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Single production of vector-like T quark decaying into Wb at the CLIC

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Abstract

Based on a model-independent framework including $SU(2)$ singlet vector-like top partner (VLQ-T), we investigate the prospect of discovering the single production of VLQ-T decaying into Wb in e^+e^- collisions at 3 TeV Compact Linear Collider (CLIC). By carrying out a full simulation for the signal and the relevant SM backgrounds, we find that for the high integrated luminosity of 3 (5) ab^{-1}, the singlet VLQ-T could be excluded in the correlated region of the coupling parameter $g^* \in [0.17, 0.5]$ ($[0.15, 0.4]$) and mass $m_T \in$ [1500 GeV, 2600 GeV] at 2σ level, and the discovered correlation region is $g^* \in [0.27, 0.5]$ ($[0.24, 0.44]$) and $m_T \in$ [1500 GeV, 2400 GeV]. The future 3 TeV CLIC is a promising hunting ground for such new particles with electroweak strength interactions.

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1. Introduction

To solve the gauge hierarchy problem [1], new vector-like quarks (VLQs) are hypothetical spin-1/2 particles that arise in many diverse scenarios, such as Little Higgs model [2], Composite Higgs model [3], and other extended models [4–7]. Unlike the chiral current of Standard Model (SM) quarks, VLQs have a pure vector current in the Lagrangian and the left- and right-handed

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components transform with the same properties under the SM electroweak symmetry group [8]. In addition, VLQs do not acquire mass by interacting with the Higgs field, so they are not excluded by measurements of Higgs-boson properties. A common feature of these VLQs is that they are expected to couple preferentially to third-generation quarks and can have both neutral-current and charged-current decays. Here we focus on the up-type vector-like T quark (VLQ-T) with charge 2/3, which can decay into Wb, Zt, or ht and generate characteristic signatures at the current and future high-energy colliders (for example see [9–26].

Up to now, the direct searches for VLQs have been performed by the ATLAS and CMS Collaborations in Run 2 [27–34]. Although there is no experimental evidence of such VLQs, the constraints on their masses have been obtained at 95% confidence level (CL) via the pair production process. For instance, given the current constraints from direct searches by the ATLAS Collaboration with an integrated luminosity of 36.1 fb^{-1}, the minimum mass of a singlet VLQ-T is set at about 1.31 TeV, for a variety of signatures via the pair production process [33]. The CMS Collaboration recently presented a search for VLQ-T pair production in the fully hadronic final state using Run 2 data [34], and excluded T-quark mass below 1.37 TeV at 95% CL for a variety of decay modes.

Compared with the hadron colliders, the future linear e^+e^- colliders could provide much cleaner environment [35–37], i.e., the final stage of Compact Linear Collider (CLIC) operating at $\sqrt{s} = 3$ TeV is expected to directly examine the pair production of new top partner of mass up to 1.5 TeV [38]. The future high-energy linear e^+e^- collider is thus a precision machine with which the properties of new VLQs can be measured precisely [39–47]. Very recently, the single VLQ-T production at the future high-energy $e\gamma$ colliders are studied in Refs. [48–50] with different decay channels. In this work, we will investigate the single production of the VLQ-T in channel $T \to Wb$ at the future 3 TeV CLIC. We expect that such work may become a complementary to other production processes in searches for the heavy VLQ-T at the future high-energy linear colliders.

This paper is organized as follows: in section 2, we brief review the couplings of VLQ-T with the SM particles, and discuss its single production at future 3 TeV CLIC. Section 3 devotes to a detailed analysis of the relevant signal and background at the CLIC. Finally, we give a summary in section 4.

2. Singlet vector-like top partner in the simplified model

Following the notation of Ref. [10], a generic parametrization of an effective Lagrangian for singlet top quark partners is given by

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

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

Certainly, the coupling parameter can also be described as other constants, i.e. $\sin\theta_L$ [8] or κ [10,13]. After comparison, we find that there is a simple relation among these coupling parameters: $g^* = \sqrt{2}\sin\theta_L = \sqrt{2}\kappa$. At 13 TeV LHC, searches for single production of T quarks have placed limits on T-quark production cross-sections for T-quark masses between 1 and 2 TeV at

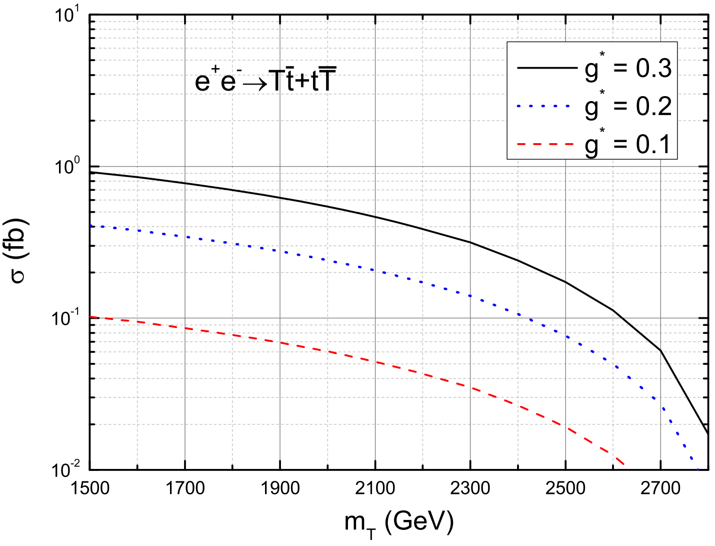

Fig. 1. Total cross sections as a function of m_T with three typical values of g^*.

95% CL for various SM couplings [51–54]. Here we take a conservative limit for the coupling parameter $g^* \le 0.5$, which is consistent with the current experiment bounds [54]. The singlet VLQ-T has three possible decay modes: $T \to bW$, tZ, and th. For $M_T \ge 1$ TeV, the branching ratios $\mathrm{BR}(T \to th) \approx \mathrm{BR}(T \to tZ) \approx \frac{1}{2}\mathrm{BR}(T \to Wb)$ is a good approximation as expected from the Goldstone boson equivalence theorem [55–60].

In order to make a prediction for the signal, we calculate the cross section for the process $e^+e^- \to T\bar{t} + t\bar{T}$ at Leading order (LO) by using MadGraph5-aMC@NLO [61]. Note that the model file of the singlet VLQ-T quark could be downloaded from the Feynrules Model Database [62] and could also be implemented via the FeynRules package [63]. The numerical values of the input parameters are taken from [64]:

$$m_Z = 91.1876\ \mathrm{GeV}, \quad \sin^2\theta_W = 0.231, \quad m_t = 172.4\ \mathrm{GeV}, \quad \alpha_s(m_Z) = 0.1185. \tag{2}$$

In Fig. 1, we have shown the dependence of the cross section σ for the process $e^+e^- \to T\bar{t} + t\bar{T}$ on the VLQ-T quark mass m_T at a 3 TeV CLIC for three typical values of g^*. As the VLQ-T quark mass grows, the cross section of single production decreases slowly due to a larger phase space. For $g^* = 0.2$ and $m_T = 1.5$ (2) TeV, the cross section can reach 0.41 (0.24) fb. Obviously, the cross section of single T-quark production is proportional to the square of the coupling strength g^* for a fixed mass.

3. Collider simulation 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 VLQ-T at the 3 TeV CLIC through the channel

$$e^+e^- \to T(\to bW^+ \to b\ell^+\nu_\ell)\bar{t}(\to \bar{b}jj) \to \ell^+ + 2b + 2j + \not{E}_T, \tag{3}$$

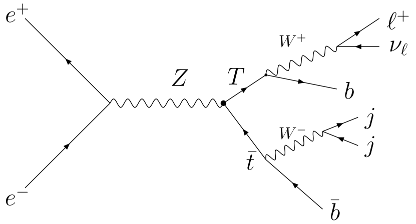

Fig. 2. Representative Feynman diagrams of the processes $e^+e^- \to T(\to bW^+)\bar{t}(\to \bar{b}jj) \to b\ell^+\nu_\ell\bar{b}jj$.

where the gauge boson W^+ decays leptonically and the top quark decays hadronically. The relevant Feynman diagrams is depicted in Fig. 2. For this channel, we can see that the signal events satisfy the following features:

(i) one boosted lepton (electron or muon) and one b-tagged jet, which come from heavy T decay, missing energy coming from neutrino;
(ii) two jets (labeled as j) come from the W boson and one b-tagged jet comes from the top quark decay.

According to the feature of the signal, the dominant SM backgrounds come from the single top production processes: $e^+e^- \to tW^-\bar{b}, \bar{t}W^+b$, and single gauge boson W production processes $e^+e^- \to W^\pm jj$. Note that the contribution from the top pair production process $e^+e^- \to t\bar{t}$ is also included in the single top production processes with the $t \to Wb$ decay [65]. Similarly, the contribution from the process $e^+e^- \to W^+W^-$ is also included in the single gauge boson production processes with the $W^\pm$ decays hadronically. We do not consider the $e^+e^- \to W^+W^-Z$, $e^+e^- \to W^+W^-h$ and $e^+e^- \to ZZZ$ production processes because their cross sections are negligible after applying our selection cuts.

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

$$p_T^\ell > 15\ \text{GeV}, \quad p_T^{b/j} > 25\ \text{GeV}, \quad |\eta_\ell| < 2.5, \quad |\eta_{b/j}| < 5 \tag{4}$$

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.

We generate the signal and background events by using MadGraph 5 and perform the parton shower and hadronization with Pythia 8.20 [66]. The fast detector simulations are performed with Delphes 3.4.2 [67] with the CLIC detector card designed for 3 TeV [68]. In our analysis, jets are clustered with the Valencia Linear Collider (VLC) algorithm [69,70] in exclusive mode and fixed one size parameter $R = 0.7$. The b-tagging efficiency and misidentification rates are taken as the medium working points (WP) (70% b-tagging efficiency) and the misidentification rates are given as a function of energy and pseudorapidity, i.e., in a bit where $E > 500$ GeV and $1.53 < |\eta| \leq 2.09$, misidentification rates are 9×10^{-3} for the medium WP. Finally, event analysis is performed by using MadAnalysis5 [71].

In Fig. 3, we draw some differential normalized distributions for signals and SM backgrounds, such as the normalized pseudorapidity distribution of the lepton, the scalar sum of the transverse energy of all final-state objects E_T, the missing energy $\not{E}_T$, and the transverse mass distribution for the T quark $M_T(b_1\ell)$. For the background, the leptons can be produced via the s-channel exchange of γ, Z as well as t-channel exchange of neutrino's, which results in the peaks at

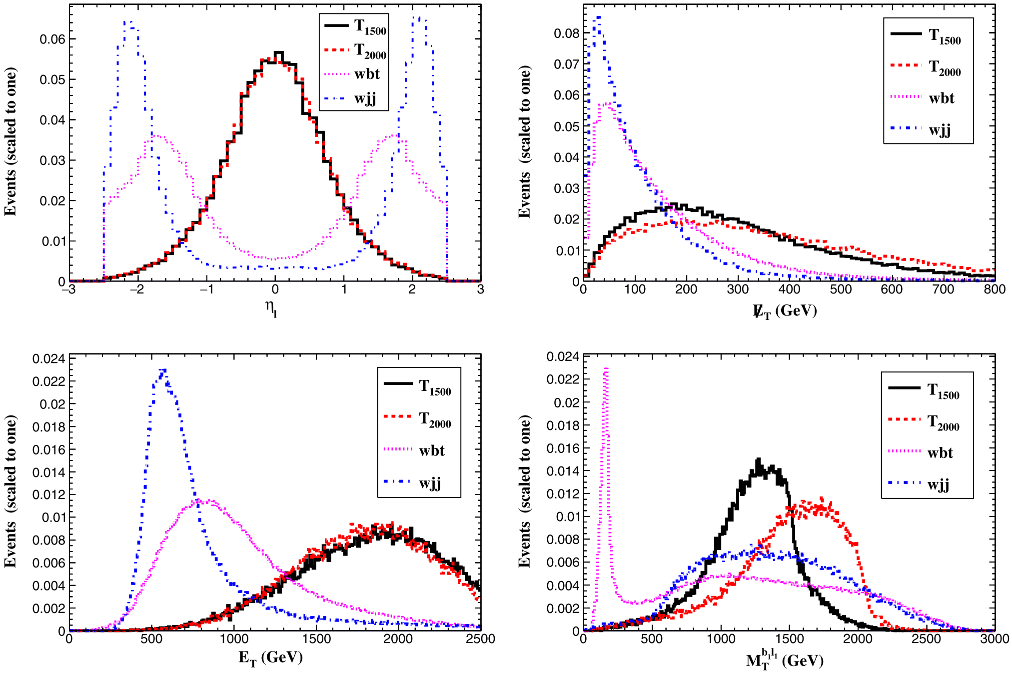

Fig. 3. Normalized distributions for the signals (with $m_T = 1500$ and 2000 GeV) and SM backgrounds at the CLIC.

higher η values. However, for the signal, the lepton is produced from the decay of the heavier VLQ-T, produced via the s-channel exchange of Z. As a result, the η distribution for the signal is more centrally peaked. We carry out the cut-based analysis by looking at some relevant kinematic variables which can help design proper cuts on them to improve the signal over the background.

- Cut-1: There are exactly one isolated lepton ($N(\ell) = 1$) with $|\eta_\ell| \leq 1$, at least two b-tagged jets.
- Cut-2: The transverse missing energy is required $\not{E}_T > 150$ GeV.
- Cut-3: The scalar sum of the transverse energy of all final-state objects E_T is required $E_T > 1300$ GeV.
- Cut-4: The transverse mass of the T quark, $M_T(b_1\ell) > 1000$ GeV. We also demand $140 \text{ GeV} < M_{b_2jj} < 210$ GeV to reduce backgrounds that do not include the top quark.

We present the cross sections of two typical signals ($m_T = 1500$ and 2000 GeV) with $g^* = 0.3$ and the relevant backgrounds after imposing the cuts in Table 1. 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 large background comes from the single top production process, with a total cross section of 0.014 fb.

To handle the relatively small event number, we will use the median significance $\mathcal{Z}$ to estimate the expected discovery and exclusion significance [72]:

$$\mathcal{Z}_{\text{disc}} = \sqrt{2\mathcal{L}_{int}[(\sigma_S + \sigma_B)\ln(1 + \sigma_S/\sigma_B) - \sigma_s]} \geq 5, \quad (5)$$

$$\mathcal{Z}_{\text{excl}} = \sqrt{2\mathcal{L}_{int}[\sigma_S - \sigma_B \ln(1 + \sigma_S/\sigma_B)]} \leq 2 \quad (6)$$

Table 1
Cut flow of the cross sections (in fb) for the signals and SM backgrounds at the 3 TeV CLIC with $g^* = 0.3$ and two typical VLQ-T quark masses.

Cuts	Signals		Backgrounds	
	1500 GeV	2000 GeV	Wbt	Wjj
Basic	0.057	0.032	0.47	4.95
Cut 1	0.044	0.026	0.07	0.09
Cut 2	0.036	0.021	0.041	0.054
Cut3	0.031	0.019	0.028	0.036
Cut4	0.017	0.011	0.014	0.003

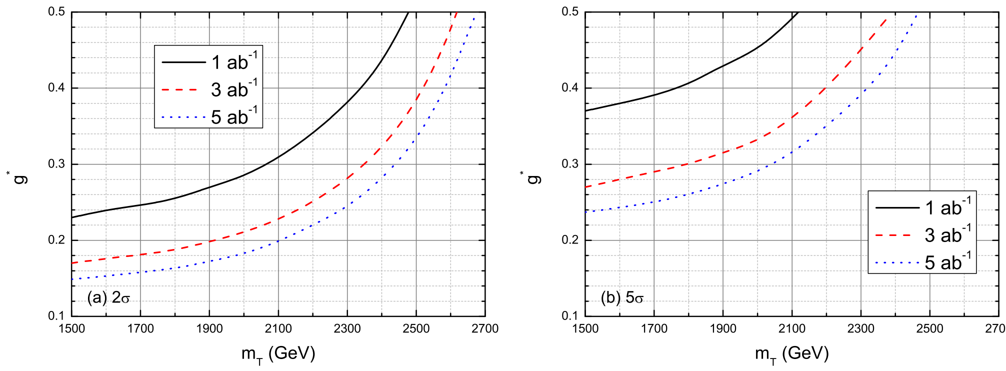

Fig. 4. 2σ exclusion limit (left) and 5σ discovery prospects (right) contour plots for the signal in $g^* - m_T$ planes at 3 TeV CLIC with three integral luminosity of 1, 3 and 5 ab^{-1}.

Table 2
Some results of searching for the singlet VLQ-T at different colliders. "\" stands for no relevant results in the reference.

Channel	Data Set	Excluding capability		Discovery capability		Reference
		g^*	m_T/TeV	g^*	m_T/TeV	
$T \to tZ$	LHC @14 TeV, 3 ab^{-1}	[0.06, 0.25]	[0.9, 1.5]	[0.10, 0.42]	[0.9, 1.5]	[17]
$T \to th$	LHC @14 TeV, 3 ab^{-1}	[0.16, 0.50]	[1.0, 1.6]	[0.24, 0.72]	[1.0, 1.6]	[18]
$T \to bW^+$	LHC @14 TeV, 3 ab^{-1}	[0.19, 0.50]	[1.3, 2.4]	[0.31, 0.50]	[1.3, 1.9]	[20]
$T \to bW^+$	$e\gamma$ collider @2 TeV, 1 ab^{-1}	[0.13, 0.50]	[0.8, 1.6]	\	\	[48]
$T \to tZ$	$e\gamma$ collider @3 TeV, 3 ab^{-1}	[0.15, 0.23]	[1.3, 2.0]	[0.23, 0.50]	[1.3, 2.0]	[49]
$T \to th$	$e\gamma$ collider @3 TeV, 3 ab^{-1}	[0.14, 0.50]	[1.3, 2.0]	[0.27, 0.50]	[1.3, 2.0]	[50]
$T \to bW^+$	CLIC@3 TeV, 3 ab^{-1}	[0.17, 0.50]	[1.5, 2.6]	[0.27, 0.50]	[1.5, 2.4]	this work
	CLIC@3 TeV, 5 ab^{-1}	[0.15, 0.40]	[1.5, 2.6]	[0.24, 0.44]	[1.5, 2.4]	

Here, $\pounds_{int}$ is the integrated luminosity and σ_S and σ_B are the signal and background cross sections, respectively. Here we do not consider the effects of the systematic uncertainties, the initial state radiation (ISR) and beamstrahlung, but we expect these will not change our results significantly.

In Fig. 4, we plot the 2σ and 5σ sensitivity reaches for the coupling strength g^* as a function of m_T at 3 TeV CLIC with three integral luminosity of 1, 3 and 5 ab^{-1}. One finds that, the VLQ-T quark can be excluded in the region of $g^* \in [0.17, 0.5]$ ([0.15, 0.4]) and $m_T \in$ [1500 GeV, 2600

GeV] at the 3 TeV CLIC with the integrated luminosity of 3 (5) ab^{-1}, while the discover region can reach $g^* \in [0.27, 0.5]$ ($[0.24, 0.44]$) and $m_T \in$ [1500 GeV, 2400 GeV]. Moreover, we list some existing results related to searching for the singlet VLQ-T in Table 2. From this table, we can find that our result is competitive and complement compared with the previous studies.

4. Conclusion

In this work, we have concentrated on the single production of the SU(2) singlet VLQ-T at the future 3 TeV CLIC via the process $e^+e^- \to T\bar{t}$ in a simplified model, in which only two free parameters are included, the VLQ-T mass m_T and the EW coupling constant g^*. We have performed a full simulation for the signals and the relevant SM backgrounds based on the decay channel $T \to bW^+ \to b\ell^+\nu_\ell$ ($\ell = e, \mu$). The 2σ exclusion limits and 5σ discovery prospects in the parameter plane of the two variables m_T and g^* have been obtained at the future 3 TeV CLIC. Our numerical results show that, at the 3 TeV CLIC with the integrated luminosity of 3 (5) ab^{-1}, the VLQ-T quark can be excluded in the region of $g^* \in [0.17, 0.5]$ ($[0.15, 0.4]$) and $m_T \in$ [1500 GeV, 2600 GeV], while the discover region can reach $g^* \in [0.27, 0.5]$ ($[0.24, 0.44]$) and $m_T \in$ [1500 GeV, 2400 GeV]. Compared with the results of some previous phenomenological studies, we find that the future 3 TeV CLIC will prove to be a promising hunting ground for such new particles which have electroweak strength interactions.

CRediT authorship contribution statement

Xin Qin: Data curation, Software, Writing – original draft. **Liu-Feng Du:** Data curation, Software. **Jie-Fen Shen:** Conceptualization, Methodology, Writing – review & editing.

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.

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References

[1] A. De Simone, O. Matsedonskyi, R. Rattazzi, A. Wulzer, J. High Energy Phys. 04 (2013) 004.
[2] N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson, J. High Energy Phys. 0207 (2002) 034.
[3] K. Agashe, R. Contino, A. Pomarol, Nucl. Phys. B 719 (2005) 165.
[4] H.J. He, T.M.P. Tait, C.P. Yuan, Phys. Rev. D 62 (2000) 011702.
[5] X.F. Wang, C. Du, H.J. He, Phys. Lett. B 723 (2013) 314–323.
[6] H.J. He, C.T. Hill, T.M.P. Tait, Phys. Rev. D 65 (2002) 055006.
[7] H.J. He, Z.Z. Xianyu, J. Cosmol. Astropart. Phys. 10 (2014) 019.
[8] J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, M. Pérez-Victoria, Phys. Rev. D 88 (2013) 094010.
[9] A. Atre, G. Azuelos, M. Carena, T. Han, E. Ozcan, J. Santiago, G. Unel, J. High Energy Phys. 1108 (2011) 080.
[10] M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi, Nucl. Phys. B 876 (2013) 376.
[11] D. Barducci, L. Panizzi, J. High Energy Phys. 12 (2017) 057.

[12] G. Cacciapaglia, A. Carvalho, A. Deandrea, T. Flacke, B. Fuks, D. Majumder, L. Panizzi, H.S. Shao, Phys. Lett. B 793 (2019) 206–211.
[13] B. Fuks, H.S. Shao, Eur. Phys. J. C 77 (2) (2017) 135.
[14] Y.J. Zhang, L. Han, Y.B. Liu, Phys. Lett. B 768 (2017) 241–247.
[15] L. Han, Y.J. Zhang, Y.B. Liu, Phys. Lett. B 771 (2017) 106–112.
[16] Y.B. Liu, Nucl. Phys. B 923 (2017) 312–323.
[17] Y.B. Liu, Y.Q. Li, Eur. Phys. J. C 77 (10) (2017) 654.
[18] Y.B. Liu, S. Moretti, Phys. Rev. D 100 (1) (2019) 015025.
[19] X.Y. Tian, L.F. Du, Y.B. Liu, Nucl. Phys. B 965 (2021) 115358.
[20] B. Yang, M. Wang, H. Bi, L. Shang, Phys. Rev. D 103 (3) (2021) 036006.
[21] S. Moretti, D. O'Brien, L. Panizzi, H. Prager, Phys. Rev. D 96 (7) (2017) 075035.
[22] S. Moretti, D. O'Brien, L. Panizzi, H. Prager, Phys. Rev. D 96 (3) (2017) 035033.
[23] A. Carvalho, S. Moretti, D. O'Brien, L. Panizzi, H. Prager, Phys. Rev. D 98 (1) (2018) 015029.
[24] A. Buckley, J.M. Butterworth, L. Corpe, D. Huang, P. Sun, SciPost Phys. 9 (5) (2020) 069.
[25] A. Deandrea, T. Flacke, B. Fuks, L. Panizzi, H.S. Shao, J. High Energy Phys. 08 (2021) 107.
[26] J.Z. Han, J. Yang, S. Xu, H.K. Wang, Nucl. Phys. B 975 (2022) 115672.
[27] M. Aaboud, et al., ATLAS Collaboration, Phys. Rev. D 98 (2018) 092005.
[28] M. Aaboud, et al., ATLAS Collaboration, J. High Energy Phys. 1812 (2018) 039.
[29] M. Aaboud, et al., ATLAS Collaboration, J. High Energy Phys. 1808 (2018) 048.
[30] M. Aaboud, et al., ATLAS Collaboration, J. High Energy Phys. 1905 (2019) 164.
[31] A.M. Sirunyan, et al., CMS Collaboration, Eur. Phys. J. C 79 (2019) 364.
[32] A.M. Sirunyan, et al., CMS Collaboration, J. High Energy Phys. 08 (2018) 177.
[33] M. Aaboud, et al., ATLAS Collaboration, Phys. Rev. Lett. 121 (2018) 211801.
[34] A.M. Sirunyan, et al., CMS, Phys. Rev. D 100 (7) (2019) 072001.
[35] H. Abramowicz, et al., CLIC Detector and Physics Study, arXiv:1307.5288 [hep-ex].
[36] J. de Blas, R. Franceschini, F. Riva, P. Roloff, U. Schnoor, M. Spannowsky, J.D. Wells, A. Wulzer, J. Zupan, S. Alipour-Fard, et al., arXiv:1812.02093 [hep-ph].
[37] R. Franceschini, Int. J. Mod. Phys. A 35 (2020) 2041015.
[38] D. Dannheim, P. Lebrun, L. Linssen, D. Schulte, S. Stapnes, arXiv:1305.5766 [physics.acc-ph].
[39] R. Kitano, T. Moroi, S.f. Su, J. High Energy Phys. 12 (2002) 011.
[40] K. Kong, S.C. Park, J. High Energy Phys. 08 (2007) 038.
[41] A. Senol, A.T. Tasci, F. Ustabas, Nucl. Phys. B 851 (2011) 289–297.
[42] K. Harigaya, S. Matsumoto, M.M. Nojiri, K. Tobioka, J. High Energy Phys. 01 (2012) 135.
[43] A.B. Mahfoudh, L. Guo, W. Liu, W.G. Ma, R.Y. Zhang, W.J. Zhang, Commun. Theor. Phys. 62 (6) (2014) 824–832.
[44] Y.B. Liu, Z.J. Xiao, Nucl. Phys. B 892 (2015) 63–82.
[45] X. Qin, J.-F. Shen, Nucl. Phys. B 966 (2021) 115388.
[46] L. Han, J.F. Shen, Eur. Phys. J. C 81 (5) (2021) 463.
[47] J.Z. Han, J. Yang, S. Xu, H.K. Wang, Phys. Rev. D 105 (1) (2022) 015005.
[48] B. Yang, H. Shao, J. Han, Eur. Phys. J. C 78 (3) (2018) 184.
[49] L. Shang, D. Zhang, B. Yang, Phys. Rev. D 100 (7) (2019) 075032.
[50] L. Shang, W. Wei, B. Yang, Nucl. Phys. B 955 (2020) 115058.
[51] A.M. Sirunyan, et al., CMS, J. High Energy Phys. 05 (2017) 029.
[52] A.M. Sirunyan, et al., CMS, Phys. Lett. B 781 (2018) 574–600.
[53] A.M. Sirunyan, et al., CMS, J. High Energy Phys. 01 (2020) 036.
[54] G. Aad, et al., ATLAS, arXiv:2201.07045 [hep-ex].
[55] For a comprehensive review, H.J. He, Y.P. Kuang, C.P. Yuan, arXiv:hep-ph/9704276.
[56] H.J. He, Y.P. Kuang, X.y. Li, Phys. Rev. Lett. 69 (1992) 2619–2622.
[57] H.J. He, Y.P. Kuang, X.y. Li, Phys. Rev. D 49 (1994) 4842–4872.
[58] H.J. He, Y.P. Kuang, C.P. Yuan, Phys. Rev. D 51 (1995) 6463–6473.
[59] H.J. He, Y.P. Kuang, C.P. Yuan, Phys. Rev. D 55 (1997) 3038–3067.
[60] H.J. He, W.B. Kilgore, Phys. Rev. D 55 (1997) 1515–1532.
[61] 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.
[62] http://feynrules.irmp.ucl.ac.be/wiki/VLQ-tsingletvl.
[63] A. Alloul, N.D. Christensen, C. Degrande, C. Duhr, B. Fuks, Comput. Phys. Commun. 185 (2014) 2250–2300.
[64] M. Tanabashi, et al., Particle Data Group, Phys. Rev. D 98 (2018) 030001.

[65] J. Fuster, I. García, P. Gomis, M. Perelló, E. Ros, M. Vos, Eur. Phys. J. C 75 (2015) 223.
[66] T. Sjöstrand, S. Ask, J.R. Christiansen, et al., Comput. Phys. Commun. 191 (2015) 159.
[67] J. de Favereau, et al., DELPHES 3, J. High Energy Phys. 02 (2014) 057.
[68] E. Leogrande, P. Roloff, U. Schnoor, M. Weber, arXiv:1909.12728 [hep-ex].
[69] M. Boronat, J. Fuster, I. Garcia, E. Ros, M. Vos, Phys. Lett. B 750 (2015) 95–99.
[70] M. Boronat, J. Fuster, I. Garcia, P. Roloff, R. Simoniello, M. Vos, Eur. Phys. J. C 78 (2018) 144.
[71] E. Conte, B. Fuks, G. Serret, Comput. Phys. Commun. 184 (2013) 222–256.
[72] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Eur. Phys. J. C 71 (2011) 1554, Erratum: Eur. Phys. J. C 73 (2013) 2501.