_W = 0.231, $$

$$ m_t = 172.4 \text{ GeV}, m_h = 125 \text{ GeV} \ [15], m_Z = 91.2 \text{ GeV}. \quad (12) $$

In addition, there are some LRTH model parameters involved in the amplitudes, they are $f(\hat{f})$ and $M$. The parameter $\hat{f}$ can be determined by requiring that the SM Higgs boson obtains an electroweak symmetry breaking VEV of 246 GeV. The top Yukawa coupling constant $y$ can also be determined by fitting the experimental value of the top quark mass.
Following Ref. [12], we vary the scale $f$ in the range of $500 \text{ GeV} \leq f \leq 1500 \text{ GeV}$ and take the mixing parameter $M = 100 \text{ GeV}, 150 \text{ GeV}, 200 \text{ GeV}$ as an example.

In fig. 2(a), we show the deviation from the SM prediction of the $Z\bar{t}t$ production cross-section $R_1 = (\sigma^{\text{LRTH}} - \sigma^{\text{SM}})/\sigma^{\text{SM}}$ as function of the scale $f$ for the three values of the mixing parameter $M$ at the ILC for $\sqrt{s} = 500 \text{ GeV}$. We can see that the deviation is negative so that the LRTH contributions decrease the SM cross-section. When the scale $f$ increases,
the deviation from the SM prediction $R_1$ become small, which indicates that the effects of the LRTH model will decouple at the high scale $f$. The maximum value of the deviation from the SM prediction $R_1$ can reach $-14\%$ in the allowed parameter space. In fig.2(b), we show the production cross section $\sigma$ as function of center-of-mass energy $\sqrt{s}$ in the LRTH model and the SM for $f = 1000$ GeV, $M = 150$ GeV at the ILC, respectively. Since the process proceeds mainly through the s-channel, we can see that the $t\bar{t}Z$ cross-sections first increase and then decrease with the increasing values of $\sqrt{s}$.

According to the Ref.\cite{16}, if only one $t\bar{t}V(V = \gamma, Z)$ coupling at a time is allowed to deviate from its SM value, a linear $e^+e^-$ collider operating at $\sqrt{s} = 500$ GeV with an integrated luminosity of $100 \sim 200$ fb$^{-1}$ would be able to probe all $Zt\bar{t}$ couplings with a precision of $1 \sim 5\%$.

IV. PRODUCTION OF $Zt\bar{t}$ AT THE LHC

The production of $Zt\bar{t}$ at the LHC can proceed through $gg$ fusion or $q\bar{q}$ annihilation, the relevant Feynman diagrams are shown in fig.3.
The relevant SM parameters are taken as follows

\[ m_t = 175 \text{ GeV}, \quad m_Z = 91.2 \text{ GeV}, \]
\[ \alpha(m_Z) = 1/128, \quad \alpha_s = 0.1172, \quad \sin^2 \theta_W = 0.231. \tag{13} \]

For the relevant LRTH parameters, we also take \( 500 \text{ GeV} \leq f \leq 1500 \text{ GeV} \) and \( M = 100 \text{ GeV}, 150 \text{ GeV}, 200 \text{ GeV} \). In our calculations, we used the CTEQ5M patron distribution functions [17].

Figure 4: The deviation from the SM prediction of the \( Zt\bar{t} \) production cross section as functions of the scale \( f \) for \( \sqrt{s} = 8 \text{ TeV} \)(a) and \( \sqrt{s} = 14 \text{ TeV} \)(b), respectively.

In fig.4(a) and fig.4(b) we show the deviation from the SM prediction \( R_2(R_3) = (\sigma^{LRTH} - \sigma^{SM})/\sigma^{SM} \) of the \( Zt\bar{t} \) production cross-section as a functions of the scale \( f \) for \( \sqrt{s} = 8 \text{ TeV} \) and \( \sqrt{s} = 14 \text{ TeV} \), respectively. We can see that the deviation from the SM prediction parameter \( R_2 \) can reach \(-14\% \) and \( R_3 \) can reach \(-23\% \). According to Ref. [18], the improvement is particularly pronounced for the \( Zt\bar{t} \) axial vector coupling which can be measured with a precision of \( 3 \sim 5\% \) at the luminosity-upgraded LHC (3000 fb\(^{-1}\)). From these two figures we also can see that the deviation from the SM prediction decrease the SM cross-section in the allowed parameter space, which makes the observation of this production channel even harder.

V. PRODUCTIONS OF \( Zt\bar{T} \) AND \( ZT\bar{t} \) AT THE LHC

Like the \( Zt\bar{t} \) production, the new production channel \( Zt\bar{T} \) or \( ZT\bar{t} \) can proceed through \( gg \) fusion or \( q\bar{q} \) annihilation at the LHC, the relevant Feynman diagrams are shown fig.5.
FIG. 5: Feynman diagrams for $Zt\bar{T}$ production in the LRTH model at the LHC.

FIG. 6: The $(Zt\bar{T} + ZT\bar{t})$ production cross section as functions of the scale $f$ for $\sqrt{s} = 8$ TeV (a) and $\sqrt{s} = 14$ TeV (b), respectively.

In fig. 6 we plot the $(Zt\bar{T} + ZT\bar{t})$ production cross-section $\sigma$ as a function of the scale $f$ and the three values of the mixing parameter $M$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV, respectively. We can see that the production cross-section $\sigma$ is very sensitive to the parameters $f$ and $M$. On the other hand, the cross-section value decreases quickly as the parameter $f$ increase. For
\[ \sqrt{s} = 14 \text{ TeV}, \ M = 150 \text{ GeV} \] and \( 500 \text{ GeV} \leq f \leq 1000 \text{ GeV} \), the value of the total hadronic cross-section is in the range \( 49.8 \text{ fb} \sim 0.22 \text{ fb} \). For the anticipated integrated luminosity of \( 100 \text{ fb}^{-1} \) even for a high integrated luminosity of \( 1000 \text{ fb}^{-1} \), when the parameter \( f \) is not too high the LHC will copiously produce the \( ZT\bar{t} \) events per year.

It has been shown that the branching ratio of \( \phi^+ \rightarrow t\bar{b} \) is approximately equal to 100\% for the mixing parameter \( M > 10 \text{ GeV} \) \[12\]. Thus, the dominant decay mode \( T \rightarrow \phi^+b \rightarrow t\bar{b}b \) can make the processes \( pp \rightarrow ZT\bar{t} + Zt\bar{T} \) give rise to the \( t\bar{b}b\bar{b}b \) final state with \( Z \rightarrow b\bar{b} \). For this final state, the main backgrounds come from the SM processes \( pp \rightarrow t\bar{t}ZZ + X \) and \( pp \rightarrow t\bar{t}hh + X \) with \( Z \rightarrow b\bar{b} \) and \( h \rightarrow b\bar{b} \), where the additional jets (light quarks or gluons) may be misidentified as \( b \)-quarks. The relevant studies \[19\] have found that the largest background \( t\bar{b}bjj \) can be suppressed by enhancing the ability to tag \( b \)-jets. Furthermore, a systematic signal-to-background analysis including the observability of the processes \( pp \rightarrow ZT\bar{t} + Zt\bar{T} \) would depend on Monte Carlo simulations, which is beyond the scope of our discussion.

VI. CONCLUSIONS

In this paper, we studied the top quark pair production associated with a \( Z \) boson in the LRTH model at the ILC and the LHC. For the production of \( Zt\bar{t} \) at the ILC, we found that the deviation from the SM prediction of the cross-section can reach over 10\% in magnitude and this effect should be observable \[20\]. For the production of \( Zt\bar{t} \) at the LHC, we found that the deviation from the SM prediction of the cross-section can reach over 5\% in magnitude when the scale \( f < 800 \text{ GeV} \). For the new production channel of \( Zt\bar{T} \) or \( ZT\bar{t} \), we found that the \( Zt\bar{T} \) production can have a sizable production rate when the scale \( f \) is not too high. Considering the dominant decay mode \( T \rightarrow \phi^+b \rightarrow t\bar{b}b \) with \( Z \rightarrow b\bar{b} \), the production of \( Zt\bar{T} \) or \( ZT\bar{t} \) may have the less background than the \( Zt\bar{t} \) production, and thus this new channel may likely be observable at the LHC.

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