PROCEEDINGS OF SCIENCE

Search for tZ' Associated Production Induced by RH tcZ' Couplings at the LHC

Tanmoy Modak[*†]
National Taiwan University
E-mail: tanmoyy@hep1.phys.ntu.edu.tw

In this article we have studied the discovery potential of right-handed tcZ' via $cg \to tZ'$ process, first in a model independent way, then in a model based on gauged $L_\mu - L_\tau$ symmetry at 14 TeV LHC. Such a model has been constructed to explain recent $B \to K^{(*)}$ anomalies observed by LHCb. Model also predicts left-hand tcZ' coupling which is strongly constrained by B and K physics and discovery of which is even beyond the reach of HL-LHC. In connection to RH tcZ' coupling, model also predicts existence of RH ccZ' couplings, which could be searched via $c\bar{c} \to Z'$ process at LHC.

The European Physical Society Conference on High Energy Physics
5-12 July
Venice, Italy

*Speaker.
†Work done in collaboration with W.-S. Hou and M. Kohda.

PoS(EPS-HEP2017)673

1. Introduction

Recent P_5' (angular observable of $B \to K^{*0}\mu^+\mu^-$ decay) [1, 2] and R_K ($\equiv \frac{\mathscr{B}(B^+\to K^+\mu^+\mu^-)}{\mathscr{B}(B^+\to K^+e^+e^-)}$) [3] anomalies observed by LHCb collaboration in the $B \to K^{(*)}$ transitions may indicate the existence new physics (NP). Although they could be due to statistical fluctuations and/or hadronic uncertainties, it is nonetheless interesting to investigate the role NP as the driver of such anomalies. Analysis by various groups indicate NP in Wilson coefficient C_9^{μ} (of the effective operator $(\bar{s}_L\gamma^{\alpha}b_L)\,(\bar{\mu}\gamma_{\alpha}\mu)$) can explain both P_5' [4, 5] and R_K [6, 7] anomalies by similar amount in beyond Standard Model (BSM) effect [8, 9].

In order to explain these anomalies, a model based on gauged $L_\mu - L_\tau$ (difference between the muon and tauon numbers promoted as gauge symmetry) symmetry [10, 11] has been constructed [12], where mixing between SM quarks and heavy vector-like quarks induce flavor changing neutral currents (FCNC). Amongst these FCNC couplings, left-handed (LH) bsZ' coupling provide a viable explanation for both P_5' and R_K anomalies. The gauged $L_\mu - L_\tau$ model is one of the possibility amongst many UV alternatives for these anomalies.

Along with LH bsZ' coupling, model also predicts several other FCNC couplings. Most notably LH tcZ' and right-handed (RH) tcZ' couplings, while the former is directly linked with LH bsZ' coupling. The latter, i.e. RH tcZ', is not well constrained by B and K physics. In our analysis we study the discovery potential of RH tcZ' coupling via $cg \to cZ'$ process at 14 TeV LHC. In pp collision, the process could be searched via $pp \to tZ' + X \to b\nu_\ell \ell^+\mu^+\mu^- + X$ process (along with conjugate process denoted as tZ' process), with $\ell = e, \mu$. The existence of RH tcZ' coupling implies non-vanishing RH ccZ' coupling, which can induce $c\bar{c} \to Z'$ process and can be searched via $pp \to Z' + X \to \mu^+\mu^- + X$ process (denoted as dimuon process) at LHC.

2. Model Framework

In order to explain the $B \to K^{(*)}$ anomalies, Ref. [12] extended the minimal gauged $L_\mu - L_\tau$ model [10, 11] by the addition of vector-like quarks $Q_L = (U_L,\, D_L)$, U_R, D_R and their chiral partners $\tilde{Q}_R = (\tilde{U}_R,\, \tilde{D}_R)$, $\tilde{U}_L$, $\tilde{D}_L$, carrying unit U(1)$'$ charge. The SM gauge singlet scalar Φ breaks the U(1)$'$ symmetry spontaneously after acquiring vev v_Φ. The vector-like quarks mix with SM quarks via Yukawa interactions given by [12]:

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

while the low energy effective Lagrangian for Z' couplings to SM quarks are given by:

$$\Delta\mathscr{L}_{\rm eff} = -Z'_\alpha \sum_{i,j=1}^{3}\left(g^L_{u_iu_j}\bar{u}_{iL}\gamma^\alpha u_{jL} + g^R_{u_iu_j}\bar{u}_{iR}\gamma^\alpha u_{jR} + g^L_{d_id_j}\bar{d}_{iL}\gamma^\alpha d_{jL} + g^R_{d_id_j}\bar{d}_{iR}\gamma^\alpha d_{jR}\right). \tag{2.2}$$

The LH bsZ' coupling g^L_{sb} can account for the P_5' and R_K anomalies and can be expressed as $\Delta C_9^\mu = \frac{g^L_{sb}\, g'}{m^2_{Z'}}$ [12]. The constrain on the g^L_{sb} coupling can be found as [13]: $0.7\times 10^{-4}\left(\frac{m_{Z'}}{150\ \text{GeV}}\right)\left(\frac{|\Delta C_9^\mu|}{(34\ \text{TeV})^{-2}}\right) \lesssim |g^L_{sb}| \lesssim 0.7\times 10^{-3}\left(\frac{m_{Z'}}{150\ \text{GeV}}\right)$.

Furthermore, the model predicts non-zero RH tcZ' coupling, $g_{ct}^R = -g' \frac{Y_{Uc} Y_{Ut} v_\Phi^2}{2 m_U^2}$, which is very weakly constrained by B and K physics, while the LH tcZ' coupling (g_{ct}^L) is related to g_{sb}^L coupling via SU(2)$_L$ relation : $g_{ct}^L \simeq V_{cs} V_{tb}^* g_{sb}^L + V_{cb} V_{tb}^* g_{bb}^L \sim g_{sb}^L + \lambda^2 g_{bb}^L$; hence strongly constrained. The non-zero RH tcZ' coupling, which is proportional to the Yukawa couplings Y_{Uc} and Y_{Ut}, induces RH ccZ' coupling ($g_{cc}^R = g' \frac{Y_{Uc}^2 v_\Phi^2}{2 m_U^2}$). The underlying Feynman diagrams that generate the effective RH tcZ' and ccZ' couplings are shown in Fig. 1.

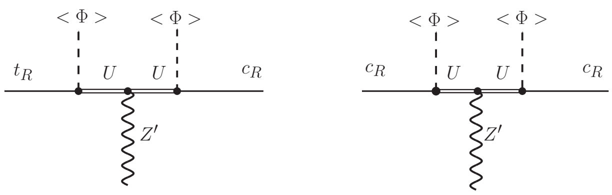

Figure 1: Feynman diagrams that induce effective RH tcZ' (left) and RH ccZ' (right) couplings.

We define the mixing angles between the heavy vector-like quark U and SM quarks as $\delta_{Uq} \equiv \frac{Y_{Uq} v_\Phi}{\sqrt{2} m_U}$, and allow the mixing parameter $\delta_{Uq} \leq \lambda \simeq 0.23$ (Cabibbo mixing angle). Under these assumptions the g_{ct}^R coupling is constrained as: $|g_{ct}^R| = \frac{m_{Z'}}{v_\Phi} |\delta_{Uc}||\delta_{Ut}| \lesssim 0.013 \times \left(\frac{m_{Z'}}{150 \text{ GeV}}\right) \left(\frac{600 \text{ GeV}}{v_\Phi}\right)$. Model also predicts g_{uc}^R coupling which is proportional to Y_{Uu} and for simplicity we set it to zero.

3. Results

Establishing the indirect connection between RH tcZ' and B anomalies, in this section we discuss the discovery potential of tZ' and dimuon processes at 14 TeV LHC. To illustrate the discovery potential, we adopt effective Lagrangian : $\Delta \mathscr{L}_{\text{eff}} \supset -g_{cc}^R \bar{c}_R \gamma^\alpha c_R Z'_\alpha - \left(g_{ct}^R \bar{c}_R \gamma^\alpha t_R Z'_\alpha + \text{h.c.}\right)$ in our analysis; while the branching ratios are approximated as: $\mathscr{B}(Z' \to \mu^+\mu^-) \simeq \mathscr{B}(Z' \to \tau^+\tau^-) \simeq \mathscr{B}(Z' \to \nu\bar{\nu}) \simeq \frac{1}{3}$.

In Fig. 2, we find the discovery potential of tZ' (left panel) and dimuon (right panel) processes at the 14 TeV LHC with 300 and 3000 fb^{-1} integrated luminosities [1]. The details of the cut-based analysis and background processes can be found out in Ref. [14]. Form Fig. 2, we find that, at the 14 TeV LHC with 300 fb^{-1} integrated luminosity, the tZ' process can be discovered for $|g_{ct}^R| = 0.025$ up to $m_{Z'} \simeq 490$ GeV; while the dimuon process can be discovered for $|g_{cc}^R| = 0.01$ up to $m_{Z'} \simeq 460$ GeV. Although the discovery potentials are analyzed with g_{ct}^R and g_{cc}^R, the results can be applied to their LH counterparts. We stress that the results of this paper are model independent apart from the assumptions on narrow width and $\mathscr{B}(Z' \to \mu^+\mu^-)$. For a model with arbitrary $\mathscr{B}(Z' \to \mu^+\mu^-)$, our results in Fig. 2 could be rescaled by $|g_{cq}^R| \to |g_{cq}^R| \sqrt{3 \times \mathscr{B}(Z' \to \mu^+\mu^-)}$, with $q = t, c$.

Finally we reinterpret our results in the gauged $L_\mu - L_\tau$ model. We choose $v_\Phi = 600$ GeV and $m_U = 3$ TeV and plot the discovery potential of tZ' and dimuon processes together in Fig.3 in the Y_{Ut} vs Y_{Uc} plane for 150 GeV and 500 GeV Z'. We find that the dimuon process can be discovered for $Y_{Uc} \gtrsim 0.7$, and in general has a better discovery probability than the tZ' process, in particular

[1]For the tZ' process we have considered several SM backgrounds: tZj, $t\bar{t}Z$, $t\bar{t}W$, WZ+heavy flavor and WZ+light-jets; while for the dimuon process we have considered Z/γ^*, $\bar{t}t$, Wt and VV (V= W, Z) processes.

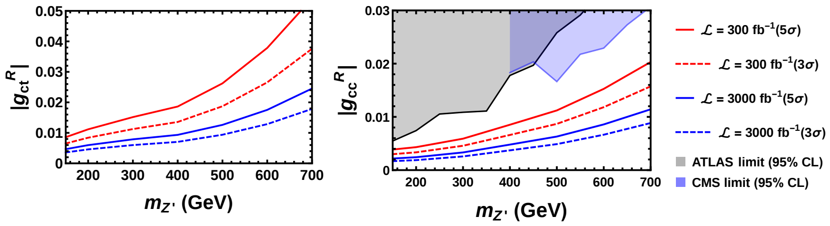

Figure 2: 5σ discovery (solid lines) and 3σ (dashed lines) reach for $pp \to tZ' + \bar{t}Z'$ (left) and dimuon (right) processes at the 14 TeV LHC with 300 fb^{-1} (red lines) and 3000 fb^{-1} (blue lines) integrated luminosities. The gray (semi-transparent blue) shaded region is excluded at 95% CL by the dimuon resonance search of ATLAS [15] (CMS [16]) with $\sim$ 13 fb^{-1} data at the 13 TeV LHC.

for small Y_{Ut}. Intriguingly, there is an overlap of the discovery regions of the two processes for $Y_{Ut} \gtrsim 0.9$ and $Y_{Uc} \gtrsim 0.7$, as can be seen in Fig.3.

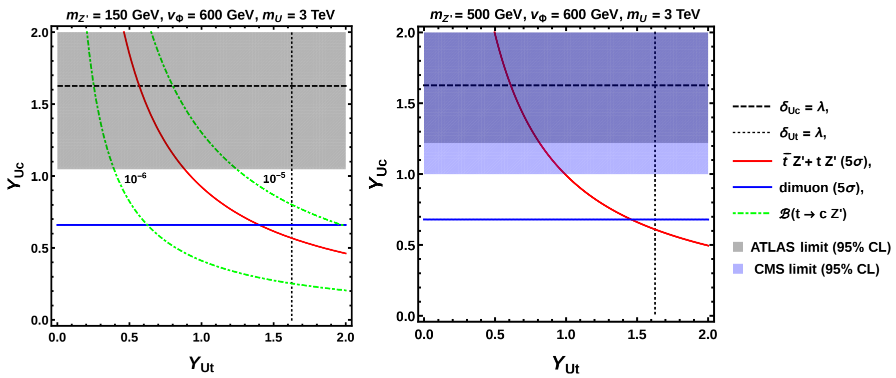

Figure 3: 5σ discovery reach of $tZ' + \bar{t}Z'$ process (red solid line) and dimuon (blue solid line) in Y_{Ut}–Y_{Uc} plane for $m_{Z'} = 150$ (left) and $m_{Z'} = 500$ (right) GeV with 3000 fb^{-1} data: Green dash-dot lines are contours for $\mathscr{B}(t \to cZ') = 10^{-6}$ and 10^{-5}. The gray and semi-transparent blue shaded regions are same as described in Fig. 2. The mixing parameter δ_{Ut} (δ_{Uc}) exceeds $\lambda \simeq 0.23$ beyond the vertical dotted (horizontal dashed) line.

4. Discussion and Summary

Motivated by recent $B \to K^{(*)}$ anomalies, we have analyzed the discovery potential of RH tcZ' coupling via $pp \to tZ' + X \to b\nu_\ell \ell^+ \mu^+ \mu^- + X$ and its conjugate process at 14 TeV LHC, with 300 and 3000 fb^{-1} integrated luminosities. We first found out the discovery potential within effective model framework and finally reinterpreted our results in a model based on gauged $L_\mu - L_\tau$ symmetry [12]. In this model, such RH tcZ' coupling is generated due to mixing of top and charm quark with heavy vector-like quraks. The existence RH tcZ' coupling implies non-zero RH ccZ' coupling, which can be searched via $pp \to Z' + X \to \mu^+\mu^- + X$ process at LHC. The model also predicts the LH tcZ' coupling which is directly linked to B anomalies via g_{bs}^L coupling by SU(2)$_L$ symmetry and lies beyond the discovery reach of HL-LHC. However, combination of both ATLAS and CMS data and QCD corrections may boost the sensitivity. We stress that RH tcZ' coupling can not be well constrained by B and K. Irrespective of the fate of B anomalies, RH tcZ' coupling has the potential of discovering a new Z' boson with dimuon as a precursor. Hence our study illustrates the RH tcZ' coupling is on the similar footing as current B anomalies and the significance of *top physics* in flavor program.

References

[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **111**, 191801 (2013) [arXiv:1308.1707 [hep-ex]].

[2] R. Aaij *et al.* [LHCb Collaboration], JHEP **1602**, 104 (2016) [arXiv:1512.04442 [hep-ex]].

[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **113**, 151601 (2014) [arXiv:1406.6482 [hep-ex]].

[4] S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D **88**, 074002 (2013) [arXiv:1307.5683 [hep-ph]].

[5] W. Altmannshofer and D.M. Straub, Eur. Phys. J. C **73**, 2646 (2013) [arXiv:1308.1501 [hep-ph]].

[6] R. Alonso, B. Grinstein and J. Martin Camalich, Phys. Rev. Lett. **113**, 241802 (2014) [arXiv:1407.7044 [hep-ph]].

[7] G. Hiller and M. Schmaltz, Phys. Rev. D **90**, 054014 (2014) [arXiv:1408.1627 [hep-ph]].

[8] T. Hurth, F. Mahmoudi and S. Neshatpour, JHEP **1412**, 053 (2014) [arXiv:1410.4545 [hep-ph]].

[9] W. Altmannshofer and D.M. Straub, Eur. Phys. J. C **75**, 382 (2015) [arXiv:1411.3161 [hep-ph]].

[10] X.G. He, G.C. Joshi, H. Lew and R.R. Volkas, Phys. Rev. D **43**, 22 (1991).

[11] R. Foot, Mod. Phys. Lett. A **6**, 527 (1991).

[12] W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Phys. Rev. D **89**, 095033 (2014) [arXiv:1403.1269 [hep-ph]].

[13] K. Fuyuto, W.-S. Hou and M. Kohda, Phys. Rev. D **93**, 054021 (2016) [arXiv:1512.09026 [hep-ph]].

[14] W. S. Hou, M. Kohda and T. Modak, Phys. Rev. D **96**, no. 1, 015037 (2017) [arXiv:1702.07275 [hep-ph]].

[15] ATLAS Collaboration, ATLAS-CONF-2016-045.

[16] CMS Collaboration, CMS-PAS-EXO-16-031.