Letter

Large $t \to cZ$ as a sign of vectorlike quarks in light of the W mass

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(Received 14 April 2022; accepted 4 August 2022; published 17 August 2022)

The rare flavor-changing top quark decay $t \to cZ$ is a clear sign of new physics and experimentally very interesting due to the huge number of top quarks produced at the LHC. However, there are few (viable) models which can generate a sizable branching ratio for $t \to cZ$—in fact vectorlike quarks seem to be the only realistic option. In this paper, we investigate all three representations (under the Standard Model gauge group) of vectorlike quarks (U, Q_1 and Q_7) that can generate a sizable branching ratio for $t \to cZ$ without violating bounds from B physics. Importantly, these are exactly the three vectorlike quarks which can lead to a sizable positive shift in the prediction for W mass, via the couplings to the top quark also needed for a sizable $\mathrm{Br}(t \to cZ)$. Calculating and using the one-loop matching of vectorlike quarks on the Standard Model effective field theory, we find that $\mathrm{Br}(t \to cZ)$ can be of the order of 10^{-6}, 10^{-5} and 10^{-4} for U, Q_1 and Q_7, respectively, and that in all three cases the large W mass measurement can be accommodated.

DOI: 10.1103/PhysRevD.106.L031704

I. INTRODUCTION

The Standard Model (SM) of particle physics contains three generations of chiral fermions, i.e., Dirac fields whose left- and right-handed components transform differently under its gauge group. While a combination of LHC searches and flavor observables excludes a chiral fourth generation [1,2], vectorlike fermions (VLFs) can be added consistently to the SM without generating gauge anomalies. In fact, VLFs appear in many extensions of the SM such as grand unified theories [3–5], composite models or models with extra dimensions [6,7] and little Higgs models [8,9] (including the option of top condensation [10–14]).

VLFs are not only interesting from the theoretical perspective, but also from the phenomenological point of view as they could be involved in an explanation of $b \to s\ell^+\ell^-$ data [15–19], the tension in $(g-2)_\mu$ [20–35] or account for the Cabibbo angle anomaly [36–45]. Furthermore, vectorlike quarks (VLQs) can lead to tree-level effects in Z-t-c and h-t-c couplings after electroweak (EW) symmetry breaking and therefore generate sizable effects in the related flavor-changing neutral current (FCNC) decays of the top quark [43–49].

There are three VLQs (U, Q_1 and Q_7) that generate a Z-t-c (and h-t-c) coupling but do not give rise to down-quark FCNCs at tree level, such that the former can be sizable. However, even these VLQs affect e.g., the W mass[1] and B decays at the loop level. Therefore, it is important to calculate and include these effects in a phenomenological analysis in order to assess the possible size of $t \to Z(h)c$ and to evaluate if one can account for the recent measurement of the W mass by the CDF Collaboration [51], which suggests that M_W is larger than the expected within the SM.

II. SETUP AND MATCHING CALCULATION

There are seven possible representations [under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$] of VLQs, given in Table I, defining them as heavy fermions which are

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[1]The contribution of VLQs to the W mass, via the oblique S and T parameters, has previously been calculated at fixed order in Ref. [50], where they studied the contribution to electroweak observables and Higgs decays only.

TABLE I. Representations of the Higgs, the SM quarks and of the VLQs under the SM gauge group. The three representations in bold are the ones relevant for our analysis as they generate flavor-changing top decays at tree level but down-quark FCNCs first appear at one-loop level.

	u	d	q	H	U	D	$\boldsymbol{Q_1}$	Q_5	$\boldsymbol{Q_7}$	T_1	T_2
$SU(3)_C$	3	3	3	1	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	1	1	2	2	2	3	3
$U(1)_Y$	2/3	−1/3	1/6	1/2	2/3	−1/3	1/6	−5/6	7/6	−1/3	2/3

triplets of $SU(3)_C$ and that can mix with the SM quarks after EW symmetry breaking, i.e., fermions which can have couplings to the SM Higgs and a SM quark. The kinetic and mass terms[2] are

$$\mathcal{L} = \sum_F \bar{F}\,(i\not{D} - M_F)F, \tag{2.1}$$

where $F = \{U, D, Q_1, Q_5, Q_7, T_1, T_2\}$ and

$$D_\mu = \partial_\mu + ig_1 Y_F B_\mu + ig_2 S^I W^I_\mu + ig_s T^A G^A_\mu. \tag{2.2}$$

Here $T^A = \frac{1}{2}\lambda^A$ and $(S^I)_{jk}$ are $0, \frac{1}{2}(\tau^I)_{jk}$, and $-i\epsilon_{Ijk}$ for the $SU(2)_L$ singlet, doublet, and triplet representations, respectively, and λ^A and τ^I are the Gell-Mann and the Pauli matrices. The (generalized) Yukawa couplings are encoded in the Lagrangian

$$\mathcal{L} = \mathcal{L}^H_{qq} + \mathcal{L}^H_{q\mathrm{VLQ}} + \mathcal{L}^H_{\mathrm{VLQVLQ}}, \tag{2.3}$$

where the first term contains the SM Yukawa couplings

$$-\mathcal{L}^H_{qq} = Y^u_{ij}\bar{q}_i\tilde{H}u_j + Y^d_{ij}\bar{q}_i H d_j + \mathrm{H.c.}, \tag{2.4}$$

the second term the Higgs interactions with vectorlike and SM quarks

$$\begin{aligned}-\mathcal{L}^H_{q\mathrm{VLQ}} = {} & \xi^U_i \bar{U}\tilde{H}^\dagger q_i + \xi^D_i \bar{D}H^\dagger q_i + \xi^{u_1}_i \bar{Q}_1\tilde{H}u_i \\ & + \xi^{d_1}_i \bar{Q}_1 H d_i + \xi^{Q_5}_i \bar{Q}_5\tilde{H}d_i + \xi^{Q_7}_i \bar{Q}_7 H u_i \\ & + \frac{1}{2}\xi^{T_1}_i H^\dagger\tau\cdot\bar{T}_1 q_i + \frac{1}{2}\xi^{T_2}_i \tilde{H}^\dagger\tau\cdot\bar{T}_2 q_i + \mathrm{H.c.},\end{aligned} \tag{2.5}$$

and the last term defines the Higgs interactions with two VLQs (given in Supplemental Material [52] as they are not relevant for our analysis). Here $i, j = \{1,2,3\}$ are flavor indices and $\tau\cdot\bar{T} = \sum_I \tau^I\bar{T}^I$.

A. SM effective field theory and Matching

We write the SM effective field theory (SMEFT) Lagrangian as

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i C_i Q_i, \tag{2.6}$$

such that the WILSON coefficients have dimensions of inverse mass squared. Using the Warsaw basis [53], the operators generating modified gauge-boson couplings to quarks are

$$Q^{(1)}_{Hq}, \quad Q^{(3)}_{Hq}, \quad Q_{Hu}, \quad Q_{Hd}, \quad Q_{Hud}, \tag{2.7}$$

and the four-quark operators generating $\Delta F = 2$ processes read

$$Q^{(1)}_{qq}, \quad Q^{(3)}_{qq}, \quad Q_{uu}, \quad Q_{dd}, \quad Q^{(1)}_{qu}, \quad Q^{(1)}_{qd}, \quad Q^{(8)}_{qu}, \quad Q^{(8)}_{qd}. \tag{2.8}$$

The explicit definitions of all these operators can be found in Ref. [53] and in Supplemental Material [52]. The dipole operators, responsible for radiative down-type quark decays after EW symmetry breaking, are Q_{dW} and Q_{dB}. In addition, we have the operator involving three Higgs fields, Q_{uH}, that generates modifications of the Higgs-up-quark coupling, including possibly flavor-changing ones, after EW symmetry breaking. Finally we also need two bosonic operators that lead to a modification to the W mass, Q_{HD} and Q_{HWB}, with their contributions approximately given by

$$\delta M_W \approx -v^2(29\,C_{HD} + 64\,C_{HWB} + \cdots)\ \mathrm{GeV}, \tag{2.9}$$

where $v \simeq 246$ GeV and $(\cdots)$ indicates SMEFT operators not relevant in our scenario with VLQs.[3] An example diagram for the W mass correction is shown on the left in Fig. 1.

The tree-level matching of the operators generating modified Z-quark couplings is given by

[2]Note that mass terms such as $m^U_i \bar{U}u_i$ can always be removed by a field redefinition, such that the kinetic terms and the mass terms take the diagonal form shown in Eq. (2.1).

[3]Note that the SMEFT effects in the W mass are known fully at leading order [54,55] but only partially at next-to-leading order (NLO) [56], since in that work flavor universality of the SMEFT coefficients is assumed. However we have checked that, after making some conservative assumptions about the flavor dependence, the NLO effects are small.

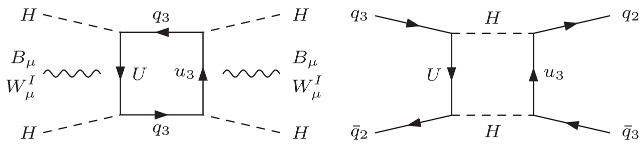

FIG. 1. Examples of Feynman diagrams showing the U contributions to the operator Q_{HD}, affecting the W-boson mass (left), and $Q_{qq}^{(1,3)}$, affecting $B_s - \bar{B}_s$ mixing (right).

$$C_{Hq}^{(1)ij} + C_{Hq}^{(3)ij} = -\frac{\xi_i^{D*}\xi_j^D}{2M_D^2} - \frac{\xi_i^{T_1*}\xi_j^{T_1}}{8M_{T_1}^2} + \frac{\xi_i^{T_2*}\xi_j^{T_2}}{4M_{T_2}^2},$$

$$C_{Hq}^{(1)ij} - C_{Hq}^{(3)ij} = \frac{\xi_i^{U*}\xi_j^U}{2M_U^2} - \frac{\xi_i^{T_1*}\xi_j^{T_1}}{4M_{T_1}^2} + \frac{\xi_i^{T_2*}\xi_j^{T_2}}{8M_{T_2}^2},$$

$$C_{Hu}^{ij} = -\frac{\xi_i^{u_1*}\xi_j^{u_1}}{2M_{Q_1}^2} + \frac{\xi_i^{Q_7*}\xi_j^{Q_7}}{2M_{Q_7}^2},$$

$$C_{Hd}^{ij} = \frac{\xi_i^{d_1*}\xi_j^{d_1}}{2M_{Q_1}^2} - \frac{\xi_i^{Q_5*}\xi_j^{Q_5}}{2M_{Q_5}^2}, \quad (2.10)$$

for Z-d_L^i-d_L^j, Z-u_L^i-u_L^j, Z-u_R^i-u_R^j, and Z-d_R^i-d_R^j, respectively. Modified W couplings to left-handed quarks arise from $C_{Hq}^{(3)}$ alone, while right-handed modifications do not appear in our scenario, due to our (later) choice to set ξ^{d_1} to zero which removes all contributions to the C_{Hud} coefficient. From these equations, we can see that only the representations U and Q_1 with coupling ξ^{u_1} and Q_7 (shown in bold in Table I) lead to effects in $t \to cZ$ while avoiding tree-level FCNCs in the down sector. An approximate formula for this branching ratio is

$$\mathrm{Br}(t \to cZ) \approx \frac{v^4}{2}\{[C_{Hq}^{(1)23} - C_{Hq}^{(3)23}]^2 + [C_{Hu}^{23}]^2\}. \quad (2.11)$$

We calculated the one-loop matching on the SMEFT for these VLQs for the operators relevant for B physics, the W mass and EW precision observables (EWPOs) using MatchMakerEFT [57] and compared the results to our own calculation, finding perfect agreement. Details of our calculation and explicit expressions for the relevant wilson coefficients are given in Supplemental Material [52].

III. PHENOMENOLOGICAL ANALYSIS

The current 95% C.L. upper bounds for $t \to cZ$ and $t \to ch$, based on the full LHC run 2 dataset, are [58–61]

$$\mathrm{Br}(t \to cZ) < 1.3 \times 10^{-4}, \qquad \mathrm{Br}(t \to ch) < 9.9 \times 10^{-4}. \quad (3.1)$$

While this already constrains some beyond the SM scenarios, at the high-luminosity (HL-)LHC [62,63], FCC-hh [64], ILC [65], or the FCC-ee [66], one can expect to be

TABLE II. Summary of current limits and future sensitivities for $t \to Zc$ and $t \to hc$. The values in brackets are the assumed systematic uncertainties on the underlying experimental measurements at the future colliders (if provided).

	$\mathrm{Br}(t \to cZ) \times 10^5$	$\mathrm{Br}(t \to ch) \times 10^5$
Current LHC (13 TeV, 139 fb^{-1})	13 [60]	99 [61]
HL-LHC (14 TeV, 3 ab^{-1})	3.13 [67] (0%) 6.65 [67] (10%)	15 [69]
HE-LHC (27 TeV, 15 ab^{-1})	0.522 [67] (0%) 3.84 [67] (10%)	7.7 [68] (0%) 8.5 [68] (10%)
FCC-hh (100 TeV, 3 ab^{-1})		7.7 [72]
FCC-hh (100 TeV, 10 ab^{-1})		2.39 [71] (5%) 9.68 [70] (10%)
FCC-hh (100 TeV, 30 ab^{-1})	0.0887 [67] (0%) 3.54 [67] (10%)	0.96 [68] (0%) 3.0 [68] (10%) 4.3 [72]
ILC (250 GeV, 2 ab^{-1})	9.1 [65]	
ILC (1 TeV, 8 ab^{-1})	2.9 [65]	
FCC-ee (350 GeV, 10 ab^{-1})	2.8 [66]	

sensitive to $t \to cZ$ branching ratios on the order of 10^{-5}–10^{-6} [65,67]. For $t \to ch$ (see Ref. [68] and references therein), sensitivities on the order of 10^{-4} and 10^{-5} for the HL-LHC [69] and FCC-hh [68,70,71] are estimated, respectively. A summary of the future prospects for these FCNC top decays is given in Table II.

For the numerical analysis we use the software package SMELLI [73,74] (based on FLAVIO [75] and WILSON [76]), with $\{\alpha, M_Z, G_F\}$ constituting the input scheme. Furthermore, we work in the down-basis such that Cabibbo-Kobayashi-Maskawa (CKM) elements appear in transitions involving left-handed up-type quarks after EW symmetry breaking, meaning that Y^d is diagonal in unbroken $SU(2)_L$ while $Y^u \approx V^\dagger \cdot \mathrm{diag}(0, 0, y_t)$, with V being the CKM matrix. Note that in our setup the determination of CKM elements is already modified at tree level. The resulting effects are consistently accounted for in SMELLI using the method described in Ref. [77] but choosing $\Gamma(K^+ \to \mu^+\nu)/\Gamma(\pi^+ \to \mu^+\nu)$, $\mathrm{Br}(B \to X_c e^+\nu)$, $\mathrm{Br}(B^+ \to \tau^+\nu)$, and $\Delta M_d/\Delta M_s$ as observables (see Supplemental Material [52] for details).

Concerning the EW fit, the long-standing tension in the W mass, previously with a significance of $\approx 1.8\sigma$ [78–80], was recently increased by the measurement of the CDF Collaboration [51]. In Ref. [81], they have made a naive combination of the existing measurements (Tevatron [51], LEP [82], ATLAS [83] and LHCb [84]), assuming a common 4.7 MeV systematic uncertainty, and give a new world average of

$$M_W^{\rm exp} = 80413.3 \pm 8.0\ {\rm MeV}. \qquad (3.2)$$

This value is 5.5σ higher than the SM prediction $M_W^{\rm SM} = 80358.7 \pm 6.0$ MeV [79].

Concerning B physics, even though the hints for lepton flavor universality (LFU) violation in $b \to s\ell^+\ell^-$ data cannot be explained by our LFU effects, an additional LFU part [85–91], generated by Z-b-s penguins, can further increase the agreement with data. In addition, box diagrams, like the one shown on the right in Fig. 1, also generate effect in $B_s - \bar{B}_s$ mixing (we use inputs from Ref. [92] for the SM prediction).

In all our analyses, we set the masses of the VLQs to 2 TeV. This is consistent with the published model-independent bounds for third-generation VLQs of $M_{\rm VLQ} > 1.31$ TeV limits from ATLAS [93] and recent conference reports [94,95] which give slightly stronger limits. We also checked single VLQ production, which is model dependent, and found the bounds for our scenarios to be weaker or nonexistent. Let us now consider the three cases of U, Q_1 and Q_7 numerically.

U.—In addition to the modified Z-t-c coupling, this VLQ also generates relevant effects in $b \to s\ell^+\ell^-$ transitions via a Z penguin, resulting in an $C_9 \approx -C_{10}/4$ pattern. In fact, mainly due to the measurements of P_5' [96] and $B_s \to \phi\mu^+\mu^-$ [97,98] there is a preference for a nonzero contribution with such a structure. The bounds from $B_s - \bar{B}_s$ mixing turn out to be weakened due to a

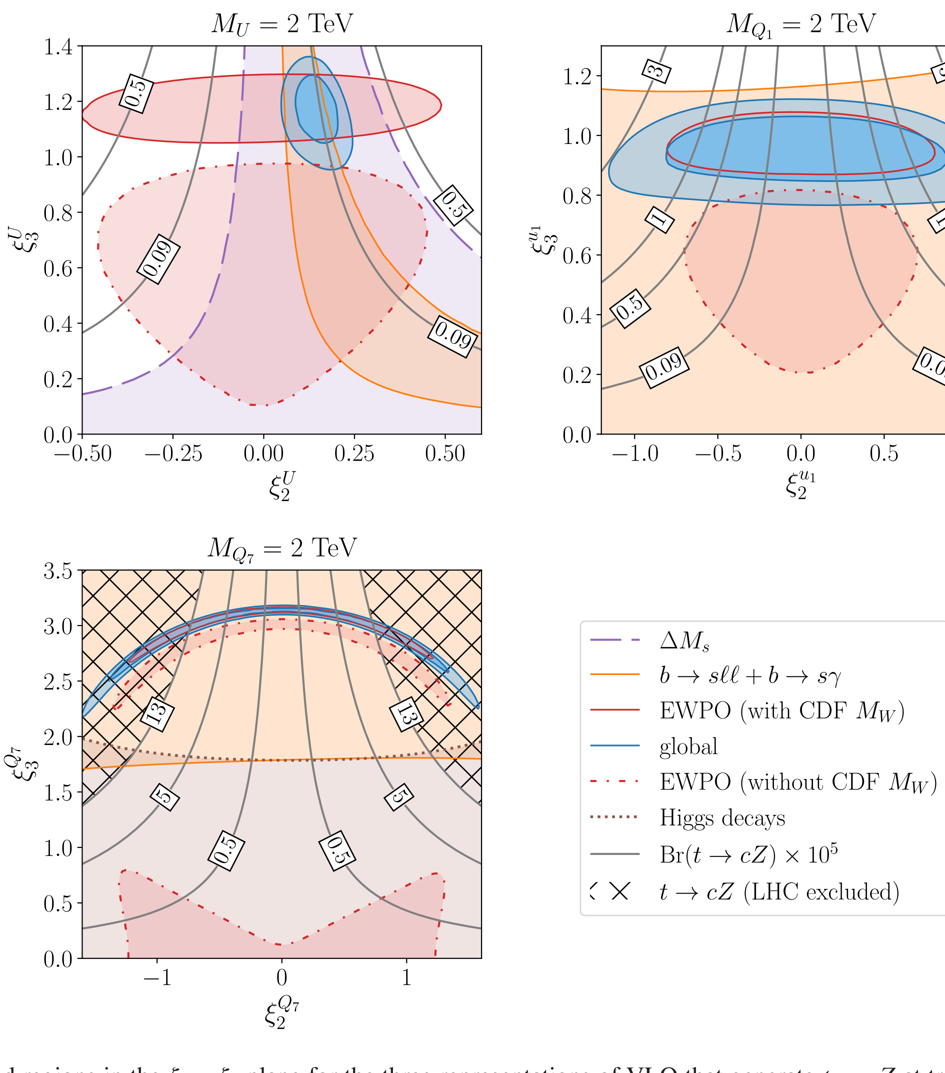

FIG. 2. Preferred regions in the $\xi_2 - \xi_3$ plane for the three representations of VLQ that generate $t \to cZ$ at tree level but give rise to down-quark FCNCs only at the loop level: U (top left), Q_1 (top right), and Q_7 (bottom left). The contour lines show the predicted size of ${\rm Br}(t \to cZ) \times 10^5$. The region preferred by all data [the global fit region with using the new experimental average in Eq. (3.2)] is shown at the 1σ and 2σ level, while the others regions correspond to 1σ. We also show in the preferred region from the EW fit without the inclusion of the new M_W result from CDF (red, dash-dotted line), where it can be seen that a large $t \to cZ$ branching ratio is also possible in this scenario. Note that in the plot for Q_7 the hatched regions on the top left and top right are already excluded by the current LHC limits on $t \to cZ$.

partial (accidental) cancellation between the one-loop matching and the renormalization group equation effect. Similarly, the contribution to $b \to s\gamma$ suffers from a cancellation, but here between terms generated by the matching on the SMEFT and integrating out the W at the weak scale ($b \to s\gamma$ is included within the $b \to s\ell^+\ell^-$ region in Fig. 2). Concerning EWPOs, a shift in M_W is dominantly generated by top-loop effects within the SMEFT (left diagram in Fig. 1), bringing theory and experiment into total agreement. Meanwhile, the second-generation coupling ξ_2^U is constrained by the total Z width. These finding are summarized in Fig. 2 (top left) where one can see that $\mathrm{Br}(t \to cZ)$ can be of the order of 2×10^{-6}, which could be probed by FCC-hh.

Q_1 with ξ^{u_1}.—The VLQ Q_1 with the couplings ξ^{u_1} is found to be a very promising candidate for sizable rates of $t \to cZ$, since it has small effects in B physics as it generates at tree level only right-handed corrections to Z-up-quark couplings. At the same time, we can get an improvement concerning the agreement between theory and experiment in M_W through the direct one-loop contribution to C_{HD} for large couplings is induced through top loops in the SMEFT (thus favoring the third-generation coupling), while large couplings to charm quarks are ruled out by the total Z width, as shown in Fig. 2 (top right). From there we see that an enhancement of $\mathrm{Br}(t \to cZ)$ up to 1×10^{-5} is possible, which could already be probed by the HE-LHC (albeit in an optimistic scenario with zero systematic errors). Note, however, that even in this quite unconstrained scenario $\mathrm{Br}(t \to ch)$ can be at most 3×10^{-6}, which is still a factor of 3 smaller than the reach of even the most optimistic FCC-hh scenario.

Q_7.—In case of the VLQ Q_7 [see Fig. 2 (bottom left)], the preferred sign for the contribution in $b \to s\ell^+\ell^-$ processes is generated, but in order for its size to be relevant, quite large couplings are required. Furthermore, for small third-generation couplings ($\xi_3^{Q_7} < 1$) an effect with the wrong sign arises in M_W, while for large couplings the sign reverses, which can be traced back to two different contributions, one proportional to $(\xi_3^{Q_7})^4$ and the other involving $(\xi_3^{Q_7})^2 y_t^2$. Note that in the regime of such large couplings, small tensions with Higgs data arise in the $h \to ZZ, WW, \gamma\gamma$ partial widths, with tensions of 1.8, 1.5, and 1.2σ, respectively. Concerning $\mathrm{Br}(t \to cZ)$, again an enhancement of the branching ratio up to 1×10^{-5} is possible, which could be probed by the HE-LHC, FCC-hh, FCC-ee, or ILC. Given the large couplings allowed by data, $\mathrm{Br}(t \to ch)$ can be enhanced up to 3×10^{-5}, therefore potentially visible at the FCC-hh if the systematic uncertainties are well controlled.

IV. CONCLUSIONS

In this paper we examined the possibility of obtaining a sizable branching ratio for $t \to cZ$ within models containing VLQs. This is only feasible for representations which solely change Z couplings to the up-type quarks at tree level while not generating down-type FCNCs at this perturbative order, i.e., U, Q_1 and Q_7. However, at the loop level, B physics and electroweak observables are still affected. We therefore calculated the one-loop matching of these VLQs onto the SMEFT operators relevant for flavor and electroweak precision observables.

Using these results, we found in our phenomenological analysis that one can generate a sizable branching ratio for $t \to cZ$ of the order of 1×10^{-6}, 1×10^{-5} and 1×10^{-4}, for U, Q_1 and Q_7, respectively. Therefore, the parameter space of Q_7 is already constrained by LHC limits on $t \to cZ$, while Q_1 and U can be tested by the HL-LHC and the FCC-hh, respectively. Importantly, these three VLQ representations are also the ones which lead to a relevant and positive shift in the W mass and can thus explain the larger value of M_W, compared to the SM prediction, obtained recently by the CDF Collaboration. In fact, accounting for a larger M_W requires sizable couplings to top quarks (see also Ref. [99]) which are also important for measurable effects in $t \to cZ$, showing that these observables are correlated. Furthermore, U and Q_7 lead to LFU effects in $b \to s\ell^+\ell^-$ which cannot explain $R(K^{(*)})$ but affect observables like P_5' and $B_s \to \phi\mu^+\mu^-$ and, in combination with LFU violating effects, can further improve the description of data. In conclusion, $t \to cZ$ is an unambiguous signal of VLQs and sizable branching ratios of it, within the range of the HL-LHC, are motivated by the recent CDF measurement of the W mass.

ACKNOWLEDGMENTS

A. C. gratefully acknowledges financial support by the Swiss National Science Foundation (PP00P_2176884). T. K. is supported by the Grant-in-Aid for Early-Career Scientists (No. 19K14706) and by the JSPS Core-to-Core Program (Grant No. JPJSCCA20200002) from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan. M. K. and F. M. acknowledge financial support from the State Agency for Research of the Spanish Ministry of Science and Innovation through the "Unit of Excellence María de Maeztu 2020–2023" award to the Institute of Cosmos Sciences (CEX2019-000918-M) and from PID2019–105614GB-C21 and 2017-SGR-929 grants.

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