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Z'-induced FCNC Decays of Top, Beauty and Strange Quarks

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We discuss about a flavor-changing neutral current (FCNC) decay of the top quark which is induced by a new massive gauge boson Z', namely $t \to cZ'$, based on a model of the gauged $L_\mu - L_\tau$ symmetry (the difference between the muon and tauon numbers). The Z' boson is phenomenologically well-motivated: (i) it can explain the anomalous data observed by LHCb in $b \to s\mu^+\mu^-$ transition if *heavy* ($m_{Z'} \gg m_b$); (ii) it can solve the muon $g-2$ anomaly if *light* ($m_{Z'} \lesssim 400$ MeV). For these two cases, we illustrate whether the decay rate of $t \to cZ'$ succeeded by $Z' \to \ell^+\ell^-$ ($\ell = \mu, \tau$) can be as large as an observable level at the LHC by taking into account B and K meson FCNC data.

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1. Introduction

With a large amount of top and anti-top quarks produced at the LHC, rare top quark decays offer a nice probe to search for physics beyond the Standard Model (SM). In particular, FCNC decays of the top quark such as $t \to qZ$ and $t \to qh$ ($q = c, u$) have been vigorously pursued by the ATLAS and CMS experiments [1]. In this talk, we consider a top quark FCNC decay which produces a new massive gauge boson Z', namely $t \to cZ'$.

The hints come from B physics. One is the so-called P_5' anomaly by LHCb [2], which was first found in angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ with 1 fb^{-1} data and, then, confirmed by the 3 fb^{-1} update. The other is the lepton flavor non-universality in $B^+ \to K^+\ell^+\ell^-$ ($\ell = e, \mu$), found by LHCb with 3 fb^{-1} data [3]. Although it is too early to tell if these $\sim 3\sigma$ anomalies are genuine, interestingly, various global analyses (see, e.g. Ref. [4]) points towards the existence of new physics contribution to C_9, the Wilson coefficient of $(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu)$. The latter can be generated if there is a new boson Z' coupling to the left-handed $b \to s$ current and vector-like muon current. In Ref. [5], an explicit Z' model was proposed based on the gauged $L_\mu - L_\tau$ symmetry [6]. If such a Z' boson exists, the SU(2)$_L$ symmetry implies the existence of the left-handed $t \to c$ current coupling to Z'. Hence, $t \to cZ'$ may occur if the Z' is lighter than the top.

The other virtue of introducing the Z' of $L_\mu - L_\tau$ is the explanation [7] of the long-standing muon $g-2$ anomaly [1]. Recently, it was pointed out [8] that a neutrino-nucleus scattering data, i.e. the neutrino trident production $\nu_\mu N \to \nu_\mu N\mu^+\mu^-$, strongly constrains the Z' mass ($m_{Z'}$) and new gauge coupling (g'), and the muon $g-2$ anomaly can be solved only if $m_{Z'} \lesssim 400$ MeV. This mass range is too low to generate the local operator $(\bar{s}b)(\bar{\mu}\mu)$ for explaining the $b \to s$ anomalies.

In the following, we study observability of $t \to cZ'$ at the LHC based on the model of Ref. [5] for the two scenarios: (i) *heavy* Z' ($m_b \ll m_{Z'} < m_t - m_c$) motivated by the $b \to s$ anomalies; (ii) *light* Z' ($2m_\mu < m_{Z'} \lesssim 400$ MeV) motivated by the muon $g-2$ anomaly. In this talk, we do not consider the case with $m_{Z'} < 2m_\mu$, as the Z' decays only into neutrino pairs and collider search should be more challenging. (See Ref. [9, 10] for interesting phenomenology in this case.)

2. Model and Heavy Z' Motivated by $b \to s\mu^+\mu^-$ Anomalies

We consider the gauged $L_\mu - L_\tau$ model of Ref. [5]. The new symmetry U(1)$'$ is introduced to gauge the $L_\mu - L_\tau$. It is spontaneously broken by the vacuum expectation value of the new Higgs field Φ with U(1)$'$ charge $+1$: $\langle\Phi\rangle = v_\Phi/\sqrt{2}$, leading to the Z' mass $m_{Z'} = g'v_\Phi$. The fermionic sector is augmented by an extra generation of vector-like quarks, i.e., $Q_L = (U_L, D_L)$, U_R, D_R, and their chiral partners $\tilde{Q}_R = (\tilde{U}_R, \tilde{D}_R)$, $\tilde{U}_L$, $\tilde{D}_L$, which are charged under U(1)$'$ with the charges $+1$ for $Q \equiv Q_L + \tilde{Q}_R$ and -1 for $U \equiv \tilde{U}_L + U_R$, $D \equiv \tilde{D}_L + D_R$, respectively. The vector-like quarks mix with the SM quarks via Yukawa couplings with Φ, given by

$$-\mathscr{L}_{\text{mix}} = \Phi \sum_{i=1}^{3} \left(\bar{\tilde{U}}_R Y_{Qu_i} u_{iL} + \bar{\tilde{D}}_R Y_{Qd_i} d_{iL} \right) + \Phi^\dagger \sum_{i=1}^{3} \left(\bar{\tilde{U}}_L Y_{Uu_i} u_{iR} + \bar{\tilde{D}}_L Y_{Dd_i} d_{iR} \right) + \text{h.c.}. \tag{2.1}$$

The SU(2)$_L$ symmetry imposes $Y_{Qu_i} = \sum_{j=1}^{3} V^*_{u_i d_j} Y_{Qd_j}$ ($i = 1, 2, 3$) with CKM matrix elements $V_{u_i d_j}$.

The heavy Q, U quarks induce $t \to cZ'$ via diagrams in Fig. 1, with the branching ratio

$$\mathscr{B}(t \to cZ') \simeq \frac{(1-x')^2(1+2x')}{2(1-x_W)^2(1+2x_W)} \left(|Y_{Qt}Y_{Qc}^*|^2 \frac{v^2 v_\Phi^2}{4m_Q^4} + |Y_{Ut}Y_{Uc}^*|^2 \frac{v^2 v_\Phi^2}{4m_U^4} \right), \tag{2.2}$$

where $x' \equiv m_{Z'}^2/m_t^2$ and $x_W \equiv m_W^2/m_t^2$. The first term is the contribution from the left-handed $t \to c$ current, related to $b \to s$ by $\mathrm{SU}(2)_L$: $Y_{Qt}Y_{Qc}^* \simeq Y_{Qb}Y_{Qs}^*$. The latter is fixed by the $b \to s\mu^+\mu^-$ data, i.e. $\Delta C_9 \simeq Y_{Qb}Y_{Qs}^*/(2m_Q^2) \simeq -(34\ \mathrm{TeV})^{-2}$ [4]. Then, one is left with the dependence on v_Φ. The neutrino trident production [5] constrains as $v_\Phi \gtrsim 540$ GeV (for $m_{Z'} \gtrsim 10$ GeV) by CCFR data [11], while the B_s mixing gives an upper bound. In the B_s mixing amplitude induced by Z' exchange, one may eliminate [12] the dependence on $Y_{Qb(s)}$ and m_Q in terms of ΔC_9. Then, allowing new physics effects up to 15%, $v_\Phi \lesssim 5.6\ \mathrm{TeV} \times (34\ \mathrm{TeV})^{-2}/|\Delta C_9|$. Therefore, the left-handed current contribution to $t \to cZ'$ is constrained as $0.8 \times 10^{-8} \lesssim \mathscr{B}(t \to cZ')_{\mathrm{LH}} \lesssim 0.8 \times 10^{-6}$.

The second term in Eq. (2.2) is induced by right-handed $t \to c$ current and is free from down-sector FCNCs. To see how large it can be, we recast it as

$$\mathscr{B}(t \to cZ')_{\mathrm{RH}} \simeq \frac{(1-x')^2(1+2x')}{2(1-x_W)^2(1+2x_W)} \frac{v^2}{v_\Phi^2} |\delta_{Ut}\delta_{Uc}^*|^2, \tag{2.3}$$

where $\delta_{Uq} \equiv Y_{Uq}v_\Phi/(\sqrt{2}m_U)$ $(q = t, c)$ is a mixing parameter between the vector-like quark U and t_R or c_R. [1] Taking reasonably large mixings $\delta_{Uq} \simeq \lambda \simeq 0.23$ for illustration, the CCFR bound ($v_\Phi \gtrsim 540$ GeV) imposes as $\mathscr{B}(t \to cZ')_{\mathrm{RH}} \lesssim 4 \times 10^{-4}$.

The decay $t \to cZ'$ with $Z' \to \ell^+\ell^-$ $(\ell = \mu, \tau)$ can be searched in $t\bar{t}$ events at the LHC. The Z' branching ratios are (a) $\tau\tau : \mu\mu : \nu\nu \simeq 1:1:1$ for $m_{Z'} > 2m_\tau$; (b) $\mu\mu : \nu\nu \simeq 1:1$ for $2m_\mu < m_{Z'} < 2m_\tau$. As the analogous mode $t \to cZ$ has been searched using $Z \to \ell^+\ell^-$ at the LHC, we can get a rough idea of sensitivity on $t \to cZ'$ by a simple scaling of Z and Z' branching ratios. The current strongest limit on $t \to cZ$ is set by CMS with full run 1 data [13]: $\mathscr{B}(t \to cZ) < 5 \times 10^{-4}$ at 95% CL. The projection [14] toward 300 fb^{-1} data in 14 TeV run is $\mathscr{B}(t \to cZ) \lesssim 10^{-5}$. Scaling by $\mathscr{B}(Z \to \ell^+\ell^-)/\mathscr{B}(Z' \to \ell^+\ell^-) \simeq 0.15$ (flavor summed), we infer current and future CMS sensitivities:

$$\mathscr{B}(t \to cZ') \lesssim \begin{cases} 8 \times 10^{-5} & [\text{CMS run 1 (naive)}], \\ 2 \times 10^{-6} & [\text{CMS 300 fb}^{-1}\ \text{(naive)}] \end{cases} \tag{2.4}$$

for the *heavy* Z'. Therefore, the right-handed current mediated $t \to cZ'$ might be probed by the current CMS dataset, while the left-handed current mediated $t \to cZ'$ seems to be slightly below the CMS sensitivity even with 300 fb^{-1} data.

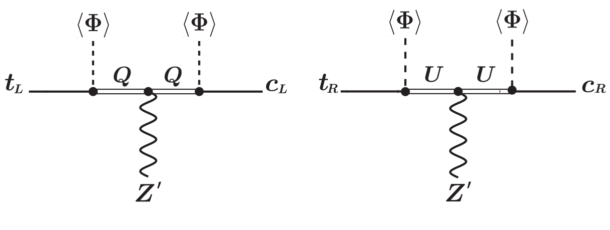

Figure 1: Feynman diagrams which induce the effective tcZ' couplings.

[1]We turn off the mixing of U with u_R, i.e. $Y_{Uu} = 0$, to avoid D meson constraints.

The search strategy should be changed for the *light* Z' ($m_{Z'} \lesssim 400$ MeV). In particular, the light Z' should exhibit a distinct signature, namely a collimated muon pair from highly boosted Z', while the $t \to qZ$ search [13] requires events with two isolated (opposite-sign and same-flavor) leptons. Nevertheless, we simply adopt Eqs. (2.4) as the target values for the light Z' case to set a standard in the following study.

3. Light Z' Motivated by Muon $g-2$ Anomaly

In this section, we investigate the $t \to cZ'$ rate with the light Z' motivated by the muon $g-2$ anomaly: $2m_\mu < m_{Z'} \lesssim 400$ MeV. In this case, $b \to sZ' \to s\mu^+\mu^-$ decays are highly constraining due to the enhanced rates by onshell and longitudinal Z', and the effective $t_L c_L Z'$ coupling, related to $b_L s_L Z'$ by SU(2)$_L$, needs to be suppressed. The $B \to K^{(*)}\mu^+\mu^-$ measurements generically imply $\mathscr{B}(t \to cZ')_{\rm LH} \ll 10^{-10}$ [10], far below the current and future CMS sensitivities of Eqs. (2.4).

The right-handed tcZ' coupling induces $b \to sZ'$ via the loop diagram in Fig. 2. Despite the loop and chiral suppression, the $b \to s\mu^+\mu^-$ data provide significant constraints on the $t_R c_R Z'$ coupling due to the enhanced rate, as explained above. Setting the mixings of Q and D with SM quarks zero for simplicity, we obtain the loop-induced bsZ' coupling: $\Delta g_{sb}\bar{s}_L\gamma^\alpha b_L Z'_\alpha$ with

$$\Delta g_{sb} = \frac{g' v_\Phi^2}{32\pi^2 v^2}\left[c_{cc}f_{cc} + (c_{tc}+c_{ct})f_{ct} + c_{tt}f_{tt}\right], \tag{3.1}$$

where $c_{ij} = V_{ib}V_{js}^* Y_{Ui} Y_{Uj}^* m_i m_j / m_U^2$ and f_{cc}, f_{ct}, f_{tt} are loop functions, logarithmically depending on m_U (see Ref. [9, 10] for details).

We can constrain the loop-induced bsZ' coupling from dimuon invariant mass ($q^2 \equiv m_{\mu\mu}^2$) spectra in $B \to K^{(*)}\mu^+\mu^-$ measurements. We argue that $B \to K\mu^+\mu^-$ is better suited to search for a possible bump by Z' than $B \to K^*\mu^+\mu^-$ due to absence of the photon peak. The full run 1 LHCb result [15] for $B \to K\mu^+\mu^-$ only covers $q^2 > 0.1$ GeV$^2 \simeq (316$ MeV$)^2$, hence, can be evaded if $m_{Z'} \lesssim 316$ MeV. On the other hand, the 1 fb^{-1} result of LHCb [16] for $B^+ \to K^+\mu^+\mu^-$ probes down to $q^2 > 0.05$ GeV$^2 \simeq (224$ MeV$)^2$, close to the dimuon threshold ($\simeq 211$ MeV). The measured q^2-spectrum below J/ψ region is rather flat in accordance with the SM prediction. Treating the average in low-q^2 [$\in (1,6)$ GeV^2] range as background, we extract [9, 10] the allowed range for new physics contribution in the 1st bin as $\Delta\mathscr{B}(B^+ \to K^+\mu^+\mu^-) = (0.86 \pm 0.59) \times 10^{-8}$, which applies for 224 MeV $\lesssim m_{Z'} \lesssim$ 1414 MeV. We take the 2σ range in numerical study.

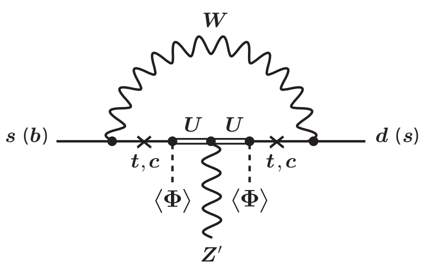

Figure 2: Feynman diagram for the loop-induced dsZ' (sbZ') coupling mediated by vector-like quark U. The crosses indicate quark-mass insertions which flip chirality for t and c.

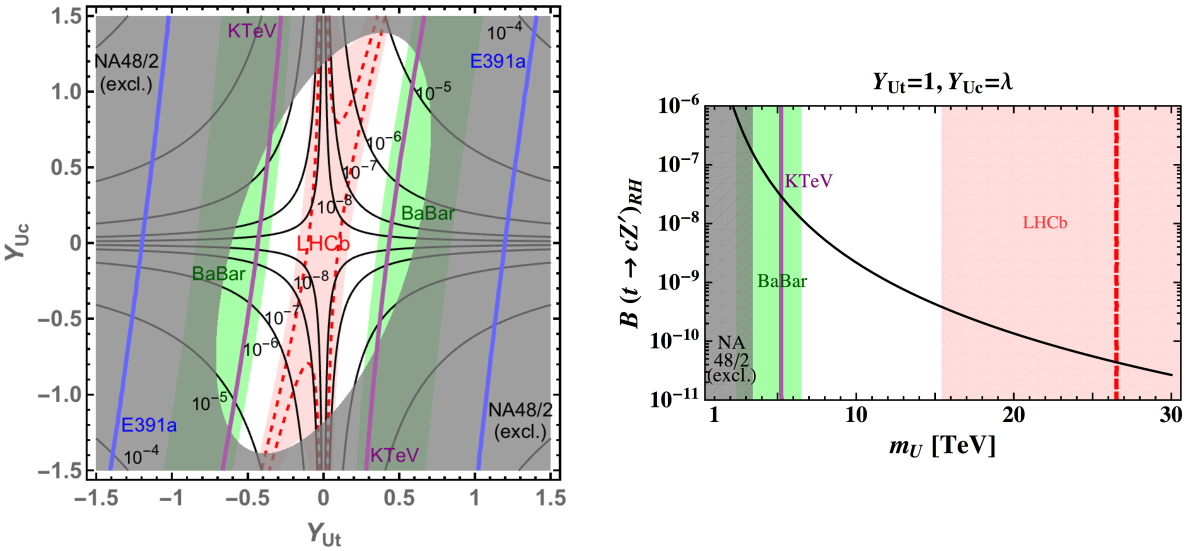

Figure 3: [left] Contours of $\mathscr{B}(t \to cZ')_{\rm RH}$ are shown by the solid-black lines on the (Y_{Ut}, Y_{Uc}) plane for $m_{Z'} = 285$ MeV, $g' = 1.3 \times 10^{-3}$ and $m_U = 2$ TeV. [right] $\mathscr{B}(t \to cZ')_{\rm RH}$ as a function of m_U for $Y_{Ut} = 1$, $Y_{Uc} = \lambda$, $m_{Z'} = 285$ MeV and $g' = 1.3 \times 10^{-3}$. In both figures, the pink-shaded region is allowed at 2σ by LHCb: $\mathscr{B}(B^+ \to K^+ Z')\mathscr{B}(Z' \to \mu^+\mu^-) < 2.0 \times 10^{-8}$; the light-green-shaded regions are favored by the BaBar excess at 2σ: $\mathscr{B}(B^+ \to K^+ Z')\mathscr{B}(Z' \to \nu\bar{\nu}) \in (0.05, 1.55) \times 10^{-5}$; the semi-transparent gray-shaded region represents 2σ exclusion by NA48/2: $\mathscr{B}(K^+ \to \pi^+ Z')\mathscr{B}(Z' \to \mu^+\mu^-) < 2.1 \times 10^{-9}$. As for red-dashed lines, see Discussion and Summary. See Ref. [9, 10] for details of other constraints.

$b \to s\nu\bar{\nu}$ data are also available to constrain the loop-induced bsZ' coupling. The BaBar [17] provides the constraint on new physics as $\Delta\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (0.35^{+0.60}_{-0.15}) \times 10^{-5}$ for $0 < m_{Z'} \lesssim 1670$ MeV, with weaker bounds from other $b \to s\nu\bar{\nu}$ modes. Although the BaBar found some excess, leading to the two-sided interval, it is not statistically significant.

The right-handed tcZ' coupling also induces $s \to dZ'$ at one-loop (see Fig. 2), hence, constrained by $K^+ \to \pi^+\mu^+\mu^-$ data. For the latter, the most precise measurement comes from NA48/2 [18]. The measured $m_{\mu\mu}$-spectrum is reasonably fitted by the linear form factor model. We see the data is most accommodating for new physics effects at $m_{\mu\mu} \sim 285$ MeV, with our extraction [9, 10]: $\Delta\mathscr{B}(K^+ \to \pi^+\mu^+\mu^-) \simeq (9.4 \pm 5.6) \times 10^{-10}$. To be tolerant for larger $t \to cZ'$ rate, we take $m_{Z'} = 285$ MeV as the benchmark in the following numerical study.

In Fig. 3 [left], the B and K decay constraints are shown on the (Y_{Ut}, Y_{Uc}) plane for $m_{Z'} = 285$ MeV, $g' = 1.3 \times 10^{-3}$ and $m_U = 2$ TeV. (See figure caption for details.) Contours of $\mathscr{B}(t \to cZ')_{\rm RH}$ are also shown by black-solid lines. Y_{Ut} is more tightly constrained than Y_{Uc} due to m_t/m_c enhancement in Eq. (3.1). The BaBar excess in $B^+ \to K^+\nu\bar{\nu}$ data conflicts with the LHCb bound on $B^+ \to K^+\mu^+\mu^-$, although they agree within 3σ. Disregarding the BaBar excess, the LHCb provides strongest constraint along Y_{Ut} direction, while the NA48/2 excludes large Y_{Uc}: $|Y_{Uc}| \lesssim 1.4$. Allowing hierarchical Yukawa couplings with $Y_{Ut} \ll Y_{Uc}$, $\mathscr{B}(t \to cZ')_{\rm RH}$ can be as large as 10^{-5}, within the reach of CMS with 300 fb^{-1} data [Eq. (2.4)].

In Fig. 3 [right], $\mathscr{B}(t \to cZ')_{\rm RH}$ is shown as a function of m_U with the same $m_{Z'}$ and g' values, for the Yukawa couplings with *normal* hierarchy: $Y_{Ut} = 1$, $Y_{Uc} = \lambda$. The LHCb constrains as $\mathscr{B}(t \to cZ')_{\rm RH} \lesssim 4 \times 10^{-10}$, beyond experimental reach in the foreseeable future.

4. Discussion and Summary

In this conference, LHCb reported [19] a search for low-mass dark bosons χ in $B^0 \to K^{*0}\chi(\to \mu^+\mu^-)$ with the 3 fb $^{-1}$ data, finding no significant signal. The new LHCb limit reads $\mathscr{B}(B^0 \to K^{*0}Z')\mathscr{B}(Z' \to \mu^+\mu^-) < 3.1 \times 10^{-9}$ at 95% CL for $m_{Z'} = 285$ MeV. This constraint is overlaid on Figs. 3 by red-dashed lines. Now, an observable level of $\mathscr{B}(t \to cZ')(\gtrsim 2 \times 10^{-6})$ is limited in funnel regions, signaling a fine-tuning between Y_{Ut} and Y_{Uc}. We found similar tendency for other Z' mass values in the light Z' scenario.

In summary, the $t \to cZ'$ rate can be as large as an observable level at the LHC by the right-handed current contribution: (i) the heavy Z' motivated by the $b \to s$ anomalies can accommodate $\mathscr{B}(t \to cZ') \gtrsim 10^{-4}$, within the expected reach of the current CMS data; (ii) the light Z' motivated by the muon $g-2$ anomaly can accommodate $\mathscr{B}(t \to cZ') \gtrsim 2 \times 10^{-6}$, within the naively expected reach of CMS with 300 fb^{-1} data, but at the cost of fine-tuning. Those parameter regions have not been probed by B and K physics, hence, the result illustrates uniqueness of *top flavor physics*.

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