



Search for single production of vector-like top partners at the Large Hadron Electron Collider

Yao-Bei Liu

Henan Institute of Science and Technology, Xinxiang 453003, PR China

Received 15 July 2017; received in revised form 9 August 2017; accepted 10 August 2017

Available online 16 August 2017

Editor: Hong-Jian He

Abstract

The new vector-like top partners with charge $2/3$ are a typical feature of many new physics models beyond the Standard Model (SM). We propose a search strategy for single production of top partners T focusing on both the $T \rightarrow Wb$ and $T \rightarrow th$ decay channels at the Large Hadron Electron Collider (LHeC). Our analysis is based on a simplified model in which the top partner is an $SU(2)$ singlet, with couplings only to the third generation of SM quarks. We study the observability of the single T through the processes $e^+p \rightarrow T(\rightarrow bW^+)\bar{\nu}_e \rightarrow b\ell^+ + \cancel{E}_T^{miss}$ and $e^+p \rightarrow T(\rightarrow th)\bar{\nu}_e \rightarrow t(\rightarrow jj'b)h(\rightarrow b\bar{b})\cancel{E}_T^{miss}$ at the LHeC with the proposed 140 GeV electron beam (with 80% polarization) and 7 TeV proton beam. For three typical T -quark masses (800, 900 and 1000 GeV), the 3σ exclusion limits on the TWb coupling are respectively presented for various values of the integrated luminosity.

© 2017 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

With the discovery of the 125 GeV Higgs boson at the Large Hadron Collider (LHC) [1], our understanding of electroweak symmetry breaking (EWSB) has been significantly enhanced. However, some unanswered questions remain which forces us to look for new physics (NP) beyond the Standard Model (SM). One of the intriguing issues that needs immediate attention is the naturalness problem [2]. Many popular models have been proposed and different solutions can be categorized based on the objects which cancel the largest Higgs radiative corrections from

E-mail address: liuyaobei@sina.com.

the top quark. Some of these models postulate the existence of new heavy fermions, such as little Higgs models [3], extra dimensions [4] and composite Higgs models [5,6]. In many cases, these new fermions are vector-like top partners, whose common feature is to decay into a SM quark and a gauge boson, or a Higgs boson. Many phenomenology studies for these new fermions have been made in the literature, see for example [7–17].

Here we mainly focus on the $SU(2)$ singlet T -quarks with charge $2/3$. Due to the Goldstone-boson equivalence theorem, the branching ratios of T into bW , tZ and th have a good approximation 2:1:1 in the limit $m_T \rightarrow \infty$. Previous studies of ATLAS and CMS Collaborations, relying on signatures induced by both the vector-like T -quark pair-production and single-production modes, impose strong constraints on the masses of the heavy quarks that are now bounded to be above about 550–950 GeV [18–20], depending on the assumed branching ratios. For the Wb channel, the current constraint from the ATLAS Collaboration set a upper limit on the parameter $C_L^{Wb} < 0.45$ which performed the search for singly produced vector-like T quark at 13 TeV with 3.2 fb^{-1} [21]. Besides, the top partner couplings to the SM particles are rather severely constrained by the electroweak precision observables [22,23], various SM-like Higgs decay channels [24] and the other indirect constraints (see for example Refs. [25,26]). On the other hand, the crucial point is that even a small mixing to the first generation may have a severe impact on single T -quark production processes [27,28]. In the previous studies [14,16,17], it has been recognized that the single production of top partners at the LHC will provide the most promising channel in searching for a heavy top partner. In fact, the collider search for top partners has become and will remain an important constraint on wide classes of new physics models. Thus it is highly motivated to investigate all sensitive search strategies within the possibly available accelerator and detector designs.

In our present paper, we study the observability of a single T -quark production at the proposed Large Hadron–Electron Collider (LHeC). The LHeC [29] would be the next high-energy $e-p$ collider which is designed to collide an electron beam with a typical energy range, 60–150 GeV with a 7 TeV or higher proton beam from the LHC. Its luminosity is projected to be as high as possibly 1 ab^{-1} , with a default value of 100 fb^{-1} [30]. Furthermore, the electron beam can be polarized and has an enormous scope to probe electroweak and Higgs boson physics [31,32]. Certainly, it is possible that the new vector-like T -quarks can mix sizably with the SM light quarks and their production cross section will be very large due to the mixing with valence quarks, but then their masses are not connected to EWSB and thus we do not consider this case. Although the $T \rightarrow tZ (\rightarrow \ell^+ \ell^-)$ channel is a primary option for most experimental searches, it has small number of events at the LHeC even for a high luminosity [33]. We expect that other channels will give a better constraint on the parameters of our model than the considered $T \rightarrow tZ$ channel. In this paper, we mainly study the observability of a single T -quark production at LHeC combine both the bW and th decay channels for three typical masses of top partners.

This paper is organized as follows. In Sec. 2, we give a brief description of the simplified model including the vector-like T -quark with charge $2/3$. In Sec. 3 we study the prospects of observing the single T production by performing a detailed analysis of the signal and backgrounds in each channel. Finally, we draw our conclusions in Sec. 4.

2. Top partner in a simplified model

It is clear that many extensions of the SM contain vector-like quark partners (and in particular top-partners), which can be classified according to their $SU(2) \times U(1)$ quantum numbers, where at least one of the partners needs to have the same electro-magnetic charge $2/3$ as the

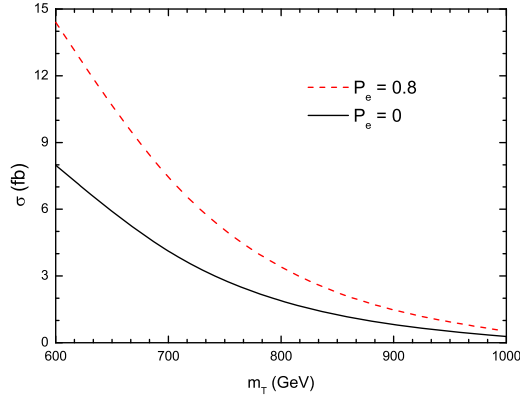


Fig. 1. The dependence of the cross sections σ on m_T for $g^* = 0.2$ and positron beam polarization $p_e = 0, 0.8$.

corresponding SM quark. A generic parametrization of an effective Lagrangian for top partners has been recently proposed in Ref. [25], where the vector-like quarks are embedded in different representations of the weak $SU(2)$ group. We here consider a simplified model where the vector-like T -quark is an $SU(2)$ singlet, with couplings only to the third generation of SM quarks. The benefit of using the simplified effective theory is that the results of the studies could be used to make predictions for more complex models including various types of top partners. The top partner sector of the model is described by the general effective Lagrangian [25]

$$\mathcal{L}_T = \frac{gg^*}{2\sqrt{2}}[\bar{T}_L W_\mu^+ \gamma^\mu b_L + \frac{g}{\sqrt{2}c_W} \bar{T}_L Z_\mu \gamma^\mu t_L - \frac{m_T}{\sqrt{2}m_W} \bar{T}_R h t_L - \frac{m_t}{\sqrt{2}m_W} \bar{T}_L h t_R] + h.c., \quad (1)$$

where m_T is the top partner mass and g^* parametrizes the single production coupling in association with a b or a top-quark. g is the $SU(2)_L$ gauge coupling constant, $c_W = \cos \theta_W$ and θ_W is the Weinberg angle.

In this simplified model, the top partner couplings to the SM particles are rather severely constrained by electroweak constraints as well as by the direct measurement of V_{tb} [34]. However, such constraints can be significantly altered in most realistic models including the vector-like quark with two or more partner multiplets [26]. Here we take a conservative range for the coupling parameter [21,34]: $g^* \leq 0.5$.

3. Event generation and analysis

During the simulation, we first extract the model file [35] of the singlet vector-like top partners by using the FeynRules package [36]. The leading order cross sections are calculated using MadGraph5-aMC@NLO [37] with CTEQ6L parton distribution function (PDF) [38] and the renormalization and factorization scales are set dynamically by default. The collider parameter is taken to be $E_e = 140$ GeV and $E_p = 7$ TeV, corresponding to a c.m. energy of approximately $\sqrt{s} = 1.98$ TeV. The SM input parameters relevant in our study are taken from [39].

In Fig. 1, we show the single production cross sections of the vector-like T depending on their masses at the LHeC for $g^* = 0.2$ and positron beam polarization $p_e = 0, 0.8$. We can see that the cross section for polarized can be about 1.8 times larger than that for unpolarized case. For

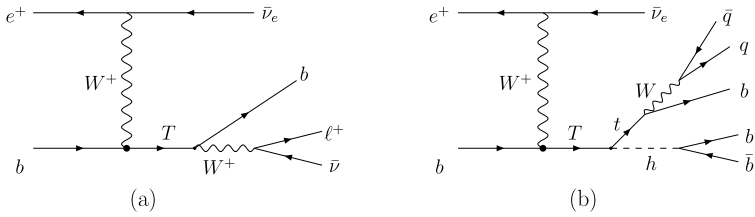


Fig. 2. The Feynman diagram for production of single T quark including the decay chains $T \rightarrow b\ell\nu$ and $T \rightarrow th \rightarrow 2j + 3b$.

$g^* = 0.2$ and $p_e = 0.8$, the cross sections are about 3.1, 1.3 and 0.5 fb for $m_T = 800, 900$ and 1000 GeV, respectively.

Next, we analyze the observation potential of each channel by performing a Monte Carlo simulation of the signal and background events and applying the suitable selection cuts to maximize the significance. The Feynman diagram of production and decay chain is presented in Fig. 2.

For the fixed T -quark mass, the corresponding free parameters are the coupling parameter g^* . We take three typical values of the T quark mass: $m_T = 800, 900, 1000$ GeV with $g^* = 0.2$. We generate all event samples in this analysis at the leading order using MadGraph5-aMC@NLO. Parton shower (both initial and final) and hadronization effects have been dealt with by PYTHIA6 [40]. For all the considered signals and backgrounds, the K-factors are taken to be 1 [41]. We apply jet and lepton energy smearing according to the following energy resolution formula [29] $\delta E/E = a/\sqrt{E/\text{GeV}} \oplus b$, where a is a sampling term and b is a constant term. For jets we take $a = 45\%$ and $b = 3\%$, and for leptons we take $a = 8.5\%$ and $b = 0.3\%$. In our analysis, we assume a b -jet tagging efficiency of $\epsilon_b = 60\%$ and a corresponding mistagging rate of $\epsilon_{g,u,d,s} = 1\%$ for light jets and $\epsilon_c = 10\%$ for a c -jet. Event analysis is performed by using MadAnalysis5 [42].

3.1. The $T \rightarrow Wb$ channel

In this section, we analyze the observation potential by performing a Monte Carlo simulation of the signal and background events and explore the sensitivity of single top partner at the LHeC through the channel

$$e^+ p \rightarrow T(\rightarrow bW^+)\bar{\nu}_e \rightarrow bW^+(\rightarrow \ell^+\bar{\nu}_\ell)\bar{\nu}_e. \tag{2}$$

For this channel, the typical signal is exactly one charged lepton, one b jet and missing energy. The main SM background are the processes containing a W boson in the final state, such as

$$\begin{aligned} e^+ p &\rightarrow bW^+\bar{\nu}_e \rightarrow \ell^+ + b + \cancel{E}_T^{miss}, \quad (\nu Wb) \\ e^+ p &\rightarrow W^+(\rightarrow \ell^+\bar{\nu}_\ell)j\bar{\nu}_e \rightarrow \ell^+ + j + \cancel{E}_T^{miss}, \quad (\nu Wj) \end{aligned} \tag{3}$$

where one light jet might be faked as b jet. For the νWb process, the dominant process is the single top production process in which the top quark decay in to Wb . We also checked that other background processes, such as the di-boson production are negligible with the selection cuts.

To reduce the backgrounds, we pick up the events that included exactly one isolated lepton and one b -tagged jet, then impose the following basic cuts:

$$p_T^{\ell,b} > 20 \text{ GeV}, |\eta_\ell| < 2.5, |\eta_b| < 5, \cancel{E}_T^{miss} > 20 \text{ GeV}. \tag{4}$$

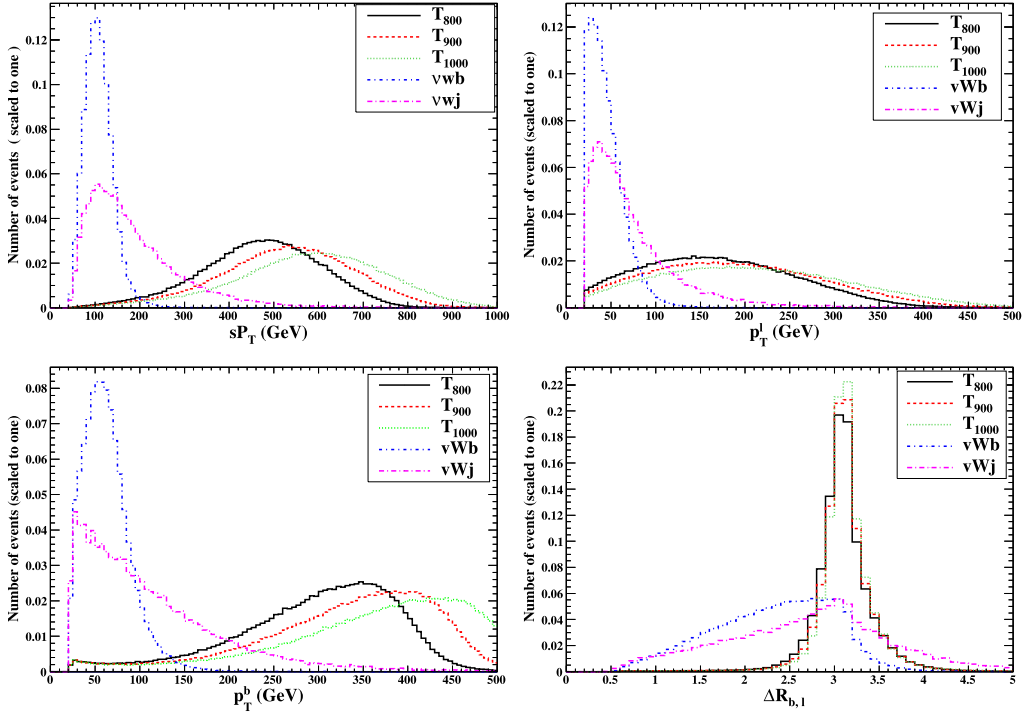


Fig. 3. Normalized distributions of the scalar sum of the transverse momenta sP_T , the transverse momenta (p_T^ℓ and p_T^b) and $\Delta R(b, \ell)$ for the signals and backgrounds.

In Fig. 3, we show the normalized distributions of the scalar sum of the transverse momenta (sP_T) of the b -tagged jet and the lepton, the transverse momenta $p_T^{\ell, b}$ and the variable $\Delta R(b, \ell)$ for the signals and backgrounds. Here $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ is the particle separation with $\Delta\phi$ and $\Delta\eta$ being the separation in the azimuth angle and rapidity respectively. Based on these kinematical distributions, we impose the following cuts to get a high significance:

- Cut 1: $sP_T > 500$ GeV.
- Cut 2: $p_T^\ell > 100$ GeV, $p_T^b > 250$ GeV and $2.8 < \Delta R(b, \ell) < 3.5$.

In Fig. 4, we show the transverse mass distribution for the $b\ell\cancel{E}_T$ system, which has been defined in Ref. [43]. From this figure, we can see that the distributions of signal have peaks around the T -quark mass while background distributions turn over at lower masses. Thus we can further reduce the backgrounds by the following cut:

- Cut 3: $M_T > 700$ GeV.

We present the cross sections of the signal and backgrounds after imposing the cuts in Table I. From the numerical results, one can see that the backgrounds are suppressed very efficiently after imposing the selections. For example, the production cross section of the νWb background drops

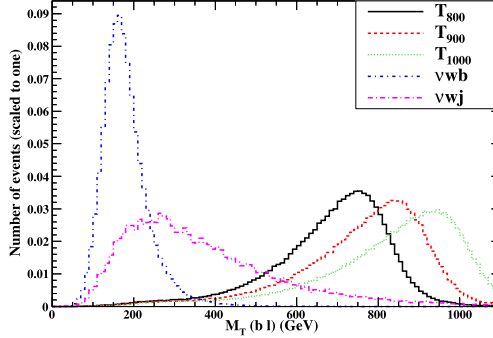


Fig. 4. Normalized transverse mass distribution of the $bl\cancel{E}_T$ system for the signals and backgrounds.

Table I

The cut flow of the cross sections (in fb) for the signal and backgrounds at the LHeC with $E_e = 140$ GeV and $E_p = 7$ TeV. Here we take $g^* = 0.2$.

Cuts	Signal			Backgrounds		
	800 GeV	900 GeV	1000 GeV	νWb	νWj	Total
Basic cuts	0.3	0.13	0.05	768	34	802
Cut 1	0.13	0.077	0.036	0.006	0.61	0.62
Cut 2	0.12	0.07	0.032	0.006	0.31	0.32
Cut 3	0.1	0.064	0.031	0.003	0.23	0.23

from 768 fb to 0.006 fb, with a reject efficiency more than 99%. The dominant SM background come from the νWj production process and is about 0.23 fb after imposing the selections.

3.2. The $T \rightarrow th$ channel

Next, we analyze the observation potential and explore the sensitivity of single T -quark at the LHeC through the channel

$$e^+ p \rightarrow T(\rightarrow th)\bar{\nu}_e \rightarrow t(\rightarrow W^+b \rightarrow jj'b)h(\rightarrow b\bar{b})\bar{\nu}_e. \tag{5}$$

The main SM background are the processes:

$$\begin{aligned} e^+ p \rightarrow th\bar{\nu}_e \rightarrow t(\rightarrow W^+b \rightarrow jj'b)h(\rightarrow b\bar{b}) + \cancel{E}_T^{miss}, \quad (\nu th) \\ e^+ p \rightarrow tZ\bar{\nu}_e \rightarrow t(\rightarrow W^+b \rightarrow jj'b)Z(\rightarrow b\bar{b}) + \cancel{E}_T^{miss}. \quad (\nu tZ) \end{aligned} \tag{6}$$

Besides, the single top and single W plus jets production processes are also the backgrounds, where one light jet might be faked as b jet.

The event selection in the 3b-tagging case first requires at least five jets satisfying the following basic cuts:

- $p_T^j > 20$ GeV, $|\eta_j| < 5$, $\Delta R_{jj} > 0.4$.
- There are at least three b-tagged jets with $|\eta_b| < 5$.
- Events with additional charged leptons are vetoed.

In Fig. 5, we show the H_T distribution for the different considered processes, where H_T

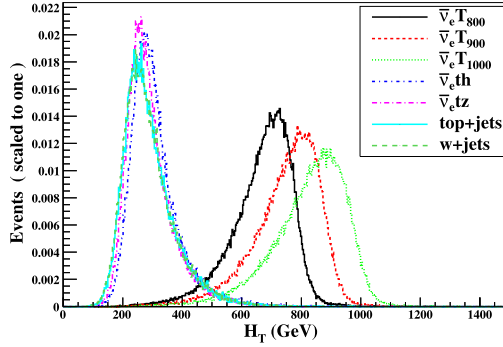


Fig. 5. Normalized distributions of the H_T for the signals and backgrounds.

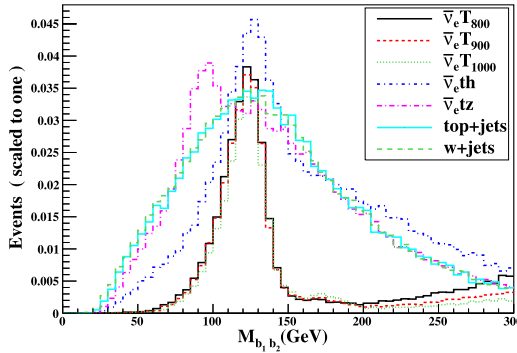


Fig. 6. Normalized distributions of the m_h for the signals and backgrounds.

denotes the scalar sum of the transverse momenta of the final state jets. The signal distribution has a considerable tail for larger values of H_T compared to background events. Therefore we choose the H_T cut

- Cut 1: $H_T > 600$ GeV.

Fig. 6 illustrates the distribution of the reconstructed Higgs boson mass of the signal and backgrounds. In order to suppress the $tZ\bar{\nu}_e$, tbb and $Wbbj$ backgrounds, we require the mass of the Higgs boson to satisfy

- Cut 2: $|m_{bb} - m_h| < 20$ GeV.

We list the results after imposing various kinematic cuts in Table II. From the numerical results, one can see that all the backgrounds are also suppressed efficiently after imposing these selections. However, due to the small production cross section for the signals, the large value of the coupling parameter g^* and the high integrated luminosity are needed to produce more final events. Note that here our results are conservative, the analysis presented can be further improved in several aspects. First is of course a more realistic estimation of the signal and backgrounds including parton shower and more detailed detector effects. Secondly, we have only applied a cut-based analysis with very simple variables. A further multivariate analysis may deliver addi-

Table II

The cut flow of the cross sections (in 10^{-2} fb) for the signal and backgrounds at the LHeC with $E_e = 140$ GeV and $E_p = 7$ TeV. Here we take $g^* = 0.2$.

Cuts	Signal			Backgrounds				
	800 GeV	900 GeV	1000 GeV	$\bar{\nu}_e t h$	$\bar{\nu}_e t Z$	$t + 2b$	$W + 3b$	Total
Basic cuts	5.2	1.92	0.64	9.5	23	27	28	87.5
Cut 1	4.4	1.84	0.6	0.16	0.39	0.43	0.47	1.45
Cut 2	1.0	0.4	0.12	0.04	0.026	0.03	0.03	0.13

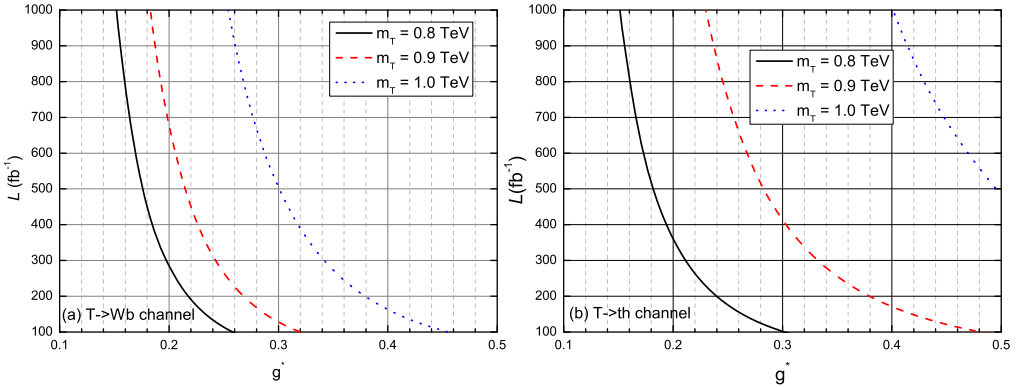


Fig. 7. 3σ contour plots for the signal in $L - g^*$ at the LHeC for (a) $T \rightarrow Wb$ channel, and (b) $T \rightarrow th$ channel.

tional gain in sensitivity. Furthermore, other techniques such as Boosted Decision Trees(BDT), Heidelberg-Eugene-Paris top-tagger (HEPTopTagger) and jet dipolarity [44–46] may be more useful to enhance the significance.

To estimate the observability quantitatively, we adopt the significance measurement [47]: $SS = \sqrt{2L}[(\sigma_S + \sigma_B) \ln(1 + \sigma_S/\sigma_B) - \sigma_S]$, where L is the integrated luminosity, σ_S and σ_B are the cross sections of signal and background, respectively. In Fig. 7, we show the excluded 3σ reaches in the plane of the integrated luminosity and the coupling parameter g^* for two channels. For $m_T = 800, 900$ and 1000 GeV, we can see that the upper limits for the $T \rightarrow Wb$ channel on the size of g^* are respectively given as about 0.2, 0.24 and 0.34 for $L = 300 \text{ fb}^{-1}$, and changed as about 0.15, 0.18 and 0.25 when the integrated luminosity is 1000 fb^{-1} . For the $T \rightarrow th$ channel, the high integrated luminosity is needed to enhance the production events due to the small production rates. For the same three top partner masses, we can see that the upper limits on the size of g^* are respectively given as about 0.15, 0.23 and 0.4 when the integrated luminosity is 1000 fb^{-1} .

4. Conclusion and discussion

The new heavy vector-like top partners with charge $2/3$ appear in many new physics models beyond the SM. In order to be as model-independent as possible we exploited a simplified model with only two free parameters, the heavy top mass and an electroweak coupling constant. In this paper we described the future LHeC potential to search for the heavy vector-like T -quark via the $T \rightarrow bW^+$ and $T \rightarrow th$ decay modes. We investigated the observability of the heavy vector-like top partner T production through the processes $e^+p \rightarrow T(\rightarrow bW^+)\bar{\nu}_e \rightarrow bW^+(\rightarrow \ell^+\bar{\nu}_\ell)\bar{\nu}_e$ and

$e^+p \rightarrow T(\rightarrow th)\bar{\nu}_e \rightarrow t(\rightarrow jj'b)h(\rightarrow b\bar{b})\bar{\nu}_e$ at the LHeC with $E_e = 140$ GeV (with 0.8 polarization) and $E_p = 7$ TeV. Since the single T production depends on the TWb coupling and the T -quark mass, we constrain the parameter space in the plane of the integrated luminosity and the coupling parameter g^* . In the bW channel, we rely on the large p_T of the lepton, the b -jet and large missing energy to suppress the backgrounds. In the th channel, we consider the all-hadronic final states and a large H_T cut can efficiently suppress the backgrounds. For $m_T = 800, 900$ and 1000 GeV, the upper limits on the size of g^* are respectively given as about 0.15, 0.18 and 0.25 with the high luminosity of 1000 fb^{-1} . We expect our analysis can represent a complementary candidate to pursue the search of a possible singlet top partner below ~ 1 TeV.

In some typical models such as the minimal Composite Higgs (CH) models [15] and the littlest Higgs model with T-parity (LHT) [48], the heavy T -quark couplings only to the third generation of SM quarks. Our results can be straightforwardly mapped within the context of the CH model and the LHT model, namely with

$$g^* \simeq \frac{ym_W}{gm_T}, \quad (\text{CH})$$

$$g^* \simeq \frac{R^2}{1+R^2} \frac{v}{f} + \mathcal{O}\left(\frac{v^2}{f^2}\right), \quad (\text{LHT}) \quad (7)$$

where y , R and f are the model parameters (for more detail, see e.g. [15,48]). For the low mass reign (i.e., $m_T \lesssim 1$ TeV), we expect our analysis can represent a viable and complementary candidate to pursue the search of the singlet vector-like T -quarks.

Now we compare the discovery reach in our results with other phenomenological studies at the LHC. In a simplified composite Higgs model, the authors of Ref. [16] project at $\sqrt{s} = 8$ TeV and 25 fb^{-1} of integrated luminosity the exclusion potential with $Br(T \rightarrow Wb) = 0.5$, obtaining a strong constraint on the TWb coupling ($g_{TbW}/g_{TbW}^{SM} < 0.2 \sim 0.3$) for $m_T \subset (700, 1000)$ GeV. For the $T \rightarrow tZ$ channel, the authors of Ref. [17] studied the dilepton signals at $\sqrt{s} = 13$ TeV with 300 fb^{-1} of integrated luminosity and the results show that the signal from the $T \rightarrow tZ \rightarrow (qq'b)(\ell^+\ell^-)$ channel is within the range of possible evidence for top partner masses up to roughly 1450 GeV with $g^* \lesssim 0.5$, while being still sensitive to g^* couplings down to 0.05 for $m_T = 0.8$ TeV. Analogously, the authors of Ref. [27] studied the trilepton signals from the $T \rightarrow tZ \rightarrow (b\ell\nu)(\ell^+\ell^-)$ channel at the LHC with $\sqrt{s} = 13$ TeV, the results show that the trilepton signal can probe possible top partner masses up to roughly 1700 GeV with $g^* \lesssim 0.5$, while being still sensitive to g^* couplings down to 0.1 for $m_T = 0.8$ TeV. Thus we can see that, for the typical mass parameter $m_T = 0.8$ TeV, the LHeC sensitivity for the TbW coupling strength is smaller than the sensitivity limits of LHC as $g^* \lesssim 0.1(0.05)$ with an integrated luminosity of 300 fb^{-1} at $\sqrt{s} = 13$ TeV [17,27]. In our previous study [33], the decay of $T \rightarrow t(\rightarrow bj\bar{j}')Z(\rightarrow \ell^+\ell^-)$ channel from the single top partner produced at the LHeC are investigated by considering the mixing between the top partner with the first and the third generation quarks. For a high integrated luminosity of 1 ab^{-1} , the upper limits on the size of g^* are given as $g^* \leq 0.29$ for $R_L = 0$ (only couplings with the third generation SM quarks) and $m_T = 0.8$ TeV. Thus we expect our analysis can represent a viable and complementary candidate to pursue the search of a possible vector-like top partner with low masses (i.e., $m_T \lesssim 1$ TeV).

Acknowledgements

This work is supported by the Joint Funds of the National Natural Science Foundation of China (Grant No. U1304112), the Foundation of Henan Educational Committee (Grant

No. 2015GGJS-059) and the Foundation of Henan Institute of Science and Technology (Grant No. 2016ZD01).

References

- [1] G. Aad, et al., ATLAS Collaboration, Phys. Lett. B 716 (2012) 1;
S. Chatrchyan, et al., CMS Collaboration, Phys. Lett. B 716 (2012) 30.
- [2] P.H. Frampton, P.Q. Hung, M. Sher, Phys. Rep. 330 (2000) 263.
- [3] N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson, J. High Energy Phys. 0207 (2002) 034;
N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson, T. Gregoire, J.G. Wacker, J. High Energy Phys. 0208 (2002) 021.
- [4] I. Antoniadis, Phys. Lett. B 246 (1990) 377;
D.B. Kaplan, Nucl. Phys. B 365 (1991) 259;
K. Agashe, G. Perez, A. Soni, Phys. Rev. D 75 (2007) 015002.
- [5] Z. Chacko, H.-S. Goh, R. Harnik, Phys. Rev. Lett. 96 (2006) 231802;
Z. Chacko, Y. Nomura, M. Papucci, G. Perez, J. High Energy Phys. 0601 (2006) 126.
- [6] K. Agashe, R. Contino, A. Pomarol, Nucl. Phys. B 719 (2005) 165;
M. Low, A. Tesi, L.-T. Wang, Phys. Rev. D 91 (2015) 095012.
- [7] H.-C. Cheng, I. Low, L.-T. Wang, Phys. Rev. D 74 (2006) 055001;
S. Matsumoto, M.M. Nojiri, D. Nomura, Phys. Rev. D 75 (2007) 055006;
Q.-H. Cao, C.S. Li, C.-P. Yuan, Phys. Lett. B 668 (2008) 24;
C.-X. Yue, H.-D. Yang, W. Ma, Nucl. Phys. B 818 (2009) 1;
C.-Y. Chen, A. Freitas, T. Han, K.S.M. Lee, J. High Energy Phys. 1211 (2012) 124;
J. Kearney, A. Pierce, J. Thaler, J. High Energy Phys. 1310 (2013) 230;
G. Burdman, Z. Chacko, R. Harnik, L. de Lima, C.B. Verhaaren, Phys. Rev. D 91 (2015) 055007;
A. Anandakrishnan, J.H. Collins, M. Farina, E. Kuflik, M. Perelstein, Phys. Rev. D 93 (2016) 075009;
N. Liu, L. Wu, B.-F. Yang, M.-C. Zhang, Phys. Lett. B 753 (2016) 664.
- [8] G. Dissertori, E. Furlan, F. Moortgat, P. Nef, J. High Energy Phys. 1009 (2010) 019;
N. Chen, H.-J. He, J. High Energy Phys. 1204 (2012) 062;
O. Matsedonskyi, G. Panico, A. Wulzer, J. High Energy Phys. 1301 (2013) 164;
B. Gripaios, T. Mueller, M.A. Parker, D. Sutherland, J. High Energy Phys. 1408 (2014) 171;
T. Flacke, J.H. Kim, S.J. Lee, S.H. Lim, J. High Energy Phys. 1405 (2014) 123;
J. Serra, J. High Energy Phys. 1509 (2015) 176;
T. DeGrand, Y. Shamir, Phys. Rev. D 92 (2015) 075039;
O. Matsedonskyi, G. Panico, A. Wulzer, J. High Energy Phys. 1604 (2016) 003;
Q.-H. Cao, D.-M. Zhang, arXiv:1611.09337 [hep-ph].
- [9] H.-S. Goh, C.A. Krenke, Phys. Rev. D 81 (2010) 055008;
Y.-B. Liu, Z.-J. Xiao, Nucl. Phys. B 892 (2015) 63;
H.-C. Cheng, S. Jung, E. Salvioni, Y. Tsai, J. High Energy Phys. 1603 (2016) 074.
- [10] Csaba Balazs, Hong-Jian He, C.-P. Yuan, Phys. Rev. D 60 (1999) 114001;
H.-J. He, N. Polonsky, S. Su, Phys. Rev. D 64 (2001) 053004;
J.A. Aguilar-Saavedra, Phys. Lett. B 625 (2005) 234;
G. Cynolter, E. Lendvai, Eur. Phys. J. C 58 (2008) 463;
J.A. Aguilar-Saavedra, J. High Energy Phys. 0911 (2009) 030;
A. Senol, A.T. Tasci, F. Ustabas, Nucl. Phys. B 851 (2011) 289;
P. Meade, M. Reece, Phys. Rev. D 74 (2006) 015010;
M.M. Nojiri, M. Takeuchi, J. High Energy Phys. 0810 (2008) 025;
R. Contino, G. Servant, J. High Energy Phys. 0806 (2008) 026;
J. Alwall, J.L. Feng, J. Kumar, S. Su, Phys. Rev. D 81 (2010) 114027;
G. Cacciapaglia, A. Deandrea, D. Harada, Y. Okada, J. High Energy Phys. 1011 (2010) 159;
J. Berger, J. Hubisz, M. Perelstein, J. High Energy Phys. 1207 (2012) 016;
X.-F. Wang, C. Du, H.-J. He, Phys. Lett. B 723 (2013) 314;
H.-J. He, Z.-Z. Xianyu, J. Cosmol. Astropart. Phys. 1410 (2014) 019;
S.-F. Ge, H.-J. He, J. Ren, Z.-Z. Xianyu, Phys. Lett. B 757 (2016) 480.
- [11] C.-H. Chen, T. Nomura, Phys. Rev. D 94 (2016) 035001;

- S. Moretti, D. O'Brien, L. Panizzi, H. Prager, arXiv:1603.09237 [hep-ph];
M. Endo, Y. Takaesu, Phys. Lett. B 758 (2016) 355;
E.L. Berger, Q.-H. Cao, Phys. Rev. D 81 (2010) 035006;
B. Holdom, Q.-S. Yan, Phys. Rev. D 83 (2011) 114031;
B. Holdom, Q.-S. Yan, Phys. Rev. D 84 (2011) 094012;
S. Yang, J. Jiang, Q.-S. Yan, X. Zhao, J. High Energy Phys. 1409 (2014) 035;
S. Gopalakrishna, T. Mandal, S. Mitra, G. Moreau, J. High Energy Phys. 1408 (2014) 079;
C. Han, A. Kobakhidze, N. Liu, L. Wu, B. Yang, Nucl. Phys. B 890 (2014) 388;
S.A.R. Ellis, R.M. Godbole, S. Gopalakrishna, J.D. Wells, J. High Energy Phys. 1409 (2014) 130;
M. Endo, K. Hamaguchi, K. Ishikawa, M. Stoll, Phys. Rev. D 90 (2014) 055027.
- [12] N. Arkani-Hamed, T. Han, M. Mangano, L.-T. Wang, Phys. Rep. 652 (2016) 1;
S. Banerjee, D. Barducci, G. Bélanger, C. Delaunay, J. High Energy Phys. 1611 (2016) 154;
A. Azatov, M. Salvarezza, M. Son, M. Spannowsky, Phys. Rev. D 89 (2014) 075001;
M. Backović, T. Flacke, S.J. Lee, G. Perez, J. High Energy Phys. 1509 (2015) 022;
N. Vignaroli, J. High Energy Phys. 1207 (2012) 158;
N. Vignaroli, Phys. Rev. D 86 (2012) 075017.
- [13] S. Dawson, E. Furlan, I. Lewis, Phys. Rev. D 87 (2013) 014007;
S. Dawson, E. Furlan, Phys. Rev. D 89 (2014) 015012;
C. Grojean, O. Matsedonskyi, G. Panico, J. High Energy Phys. 1310 (2013) 160;
D. Barducci, A. Belyaev, J. Blamey, S. Moretti, L. Panizzi, H. Prager, J. High Energy Phys. 1407 (2014) 142;
D. Barducci, A. Belyaev, M. Buchkremer, G. Cacciapaglia, A. Deandrea, S. De Curtis, J. Marrouche, S. Moretti, L. Panizzi, J. High Energy Phys. 1412 (2014) 080;
D. Pappadopulo, A. Thamm, R. Torre, A. Wulzer, J. High Energy Phys. 1409 (2014) 060;
O. Matsedonskyi, G. Panico, A. Wulzer, J. High Energy Phys. 1412 (2014) 097;
M. Backović, T. Flacke, J.H. Kim, S.J. Lee, Phys. Rev. D 92 (2015) 011701.
- [14] N. Gutierrez, J. Ferrando, D. Kar, M. Spannowsky, Phys. Rev. D 90 (2014) 075009;
S. Beauceron, G. Cacciapaglia, A. Deandrea, J.D. Ruiz-Alvarez, Phys. Rev. D 90 (2014) 115008;
M. Backovic, T. Flacke, J.H. Kim, S.J. Lee, J. High Energy Phys. 1604 (2016) 014.
- [15] A. De Simone, O. Matsedonskyi, R. Rattazzi, A. Wulzer, J. High Energy Phys. 1304 (2013) 004.
- [16] J. Li, D. Liu, J. Shu, J. High Energy Phys. 1311 (2013) 047.
- [17] J. Reuter, M. Tonini, J. High Energy Phys. 1501 (2015) 088.
- [18] ATLAS Collaboration, ATLAS-CONF-2013-018, ATLAS-CONF-2014-036, ATLAS-CONF-2013-060, J. High Energy Phys. 1510 (2015) 150;
ATLAS Collaboration, J. High Energy Phys. 1508 (2015) 105;
ATLAS Collaboration, J. High Energy Phys. 1602 (2016) 110;
ATLAS Collaboration, Eur. Phys. J. C 76 (2016) 442;
ATLAS Collaboration, Phys. Lett. B 758 (2016) 249.
- [19] CMS Collaboration, CMS-PAS-JME-13-007, Phys. Lett. B 729 (2014) 149;
CMS Collaboration, Phys. Rev. D 93 (2016) 012003, CMS-PAS-B2G-16-002, CMS-PAS-B2G-15-008.
- [20] ATLAS Collaboration, ATLAS-CONF-2016-013, ATLAS-CONF-2016-101; CMS Collaboration, CMS-PAS-B2G-16-005.
- [21] ATLAS Collaboration, ATLAS-CONF-2016-072.
- [22] M.E. Peskin, T. Takeuchi, Phys. Rev. D 46 (1992) 381;
G. Altarelli, R. Barbieri, Phys. Lett. B 253 (1991) 161;
J. Hubisz, P. Meade, Phys. Rev. D 71 (2005) 035016;
H.-J. He, T.M.P. Tait, C.-P. Yuan, Phys. Rev. D 62 (2000) 011702;
H.-J. He, C.T. Hill, T.M.P. Tait, Phys. Rev. D 65 (2002) 055006;
J. Hubisz, P. Meade, A. Noble, M. Perelstein, J. High Energy Phys. 0601 (2006) 135;
S. Dawson, E. Furlan, Phys. Rev. D 86 (2012) 015021;
C.-Y. Chen, S. Dawson, E. Furlan, Phys. Rev. D 96 (2017) 015006.
- [23] A. Djouadi, J.H. Kuhn, P.M. Zerwas, Z. Phys. C 46 (1990) 411;
F. Boudjema, A. Djouadi, C. Verzegnassi, Phys. Lett. B 238 (1990) 423;
R.S. Chivukula, B. Coleppa, S.D. Chiara, E.H. Simmons, H.-J. He, M. Kurachi, M. Tanabashi, Phys. Rev. D 74 (2006) 075011;
E.L. Berger, Q.-H. Cao, I. Low, Phys. Rev. D 80 (2009) 074020;
J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, M. Perez-Victoria, Phys. Rev. D 88 (2013) 094010.

- [24] A. Atre, M. Chala, J. Santiago, *J. High Energy Phys.* 1305 (2013) 099;
A. Djouadi, *Eur. Phys. J. C* 73 (2013) 2498;
C.-Y. Chen, S. Dawson, I.M. Lewis, *Phys. Rev. D* 90 (2014) 035016;
A. Djouadi, J. Quevillon, R. Vega-Morales, *Phys. Lett. B* 757 (2016) 412;
X.-F. Wang, C. Du, H.-J. He, *Phys. Lett. B* 723 (2013) 314;
T. Abe, M. Chen, H.-J. He, *J. High Energy Phys.* 1301 (2013) 082;
J. Baglio, A. Djouadi, *J. High Energy Phys.* 1103 (2011) 055;
S. Fichet, G. Moreau, *Nucl. Phys. B* 905 (2016) 391;
A. Angelescu, A. Djouadi, G. Moreau, *Eur. Phys. J. C* 76 (2016) 99.
- [25] M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi, *Nucl. Phys. B* 876 (2013) 376.
- [26] F. del Aguila, M. Perez-Victoria, J. Santiago, *J. High Energy Phys.* 0009 (2000) 011;
G. Cacciapaglia, A. Deandrea, L. Panizzi, N. Gaur, D. Harada, Y. Okada, *J. High Energy Phys.* 1203 (2012) 070;
F.J. Botella, G.C. Branco, M. Nebot, *J. High Energy Phys.* 1212 (2012) 040;
K. Ishiwata, Z. Ligeti, M.B. Wise, *J. High Energy Phys.* 1510 (2015) 027;
A.K. Alok, S. Banerjee, D. Kumar, S.U. Sankar, D. London, *Phys. Rev. D* 92 (2015) 013002;
F.J. Botella, G.C. Branco, M. Nebot, M.N. Rebelo, J.I. Silva-Marcos, *Eur. Phys. J. C* 77 (2017) 408;
S.A.R. Ellis, R.M. Godbole, S. Gopalakrishna, J.D. Wells, *J. High Energy Phys.* 1409 (2014) 130;
G. Cacciapaglia, A. Deandrea, N. Gaur, D. Harada, Y. Okada, L. Panizzi, *J. High Energy Phys.* 1509 (2015) 012.
- [27] L. Basso, J. Andrea, *J. High Energy Phys.* 1502 (2015) 032.
- [28] A. Atre, G. Azuelos, M. Carena, T. Han, E. Ozcan, J. Santiago, G. Unel, *J. High Energy Phys.* 1108 (2011) 080;
S. Beauceron, G. Cacciapaglia, A. Deandrea, J.D. Ruiz-Alvarez, *Phys. Rev. D* 90 (2014) 115008;
Y.-B. Liu, *Phys. Rev. D* 95 (2017) 035013;
L. Han, Y.-J. Zhang, Y.-B. Liu, *Phys. Lett. B* 771 (2017) 106.
- [29] J. Abelleira Fernandez, et al., LHeC Study Group, *J. Phys. G* 39 (2012) 075001.
- [30] O. Bruening, M. Klein, *Mod. Phys. Lett. A* 28 (2013) 1330011;
S. Mondal, S.K. Rai, *Phys. Rev. D* 93 (2016) 011702.
- [31] T. Han, B. Mellado, *Phys. Rev. D* 82 (2010) 016009;
X.-P. Li, L. Guo, W.-G. Ma, R.-Y. Zhang, L. Han, M. Song, *Phys. Rev. D* 88 (2013) 014023;
H.-Y. Bi, R.-Y. Zhang, H.-Y. Han, Y. Jiang, X.-G. Wu, *Phys. Rev. D* 95 (2017) 034019;
S.P. Das, J. Hernandez-Sanchez, S. Moretti, A. Rosado, R. Xoxocotzi, *Phys. Rev. D* 94 (2016) 055003.
- [32] W. Liu, H. Sun, X.-J. Wang, X. Luo, *Phys. Rev. D* 92 (2015) 074015;
Y.-L. Tang, C. Zhang, S.-H. Zhu, *Phys. Rev. D* 94 (2016) 011702;
S. Liu, Y.-L. Tang, C. Zhang, S.-H. Zhu, *Eur. Phys. J. C* 77 (2017) 457;
B. Coleppa, M. Kumar, S. Kumar, B. Mellado, *Phys. Lett. B* 770 (2017) 335.
- [33] Y.-J. Zhang, L. Han, Y.-B. Liu, *Phys. Lett. B* 768 (2017) 241.
- [34] S. Chatrchyan, et al., CMS Collaboration, *J. High Energy Phys.* 1212 (2012) 035.
- [35] https://feynrules.irmp.ucl.ac.be/wiki/VLQ_tsingletvl.
- [36] A. Alloul, N.D. Christensen, C. Degrande, C. Duhr, B. Fuks, *Comput. Phys. Commun.* 185 (2014) 2250.
- [37] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro, *J. High Energy Phys.* 1407 (2014) 079.
- [38] J. Pumplin, A. Belyaev, J. Huston, D. Stump, W.K. Tung, *J. High Energy Phys.* 0602 (2006) 032.
- [39] K.A. Olive, et al., Particle Data Group, *Chin. Phys. C* 38 (2014) 090001.
- [40] T. Sjostrand, S. Mrenna, P.Z. Skands, *J. High Energy Phys.* 0605 (2006) 026.
- [41] B. Jager, *Phys. Rev. D* 81 (2010) 054018.
- [42] E. Conte, B. Fuks, G. Serret, *Comput. Phys. Commun.* 184 (2013) 222.
- [43] E. Conte, B. Dumont, B. Fuks, C. Wymant, *Eur. Phys. J. C* 74 (2014) 3103.
- [44] J.M. Butterworth, A.R. Davison, M. Rubin, G.P. Salam, *Phys. Rev. Lett.* 100 (2008) 242001.
- [45] T. Plehn, M. Spannowsky, M. Takeuchi, D. Zerwas, *J. High Energy Phys.* 1010 (2010) 078.
- [46] A. Hook, M. Jankowiak, J.G. Wacker, *J. High Energy Phys.* 1204 (2012) 007.
- [47] G. Cowan, K. Cranmer, E. Gross, O. Vitells, *Eur. Phys. J. C* 71 (2011) 1554.
- [48] M. Blanke, A.J. Buras, A. Poschenrieder, et al., *J. High Energy Phys.* 0701 (2007) 066.