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Single vector-like T-quark search via the $T \to Wb$ decay channel at the LHeC

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A B S T R A C T

In this letter, we analyze the prospects of observing the new vector-like T-quark in the leptonic $T \to bW$ decay channel at the Large Hadron Electron Collider (LHeC). The results show that the mixing between the T-quark with the first generation quarks can largely enhance the production cross section. We further study the observability of the single T through the process $e^+p \to T(\to bW^+)\bar{\nu}_e \to b\ell^+ + \not{E}_T^{miss}$ at the LHeC with the proposed 140 GeV electron beam (with 80% polarization) and 7 TeV proton beam. To be as model-independent as possible, a simplified model method with only two free parameters (g^* and R_L) has been applied. For three typical T-quark masses, the 3σ exclusion limits as well as the 5σ discovery region are respectively presented in terms of parameter space regions.

1. Introduction

To stabilize the discovered 125 GeV Higgs boson mass [1] and protect it from dangerous quadratic divergences [2], new heavy fermions are predicted in many physics models beyond the Standard Model (SM), such as little Higgs models [3], extra dimensions [4], twin Higgs models [5] and composite Higgs models [6]. In many cases, these new fermions are heavy vector-like top partners T, whose common feature is to decay into a SM quark and a gauge boson (W/Z), or a Higgs boson. Quite a few phenomenology studies for these new heavy fermions have been discussed in the literature, see for example [7–19]. Here we focus on the case of a $SU(2)_L$ singlet vector-like T-quark.

Up to now, previous studies of ATLAS and CMS Collaborations have established lower bounds on the T-quark mass in the range of 550–950 GeV [20–22], depending on the assumed branching ratios. On the other hand, the indirect searches for the heavy T-quarks through their contributions to the electroweak precision observables, such as the oblique parameters S and T [23], Z-pole observables [24] and various Higgs decay channels [25] have also been extensively investigated. As a simplifying assumption supported by theoretical expectations, most of these studies are based on the assumption that the heavy T-quarks only mix to the third quark generation. However, the new T-quarks can mix in a sizable way with the light generations by considering the constraints from flavor physics (see for example [26–31]). Due to the presence of valence quarks in the initial state, the crucial point is that even a small mixing to the first generation may have a severe impact on single T-quark production processes [32,33]. For example, the authors in Ref. [34] studied the discovery potential for $T \to tZ$ in the trilepton channel at the 13 TeV LHC for a singlet T-quark mixing with the first generation. Very recently, we have studied the observability of the heavy T-quark through the process $pp \to T(\to th)j \to t(\to b\ell\nu_\ell)h(\to \gamma\gamma)j$ at the high-luminosity (HL)-LHC [35].

From the upcoming experiment perspective, the proposed Large Hadron-Electron Collider (LHeC) [36] 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. The LHeC might deliver data samples of approximately 100 fb^{-1} and at the end of full data accumulation with 1000 fb^{-1} (with a higher detector coverage) [37]. Furthermore, the electron beam can be polarized [37] and has an enormous scope to probe electroweak and Higgs boson physics [38,39]. Although the $T \to tZ(\to \ell^+\ell^-)$ channel is a primary option for most experimental searches [40,41], it has small number of events even for a high luminosity [42]. Due to a larger expected cross section for the $T \to Wb$ decay mode, we expect that this channel will give a better constraint on the parameters of our model than the previously considered search $T \to Zt$ [42]. Therefore in this paper we mainly study the observability of a single T-quark

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production at the LHeC for the bW decay channel. We consider the case that the vector-like T-quark has a small mixing to the first generation in the framework of a simplified model. We expect that such decay channels at the LHeC may become complementary to other production processes in the searches for the heavy vector-like T-quark at the LHC.

The rest of the paper is organized as follows. In Sec. 2 we briefly describe the main features of the simplified model and calculate the single T production at the LHeC and its decay channels that we consider in this paper. In Sec. 3 we turn to study the prospects of observing the single T production by performing a detailed analysis of the signal and backgrounds. Finally, we conclude in Sec. 4.

2. The simplified model and single T production at the LHeC

It is clear that the vector-like T-quarks with charge $2/3$ share similar final state topologies, with different branching ratios and single production couplings depending on the particular underlying model. Thus, following [28], we here consider a simplified model where the heavy vector-like T quark is an $SU(2)$ singlet with charge $2/3$, with couplings to both the first and the third generation of SM quarks. The top-partner sector of the model is described by the general effective Lagrangian (showing only the couplings relevant for our analysis) [28]

$$\mathcal{L}_T = \frac{gg^*}{\sqrt{2}}\left\{\sqrt{\frac{R_L}{1+R_L}}\,[\bar{T}_L W_\mu^+\gamma^\mu d_L] + \sqrt{\frac{1}{1+R_L}}[\bar{T}_L W_\mu^+\gamma^\mu b_L] + \frac{1}{\sqrt{2}\cos\theta_W}\sqrt{\frac{R_L}{1+R_L}}[\bar{T}_L Z_\mu^+\gamma^\mu u_L] + \frac{1}{\sqrt{2}\cos\theta_W}\sqrt{\frac{1}{1+R_L}}[\bar{T}_L Z_\mu^+\gamma^\mu t_L]\right\} + h.c., \quad (1)$$

where g is the $SU(2)_L$ gauge coupling constant and θ_W is the Weinberg angle, $v \simeq 246$ GeV, and the subscripts L and R label the chiralities of the fermions. There are two free parameters: g^* and R_L, which respectively denote the coupling strength and generation mixing coupling. The limits on these parameters come from the flavor physics and the oblique parameters, which have been studied in Refs. [26–28]. A full study of the precision bounds of this particular model is beyond the scope of this paper. Here we take a conservative range for these parameter [16,43]:

$$0.1 \le g^* \le 0.5, \quad 0 \le R_L \le 2. \quad (2)$$

The tree level Feynman diagrams for the process $e^+p \to \bar{\nu}_e T$ are plotted in Fig. 1, where the T-quark is produced due to the interaction with the b quark or due to the interaction with light quarks. From the Lagrangian in eq. (1), we know that the production cross sections are very sensitive to the strengths of the WTq couplings.

The model file [44] of the singlet vector-like T-quark is implemented via the FeynRules package [45]. The leading order cross sections are calculated using MadGraph5-aMC@NLO [46] and checked by CalcHEP [47] with CTEQ6L parton distribution function (PDF) [48] 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. Here we take the positron (electron) beam being 0.8 (-0.8) polarized. The SM input parameters relevant in our study are taken from [49]. Considering the current bounds on the singlet T-quark masses, we take three typical values: 800, 900, and 1000 GeV.

In Fig. 2, we show the single production cross sections of the T (left) and $\bar{T}$ (right) depending on the mixing parameter R_L at the LHeC for $g^* = 0.1$ and several typical values of m_T. One can see that: (i) the production cross sections are very sensitive to R_L. This is because the mixing with the first generation can largely enhance the single production, especially due to the presence of valence quarks in the initial state. (ii) For the same nonzero value of R_L, the production cross section of $e^+p \to T\bar{\nu}_e$ is larger than that for the conjugate process $e^-p \to \bar{T}\nu_e$ due to the difference between the d-quark and $\bar{d}$-quark PDF of the proton.

In Fig. 3, we show the dependence of the cross sections $\sigma * Br(T \to XY)$ on the mixing parameter R_L at the LHeC. One can see that for the small range of R_L (i.e. $R_L \le 0.2$), the production cross section increases largely with the increase of R_L. While for the relatively large value of R_L (i.e. $R_L \ge 1$), the production cross section will become slightly smaller for increasing R_L. This is mainly because of the increased admixture of valence quarks in production, mitigated by a reduced $T \to Wb$ branching ratio with R_L increas-

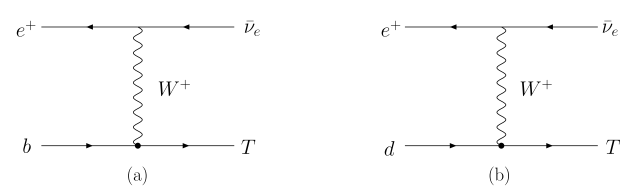

Fig. 1. The Feynman diagrams for single production of T at the LHeC for the process $e^+p \to \bar{\nu}_e T$.

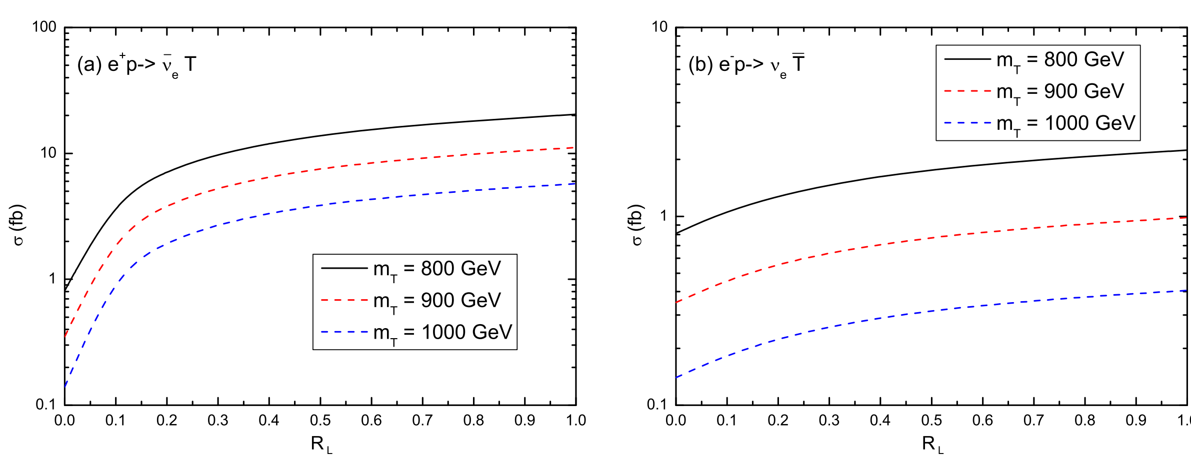

Fig. 2. The dependence of the cross sections σ on the mixing parameter R_L with $g^* = 0.1$ and three typical T quark masses for the processes (a) $e^+p \to T\bar{\nu}_e$ and (b) $e^-p \to \bar{T}\nu_e$, respectively.

ing. For instance, the value of $Br(T \to bW)$ is about 0.5 for $RL = 0$, and changed as about 0.35 for $R_L = 0.5$.

3. Event generation and analysis

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

$$e^+p \to T(\to bW^+)\bar{\nu}_e \to bW^+(\to \ell^+\bar{\nu}_\ell)\bar{\nu}_e. \quad (3)$$

The Feynman diagram of production and decay chain is presented in Fig. 4.

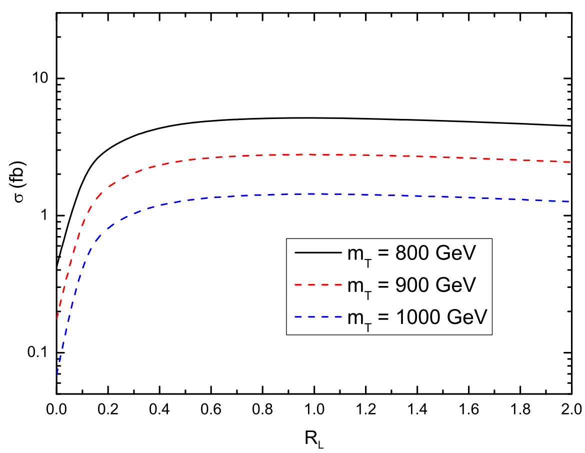

Fig. 3. The dependence of the cross sections σ on the mixing parameter R_L with $g^* = 0.1$ and three typical T quark masses for the process $e^+p \to T\bar{\nu}_e \to W^+b\bar{\nu}_e$.

For the fixed T-quark mass, the corresponding free parameters are the free parameters g^* and R_L. We take three typical values of the T quark mass: $m_T = 800, 900, 1000$ GeV with $g^* = 0.1$ and $R_L = 0.5$. We generate all event samples in this analysis at the leading order using MadGraph5-aMC@NLO with CTEQ6L PDF and PYTHIA [50] is used for parton showering and hadronization. For all the considered signals and backgrounds, the K-factors are taken to be 1 [51]. We apply jet and lepton energy smearing according to the following energy resolution formula [36]

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b, \quad (4)$$

where $a = 0.45\ \text{GeV}^{1/2}$, $b = 0.03$ for jets and $a = 0.085\ \text{GeV}^{1/2}$, $b = 0.003$ for leptons and the symbol $\oplus$ represents a quadrature sum. Event analysis is performed by using the program of MadAnalysis5 [52].

For the bW 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

$$e^+p \to t(\to bW^+)\bar{\nu}_e \to \ell^+ + b + \not{E}_T^{miss}, \quad (\bar{\nu}t)$$
$$e^+p \to W^+(\to \ell^+\bar{\nu}_\ell)j\bar{\nu}_e \to \ell^+ + j + \not{E}_T^{miss}, \quad (\bar{\nu}W^+j)$$

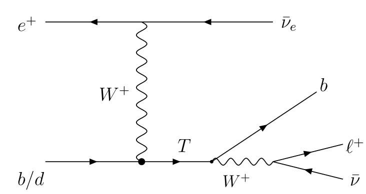

Fig. 4. The Feynman diagram for production of single T quark including the decay chain $T \to bW \to b\ell\nu$.

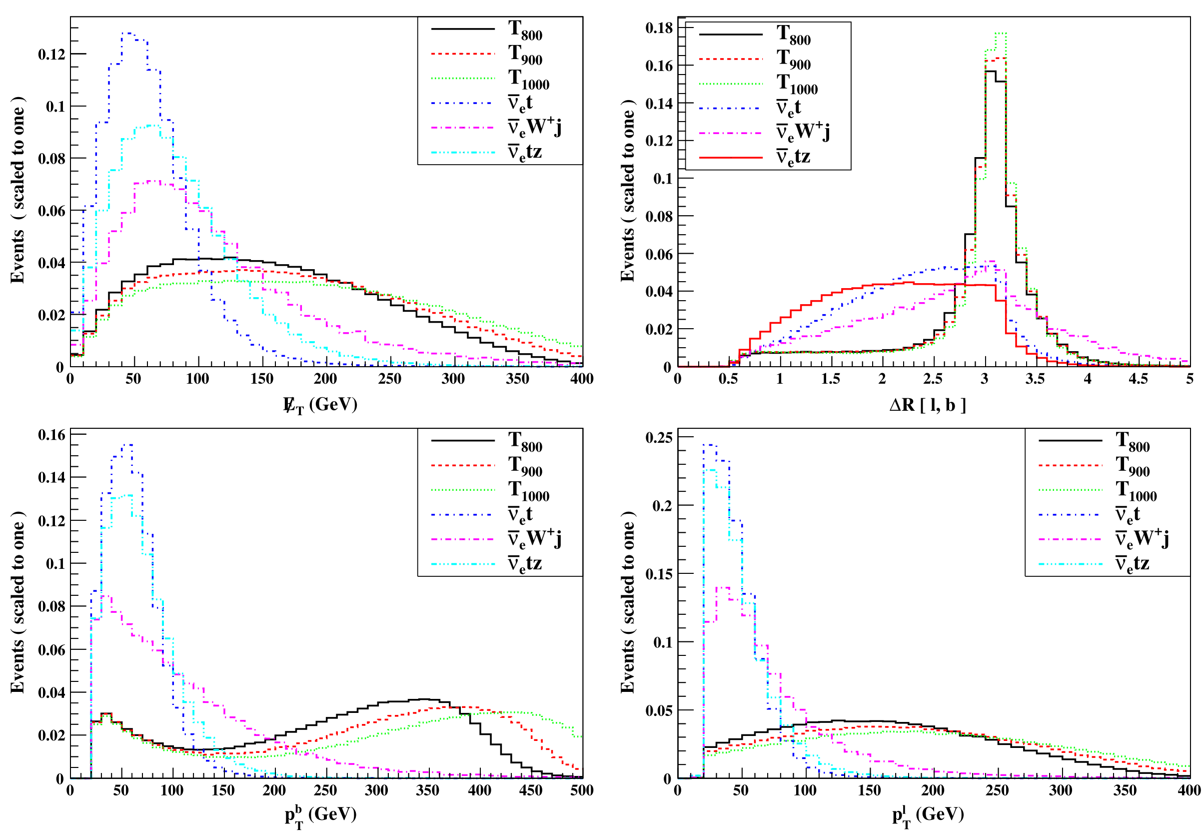

Fig. 5. Normalized distributions of $\not{E}_T$, $\Delta R(b, \ell)$ and the transverse momentums (p_T^b and p_T^ℓ) for the signals and backgrounds.

$$e^+p \to t(\to bW^+ \to b\ell^+\bar{\nu})Z(\to \nu\bar{\nu})\bar{\nu}_e$$
$$\to \ell^+ + b + \not{E}_T^{miss}, \quad (\bar{\nu}tZ) \tag{5}$$

where one light jet might be faked as b jet. We also checked that other background processes, such as the di-boson production are negligible with the selection cuts.

In our simulation, we first impose the following basic cuts to reduce the backgrounds:

- There is exactly one isolated lepton with $p_T^\ell > 20$ GeV and $|\eta_\ell| < 3$.
- There are exactly one b-tagged jet with $p_T^b > 20$ GeV and $|\eta_b| < 5$.
- The missing transverse momentum $\not{E}_T^{miss}$ is required to be larger than 20 GeV.

In Fig. 5, we show the normalized distributions of the missing transverse momentum $\not{E}_T$, the transverse momentums $p_T^{\ell,b}$ and the variable $\Delta R(b, \ell)$ for the signals and backgrounds. Based on these kinematical distributions, we impose the following cuts to get a high significance:

- Cut 1: $\not{E}_T > 130$ GeV.
- Cut 2: $p_T^\ell > 100$ GeV, $p_T^b > 200$ GeV and $2.8 < \Delta R(b, \ell) < 3.5$.

A very important selection cut, which is needed to suppress the background from the top quark production, is that the invariant mass of the lepton and b-jet pairs, $M_{b\ell}$, is above 170 GeV. This can forbid that the lepton and the b originate from the decay of a top quark. The invariant mass of the b-tagged jet and the lepton is plotted in Fig. 6 for the signals and the backgrounds. Thus we can further reduce the backgrounds by the following cut:

- Cut 3: $M_{b\ell} > 350$ GeV.

We present the cross sections of the signal and backgrounds after imposing the cuts in Table 1. From Table 1, one can see that all the backgrounds are suppressed very efficiently after imposing the selections. To estimate the observability quantitatively, we adopt the significance measurement [53]

$$SS = \sqrt{2\mathcal{L}_{int}[(\sigma_S + \sigma_B)\ln(1 + \sigma_S/\sigma_B) - \sigma_S]}, \tag{6}$$

where σ_S and σ_B are the signal and background cross sections and $\mathcal{L}_{int}$ is the integrated luminosity. Here we define the discovery significance as $SS = 5$ and exclusion limits as $SS = 3$.

In Figs. 7–8, we plot the excluded 3σ and 5σ discovery reaches in the plane of $g^* - R_L$ for three fixed typical T masses at the LHeC with 100 and 1000 fb^{-1} of integrated luminosity. As displayed in Fig. 3, the cross section for the final state reaches a maximum for $R_L \simeq 0.5$ due to the mixing effects. One can see that, for $m_T = 800, 900, 1000$ GeV and $R_L = 0.5$, the 5σ level discovery sensitivity of g^* is respectively about $0.1, 0.12, 0.16$ for $\mathcal{L}_{int} =$ 100 fb^{-1} and $R_L = 0.5$, and changed as about $0.05, 0.06, 0.08$ for

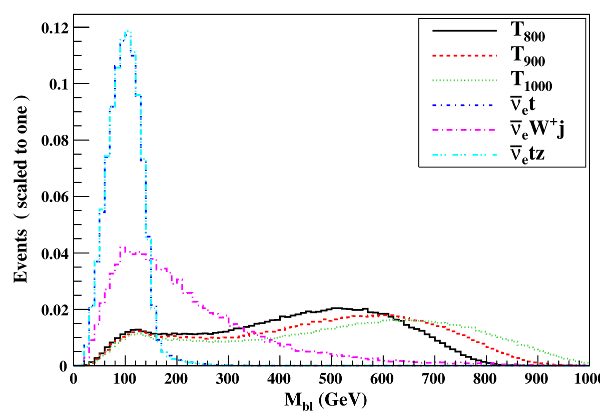

Fig. 6. Normalized invariant mass distribution of $b\ell$ system for the signals and backgrounds.

Table 1
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 the parameters as $g^* = 0.1$ and $R_L = 0.5$.

Cuts	Signal			$\bar{\nu}_e t$	$\bar{\nu}_e W^+ j$	$\bar{\nu}_e tZ$
	800 GeV	900 GeV	1000 GeV			
Basic cuts	0.81	0.4	0.23	768	34	0.19
Cut 1	0.46	0.27	0.14	15.4	7.8	0.018
Cut 2	0.24	0.16	0.09	0.0036	0.3	4.3×10^{-6}
Cut 3	0.23	0.16	0.09	0.001	0.18	1.2×10^{-6}

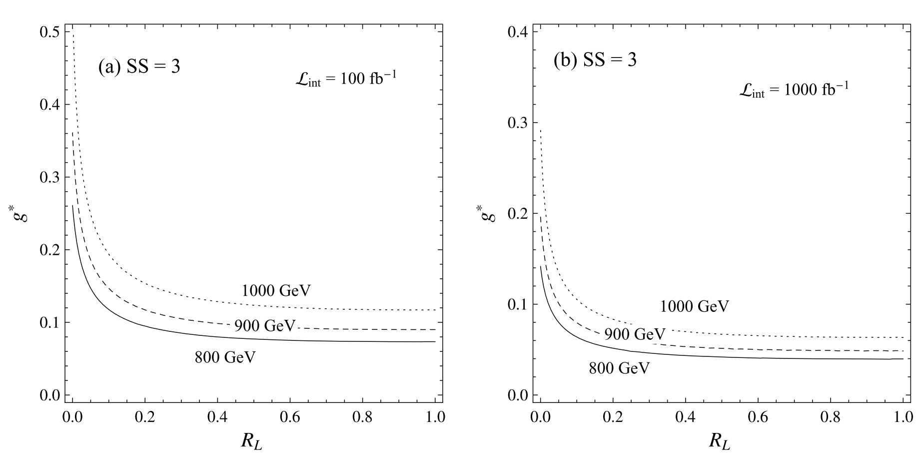

Fig. 7. 3σ contour plots for the signal in $g^* - R_L$ at the LHeC with 100 (left) and 1000 (right) fb^{-1} of integrated luminosity.

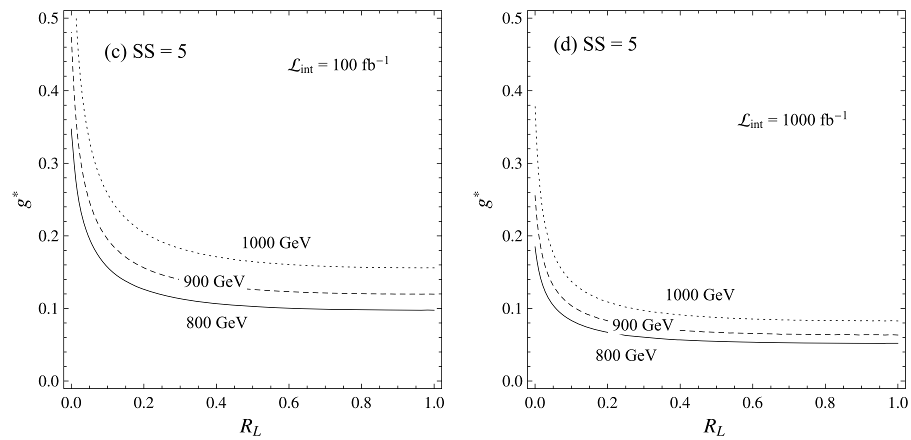

Fig. 8. 5σ contour plots for the signal in $g^* - R_L$ at the LHeC with 100 (left) and 1000 (right) fb^{-1} of integrated luminosity.

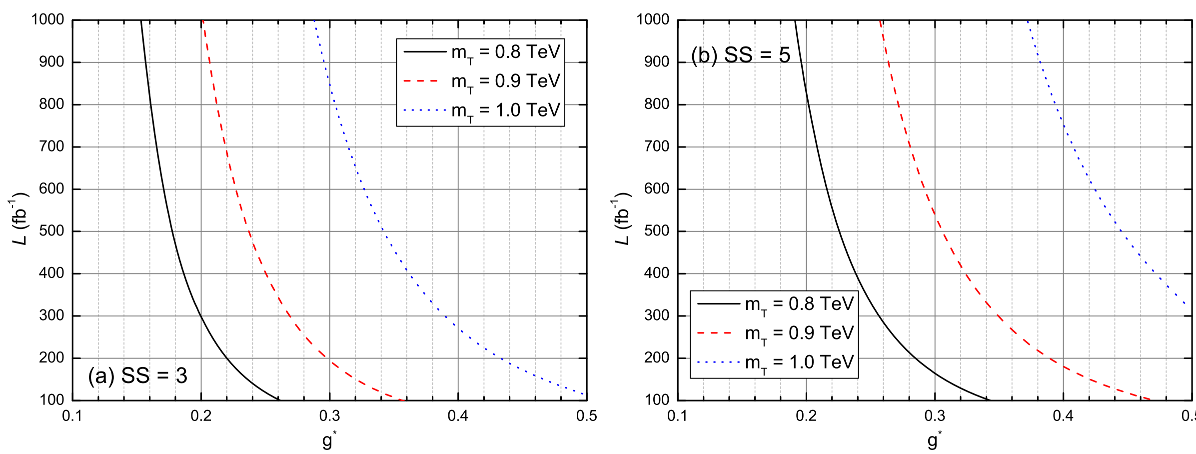

Fig. 9. 3σ (left) and 5σ (right) contour plots for the signal in $L - g^*$ at the LHeC for $R_L = 0$.

$\mathcal{L}_{int} = 1000$ fb^{-1}. If no signal is observed, it means that the coupling strength parameter g^* can not be too large. From the 3σ exclusion limits one can see that, for $m_T = 800, 900, 1000$ GeV and $\mathcal{L}_{int} = 1000$ fb^{-1}, the upper limits on the size of g^* are given as $g^* \leq 0.14, 0.20, 0.3$ for $R_L = 0$, and changed as $g^* \leq 0.04, 0.05, 0.06$ for the non-vanishing R_L.

Certainly, in some typical models such as the minimal $M1_5$ Composite Higgs (CH) models [15] and the littlest Higgs model with T-parity (LHT) [54], the heavy T-quark couplings only to the third generation of SM quarks. Due to the Goldstone-boson equivalence theorem, the branching fractions of T into bW, tZ and th are a good approximation given by ratios $2:1:1$ in the limit $m_T \gg m_t$. For comparison, we show in Fig. 9 the excluded 3σ and 5σ discovery reaches in the plane of the integrated luminosity and the coupling parameter g^* for $R_L = 0$. For $m_T = 800$ (900) GeV, we can see that the 5σ C.L. discovery sensitivity of g^* is 0.34 (0.48), 0.26 (0.35) and 0.19 (0.26) when the integrated luminosity is 100, 300 and 1000 fb^{-1}, respectively. Otherwise, the upper limits on the size of g^* are given as about 0.26 (0.36), 0.2 (0.27) and 0.15 (0.2) when the integrated luminosity is 100, 300 and 1000 fb^{-1}, respectively. Our results can be straightforwardly mapped within the context of the CH model and the LHT model, namely with [15,54]

$$g^* \simeq \frac{y m_W}{g m_T}, \quad \text{(CH)}$$
$$g^* \simeq \frac{R^2}{1+R^2}\frac{v}{f} + \mathcal{O}(\frac{v^2}{f^2}), \quad \text{(LHT)} \qquad (7)$$

where y, R and f are the model parameters (for more detail, see e.g. [15,54]).

We can now draw a comparison with other existing studies for searches via the leptonic $T \to Wb$ channel at the LHC. For example, the authors of Ref. [18] project at $\sqrt{s} = 13$ TeV and 100 fb^{-1} of integrated luminosity the exclusion potential with $Br(T \to Wb) = 0.5$, obtaining an exclusion reach up to 2.0 TeV for single production if $c_L^{Wb} \geq 0.4$. Analogously, in [19] the authors obtain an expected exclusion reach for masses up to 1.0 TeV for the leptonic $T \to Wb$ channel, including both pair and single production, with $\sqrt{s} = 14$ TeV and 30 fb^{-1} of integrated luminosity. Thus, our analysis can represent a viable and complementary candidate to pursue the search of a possible heavy T-quark.

4. Conclusion

In this letter we described the future LHeC potential to search for the heavy vector-like T-quark via the $T \to bW^+$ decay mode. We investigated the observability of the heavy vector-like top partner T production through the process $e^+p \to T(\to bW^+)\bar{\nu}_e \to bW^+(\to \ell^+\bar{\nu}_\ell)\bar{\nu}_e$ at the LHeC with $E_e = 140$ GeV (with 0.8 polarization) and $E_p = 7$ TeV. From our numerical calculations and the phenomenological analysis we found the following points:

1. Due to the presence of valence quarks in the initial state, the mixing between the T-quark with the first generation can largely enhance the production cross section. Furthermore, the production cross section of $e^+p \to T\bar{\nu}_e$ is more larger than

that for the conjugate process $e^- p \to \bar{T} \nu_e$ due to the difference between the d-quark and $\bar{d}$-quark PDF of the proton.

2. For the nonzero value of R_L, the future LHeC may observe the above signals at the 5σ confidence level. Otherwise, for $m_T = 800, 900, 1000$ GeV, the upper limits on the size of g^* are given as $g^* \le 0.09\ (0.04), 0.11\ (0.05), 0.12\ (0.06)$ with $\mathcal{L}_{int} = 100\ (1000)$ fb^{-1}.
3. In some typical models where the new vector-like T-quark only couplings to the third generation of SM quarks, for $m_T =$ 800 (900) GeV, the upper limits on the size of g^* are given as about 0.26 (0.36), 0.2 (0.27) and 0.15 (0.2) when the integrated luminosity is 100, 300 and 1000 fb^{-1}, respectively.

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