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Pair production of the vectorlike top partner at the CLIC

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Abstract

New vectorlike T-quarks (VLQ-T) have been predicted in many scenarios of new physics beyond the Standard Model, the current mass exclusion limits from LHC experiments will be relaxed by the presence of additional decay channels. In this work, we investigate the prospect of discovering the pair production of VLQ-T at the future 3 TeV Compact Linear Collider (CLIC), by focusing on the final signals via the standard decay channel $T \to Wb$ where one of the W bosons decays leptonically and the other decays hadronically. By performing a rapid detector simulation of the signal and background events as well as considering the initial state radiation and beamstrahlung effects, the exclusion limit at the 95% confidence level and the 5σ discovery prospects are, respectively, obtained on the integrated luminosity and the branching ratio of $T \to Wb$ for three typical VLQ-T masses.

1. Introduction

The new vector-like quarks (VLQs) have been predicted in many new physics models beyond the Standard Model (SM) at the TeV scale [1], such as little Higgs [2–5], which gave the first general analysis of the unitarity bounds for Little Higgs Models and stressed the importance of UV completion for all Little Higgs models on the market, composite Higgs [6], and other extended models [7–10]. Such new fermions are spin 1/2 particles characterised by having the left- and right-handed components defined by the same colour and electroweak (EW) quantum numbers [11]. Hence, such VLQs could be still viable under the present searches, while an extra

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fourth generation of SM-like quarks [12,13] should be much heavier due to the electroweak precision constraints and thus certain nonperturbative method is needed to reliably analyze the strongly coupled Yukawa sector of these extra heavy chiral quarks. A common feature that they are assumed to decay to a SM third-generation quark with a SM gauge boson, or a Higgs boson, which can generate characteristic signatures at the current and future high-energy colliders (for example see [14–26]).

For a vector-like T-quark (VLQ-T) with electromagnetic charge 2/3, direct searches generally assume the standard decay channels: $T \to bW$, tZ, and tH. In the last few years, searches at the LHC for VLQ-T have been performed and presented by the ATLAS and CMS Collaborations, with the lower mass bounds on T reaching up to about 740-1370 GeV at 95% confidence level (C.L.) for a variety of above standard decay channels [27–32]. However, such bound would be relaxed, especially if one looks beyond the minimal models where the VLQ-T can have new decay channels. Recently, non-standard or exotic decays of the vector-like quarks in different set-ups with different collider signatures have been considered in the literature [33–45].

Due to much cleaner environment, the future high-energy linear e^+e^- collider is thus a precision machine with which the properties of new VLQs can be measured precisely [46,47]. Any such new particle can be produced at the future Compact Linear Collider (CLIC) operating at $\sqrt{s} = 3$ TeV with sizable rate up to the kinematic limit of 1.5 TeV, and in some cases up to 3 TeV via single production mechanisms [48]. Recently, the single VLQs production at the CLIC is studied in Refs. [49–56] with different decay channels. However, unlike the pair production, single productions are model dependent, i.e., the exclusion limits from single production searches depend not only on the branching ratios (BRs) but also on the absolute magnitude of the unknown EW coupling parameters. For this study, we stick to the regions of the parameter space where the EW coupling parameter is much smaller than unity, thus the single-production search limits on VLQs become weaker than the pair production ones. In this work, we will investigate the pair production of the VLQ-T in the decay channel $T \to Wb$ at the future 3 TeV CLIC, where the exotic decay channels are open for the VLQ-T and the branching ratio of $T \to Wb$ is taken as a free parameter.

This paper is organized as follows: in Sec. 2, we brief describe the couplings of the singlet VLQ-T with the SM particles and the current constraints on its mass. In section 3, we discuss the pair production process at the 3 TeV CLIC, and perform a detailed collider analysis of the relevant signals and backgrounds. Finally, we give a summary in Sec. 4.

2. VLQ-T in the simplified model

A generic parametrization of an effective Lagrangian for singlet VLQ-T is given by [57]

$$\mathcal{L}_{\rm eff} = \frac{g\kappa_T}{\sqrt{2}}[\frac{1}{\sqrt{2}}\bar{T}_L W_\mu^+ \gamma^\mu b_L + \frac{1}{2c_W}\bar{T}_L Z_\mu \gamma^\mu t_L - \frac{m_T}{2m_W}\bar{T}_R h t_L - \frac{m_t}{2m_W}\bar{T}_L h t_R] + \frac{2e}{3}\bar{T}\gamma^\mu T A_\mu + \frac{e}{s_W c_W}(\frac{1}{2} - \frac{2}{3}s_W^2)\bar{T}\gamma^\mu T Z_\mu + h.c., \quad (1)$$

where g is the $SU(2)_L$ gauge coupling constant, and θ_W is the Weinberg angle. There are two free parameters: the VLQ-T quark mass m_T and the coupling strength to SM quarks in units of standard couplings, κ_T.

The VLQ searches at the LHC assume that a top partner can only decay to a third-generation quark and a SM boson. For a heavy VLQ-T, the relationship of the BRs of three standard decay modes is BR$(T \to th) \approx$ BR$(T \to tZ) \approx \frac{1}{2}BR(T \to Wb)$, which is a good approximation as expected from the Goldstone boson equivalence theorem [58–62]. Assuming $Br(T \to Wb) +$

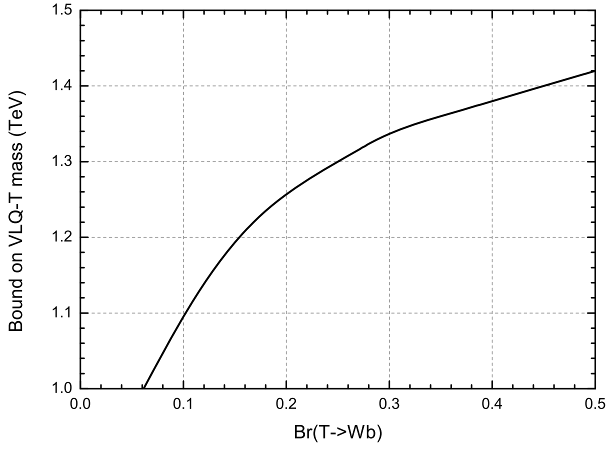

Fig. 1. LHC exclusion limits on VLQ-T as a function of $Br(T \to Wb)$ in the singlet T model including non-standard decay modes.

$Br(T \to tZ) + Br(T \to th) = 1$, the current mass limit on a weak-singlet VLQ-T stands at 1.27 TeV [63]. However, such limit would be relaxed significantly if the exotic decay channels exist. With the introduction of the new decay modes, the assumption on the Wb decays changes to

$$Br(T \to Wb) \simeq (1 - \beta_{new})/2, \tag{2}$$

where β_{new} is the BR for the new exotic decay channel, such as $T \to tS$ (an additional scalar or pseudoscalar particle). Thus, one can recast the bounds from the latest searches at the LHC in each final state and pick the strongest limit. In Fig. 1, we show the recast mass limits on VLQ-T in the presence of the new exotic decay mode from Ref. [43].

3. Collider simulation and analysis

In order to make a prediction for the signal, we calculate the production cross section for the process $e^+e^- \to T\bar{T}$ at leading order (LO). Note that here the effects of initial state radiation (ISR) and beamstrahlung are also considered at 3 TeV CLIC by using the scheme named clic3000ll in the updated version (v3.3.2) of MadGraph5-aMC@NLO [64].

In Fig. 2, we show the dependence of the cross sections σ as a function of m_T with (without) ISR and beamstrahlung effects. One can see that the cross sections can be changed with ISR and beamstrahlung effects compared with those without ISR and beamstrahlung effects. In the region of $m_T \in$ [800, 1450] GeV, the ratios of cross sections with and without ISR and beamstrahlung effects are changed from 1.07 to 0.57, thus it is necessary to consider these effects at future 3 TeV CLIC. For $m_T = 1.0$ (1.45) TeV, the cross section can reach about 20.8 (5.1) fb with ISR and beamstrahlung effects.

Considering the current LHC bound from the single production process [65], the coupling parameter κ_T should be very small, so the singlet VLQ-T can be assumed with narrow decay widths. Under the narrow-width approximation (NWA), it is possible to separate and factorize production and decay of the heavy quarks, thus allowing for a model-independent analysis of the results [66]. For the process $e^+e^- \to T\bar{T} \to W^+bW^-\bar{b}$, the cross section can be given by

$$\sigma_{WbWb} \equiv \sigma_{e^+e^- \to T\bar{T}} \times Br^2(T \to Wb). \tag{3}$$

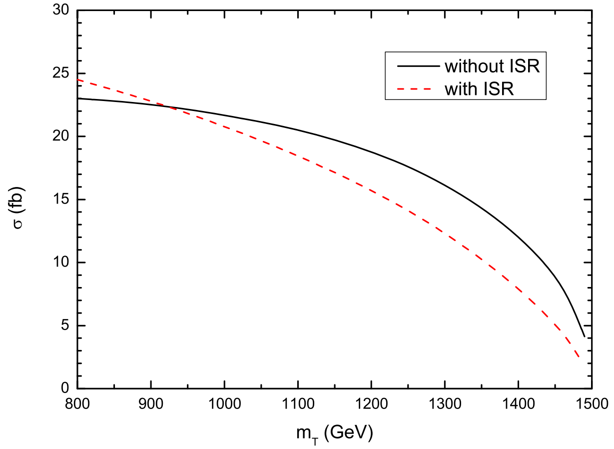

Fig. 2. Total cross section of σ as a function of m_T at 3 TeV CLIC with and without ISR effects.

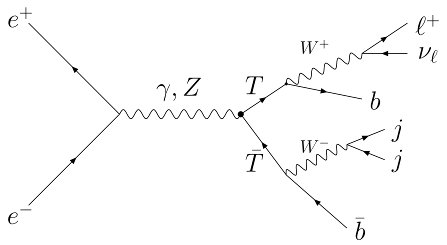

Fig. 3. Representative Feynman diagrams of the processes $e^+e^- \to T(\to bW^+ \to b\ell^+\nu)\bar{T}(\to \bar{b}jj)$.

In the remainder of this article, we will take the branching ratios BR$(T \to Wb)$ as a free parameter.

Next, we analyze the observation potential by performing a Monte Carlo simulation of the signal and background events and explore the sensitivity of VLQ-T through the channel

$$e^+e^- \to T(\to bW^+)\bar{T}(\to \bar{b}W^-) \to \ell^\pm + 2b + 2j + \not{E}_T, \quad (4)$$

where one of the W bosons decays leptonically ($\ell = e, \mu$) and the other decays hadronically. The relevant Feynman diagrams are depicted in Fig. 3.

The signal events satisfy the following features: one boosted lepton (electron or muon) and two b-tagged jet and two light jets (labeled as j) coming from the W boson, which come from heavy T decay, and missing energy ($\not{E}_T$). The dominant SM backgrounds come from the processes $e^+e^- \to t\bar{b}W^-, e^+e^- \to ZW^+W^-, e^+e^- \to hW^+W^-$. Besides, the ZW fusion processes $e^+e^- \to e^-\bar{\nu}_e\bar{b}t$ and $e^+e^- \to e^-\bar{\nu}_e b\bar{b}jj$ could also be relevant backgrounds. Note that the top pair production process is included the single top production process with the top quark on-shell decay mode $t \to Wb$, the conjugate processes of signal and backgrounds have been included in our calculations. We list the production cross sections before decay and the decay modes in Table 1.

Monte Carlo event simulations for the signal and SM background are generated at LO by using MadGraph5-aMC@NLO. Then we use Pythia 8.20 [67] for the parton shower, and make a fast detector simulation by Delphes 3.4.2 [68] with the CLIC detector card designed for 3 TeV [69].

Table 1
Cross sections of SM backgrounds with and without the ISR and beamstrahlung effects and decay mode at the 3 TeV CLIC.

Process	Cross section (with ISR)	Cross section (no-ISR)	Decay modes
$e^+e^- \to tbW$	28.7 fb	19.2 fb	$t \to W^+b$ ($\bar{t} \to W^-\bar{b}$), $W \to \ell\nu$, $W \to jj$
$e^+e^- \to ZW^+W^-$	35.7 fb	33 fb	$Z \to b\bar{b}$, $W \to \ell\nu$, $W \to jj$
$e^+e^- \to hW^+W^-$	1.33 fb	1.13 fb	$h \to b\bar{b}$, $W \to \ell\nu$, $W \to jj$
$e^+e^- \to \ell\nu bt$	17.9	18.6	$t \to W^+b$ ($\bar{t} \to W^-\bar{b}$), $W \to \ell\nu$, $W \to jj$
$e^+e^- \to \ell\nu b\bar{b}jj$	0.57 fb	0.95 fb	—

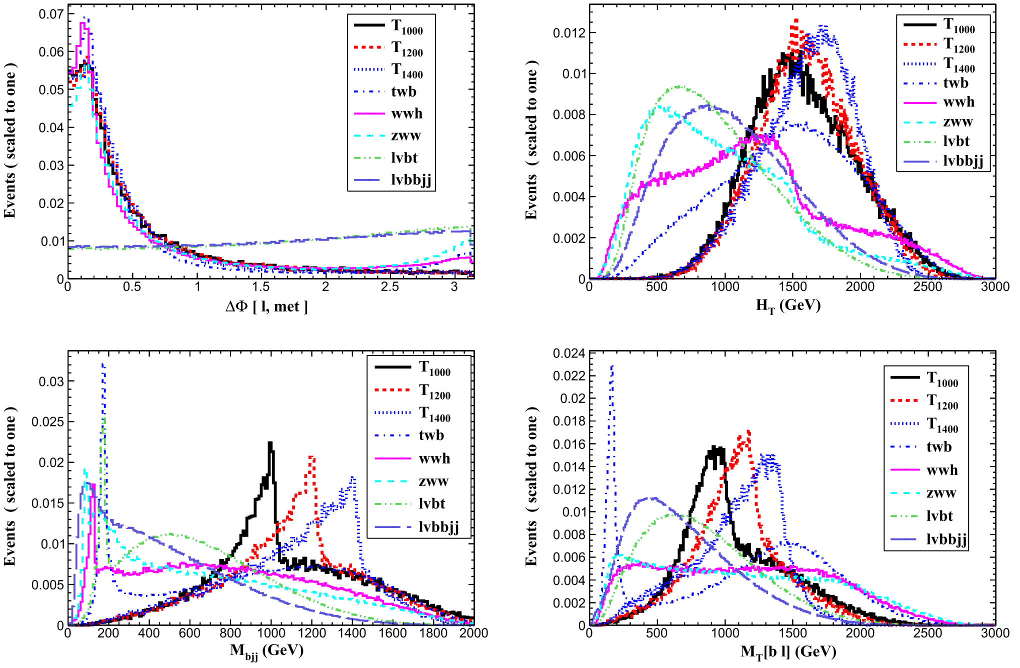

Fig. 4. Normalized distributions for the signals (with $m_T = 1000$, 1200, 1400 GeV) and SM backgrounds.

In our analysis, jets are clustered with the Valencia Linear Collider (VLC) algorithm [70,71] in exclusive mode with a fixed number of jet $N = 4$ and fixed one size parameter $R = 0.7$. In order to excessively increase the signal efficiency, the b-tagging efficiency is taken as the loose working points with 90% b-tagging efficiency. Finally, event analysis is performed by using MadAnalysis5 [72].

To identify objects, we choose the basic cuts at parton level for the signals and SM backgrounds as follows:

$$p_T^{\ell/j/b} > 25 \text{ GeV}, \quad |\eta_{\ell/b/j}| < 2.5, \quad \Delta R_{ij} > 0.4, \quad \not{E}_T > 20 \text{ GeV}, \tag{5}$$

where $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2}$ denotes the separation in the rapidity-azimuth plane, $p_T^{\ell,b,j}$ are the transverse momentum of leptons, b-jets, and light jets.

The signal kinematics for the VLQ-T pair production is quite different from the background processes, which would help for our signal reconstruction and background suppression. In Fig. 4,

Table 2
Cut flow of the cross sections (in fb) for the signals and SM backgrounds with $Br(T \to Wb) = 100\%$ and three typical VLQ-T quark masses.

Cuts	Signals			Backgrounds				
	1000 GeV	1200 GeV	1400 GeV	$tW^-\bar{b}$	ZW^+W^-	hW^+W^-	$\ell\nu bt$	$\ell\nu bbjj$
Basic	4.59	3.52	1.78	7.31	1.91	0.19	8.0	0.35
Cut 1	2.58	2.45	1.26	5.22	1.29	0.04	1.78	0.04
Cut 2	2.46	1.89	1.0	2.84	0.08	0.012	0.51	0.01
Cut 3	0.51	0.41	0.21	0.022	0.0014	0.0008	0.015	0.00014

we plot some differential distributions for signals and SM backgrounds, such as the azimuthal angle between the charged lepton and $\not{E}_T$, denoted by $\triangle\phi(\ell, \not{E}_T)$, the scalar sum of the transverse energy of all final-state jets H_T, the transverse mass distribution for one T quark $M_T(b\ell)$, and the invariant mass distributions for the other M_{bjj}. For the signal, the lepton and neutrino which carries large momentum from the decay of the heavy VLQ-T. We therefore expect there to be a small $\triangle\phi$ between these two very boosted objects. Based on these kinematical distributions, we can impose the following set of cuts:

- Cut 1: There are exactly one isolated lepton ($N(\ell) = 1$), at least three jets ($N(j) \geq 3$) and at least two b-tagged jets ($N(b) \geq 2$) with $\Delta R_{b_1,b_2} > 1$. Besides, the separation between the lepton and missing energy is required $\triangle\phi(\ell, \not{E}_T) < 0.7$.
- Cut 2: The scalar sum of the transverse momentum of final states is required $H_T > 1000$ GeV.
- Cut 3: The transverse mass and the invariant mass of the VLQ-T are both required to larger than 700 GeV.

We present the cross sections of three typical signals ($m_T = 1000, 1200, 1400$ GeV) and the relevant backgrounds after imposing the cuts in Table 2. One can see that all the SM backgrounds are suppressed very efficiently, while the signals still have a relatively good efficiency at the end of the cut flow. The largest SM background is the single top production process with the cross section of about 0.022 fb.

In order to analyze the observability, we use the median significance to estimate the expected discovery and exclusion significance [73]:

$$\mathcal{Z}_{\rm disc} = \sqrt{2\left[(s+b)\ln\left(\frac{(s+b)(1+\delta^2 b)}{b+\delta^2 b(s+b)}\right) - \frac{1}{\delta^2}\ln\left(1+\delta^2\frac{s}{1+\delta^2 b}\right)\right]}$$
$$\mathcal{Z}_{\rm excl} = \sqrt{2\left[s - b\ln\left(\frac{b+s+x}{2b}\right) - \frac{1}{\delta^2}\ln\left(\frac{b-s+x}{2b}\right)\right] - (b+s-x)\left(1+\frac{1}{\delta^2 b}\right)}, \quad (6)$$

with

$$x = \sqrt{(s+b)^2 - 4\delta^2 s b^2/(1+\delta^2 b)}. \quad (7)$$

Here, s and b represent signal and background events, respectively, and they could be obtained by multiplying the total signal and SM background cross sections by the integrated luminosity; δ is the percentage systematic error on the SM background estimate. In the idealized limit of a perfectly known background prediction, $\delta = 0$, these expressions would reduce to

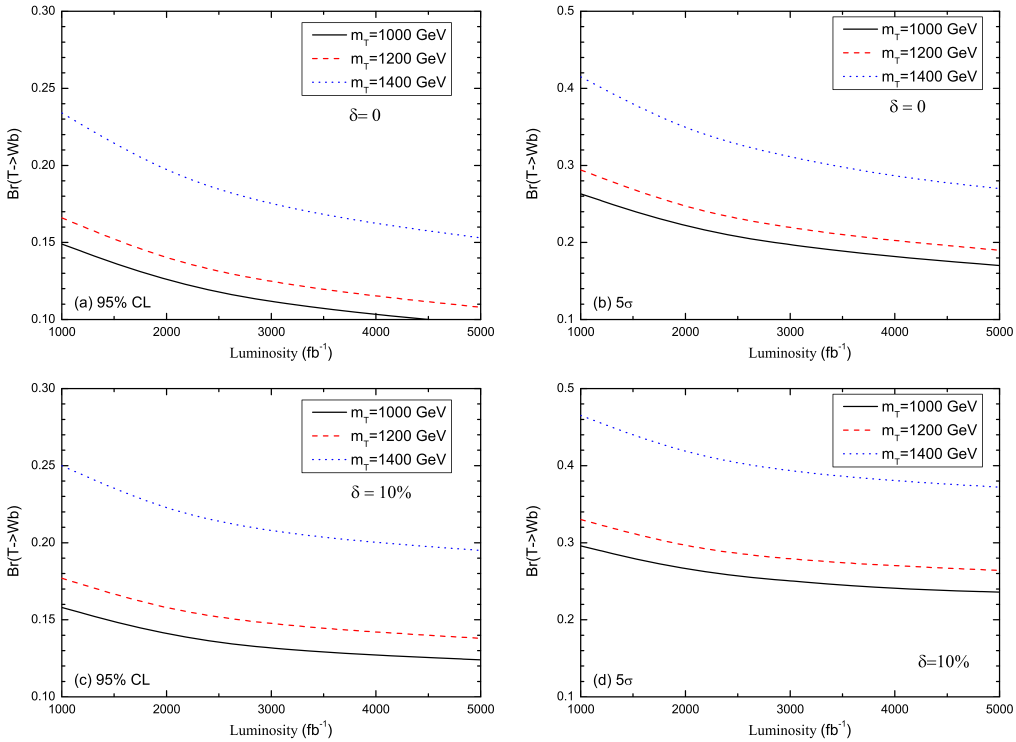

Fig. 5. Exclusion limit (at 95% CL) and discovery prospects (at 5σ) contour plots for the signal in $(Br(T \to Wb) - \mathcal{L})$ planes at future 3 TeV CLIC for $\delta = 0$ and $\delta = 10$ with three typical values of VLQ-T masses.

$$\mathcal{Z}_{\text{disc}} = \sqrt{2[(s+b)\ln(1+s/b) - s]}, \\ \mathcal{Z}_{\text{excl}} = \sqrt{2[s - b\ln(1+s/b)]}. \tag{8}$$

In the following analysis, we assumed two typical systematic uncertainties: $\delta = 0$ and 10%.

In Fig. 5, we plot the 95% CL exclusion limit and 5σ sensitivity reaches for the branching ratio $Br(T \to Wb)$ as a function of the integrated luminosity $\mathcal{L}$ with three typical VLQ-T masses, respectively. One can see that, with a realistic 10% systematic error, the sensitivities are slightly weaker than those without any systematic error. We obtain that, for $m_T = 1000$ (1400) GeV, the singlet VLQ-T can be excluded in the region of $Br(T \to Wb) \in [0.12, 0.16]$ ([0.19, 0.25]) and $\mathcal{L} \in [1000, 5000]$ fb^{-1} at the future 3 TeV CLIC, while the discover region can reach $Br(T \to Wb) \in [0.24, 0.30]$ ([0.37, 0.46]).

We can now perform a comparison with the results in Ref. [43]. For a heavy VLQ-T with mass 1400 GeV, the branching ratio of $T \to Wb$ should be smaller than about 0.45, as shown in Fig. 1. Considering a realistic 10% systematic error, the singlet VLQ-T can be excluded in the region of $Br(T \to Wb) \in [0.19, 0.25]$ and $\mathcal{L} \in [1000, 5000]$ fb^{-1} at the future 3 TeV CLIC, which could provide better sensitivity than the current experimental results obtained from the current 13 TeV LHC.

4. Conclusion

In this work, we have concentrated on the pair production of the singlet VLQ-T at the future 3 TeV CLIC in a simplified model where the exotic decay channels exist. We first reinterpret the latest mass-exclusion limits for VLQ-T in terms of the branching ratio of the standard decay channel $T \to Wb$. With the increasing branching in the extra decay mode, the existing limits on VLQs can relax by up to $300 - 500$ GeV, such limits are independent of the exact nature of the additional decay modes.

Then we have performed a full simulation for the signals and the relevant SM backgrounds via the Wb decay channel, where one of the W bosons decays leptonically and the other decays hadronically. Considering the systematic error case of $\delta = 10\%$, the 95% CL exclusion limits and 5σ discovery prospects in the parameter plane of the two variables $Br(T \to Wb)$ and the integral luminosity have been obtained for three typical VLQ-T masses. The results show that, for $m_T = 1000$ (1400) GeV, the singlet VLQ-T can be excluded in the region of $Br(T \to Wb) \in [0.12, 0.16]$ ([0.19, 0.25]) and $\mathcal{L} \in [1000, 5000]$ fb^{-1}, while the discover region can reach $Br(T \to Wb) \in [0.24, 0.30]$ ([0.37, 0.46]). We therefore expect that the signatures studied here will provide complementary information for detecting such singlet VLQ-T quark including non-standard decay modes at the future 3 TeV CLIC.

CRediT authorship contribution statement

Xin Qin: Conceptualization, Methodology, Writing – review & editing. **Chang Wang:** Data curation, Software, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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