Signature of tcZ' couplings via tZ' associated production at the LHC

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EPS Conference on High Energy Physics Venice, Italy 2017

Introduction:

- The study of top quark's (t) properties in detail is one of the major program of Large Hadron Collider (LHC).
- As a proton-proton (pp) collision machine, LHC will produce top quarks in abundance and will essentially act as top factory and will offer a unique probe for top physics.
- ATLAS and CMS collaborations have performed analysis to discover FCNC processes such as $t \to Zc$ and tZ FCNC process in the Run-1.
- In our analysis we have studied the discovery potential of right handed (RH) tcZ' via $cg \to tZ'$ process at 14 TeV LHC run, first in a model independent way, then in a model based on gauged $L_\mu - L_\tau$ symmetry.
- Such a model provides an explanation for the recent anomalies in the $b \to s\ell\ell$ transition such as P_5', R_K and R_{K^*}.
- Model predicts left handed (LH) tcZ' coupling which is directly related to LH bsZ' coupling and strongly constrained by B_s^0 mixing.
- Model also predicts RH ccZ' coupling along with RH tcZ'. This induce parton level process $c\bar{c} \to Z'$ and $cg \to tZ'$ which could be discovered at LHC in it's Run-2.
- We show that the tZ' process can provide a clean probe RH tcZ' coupling which is not constrained by flavor physics. Our analysis is motivated by but not directly linked to $b \to s\ell\ell$ anomalies.

Model framework:

- The minimal gauged $L_\mu - L_\tau$ model [He et al., R. Foot]: $\mathcal{L} \supset -g'\left(\bar{\mu}\gamma_\alpha\mu + \bar{\nu}_{\mu L}\gamma_\alpha\nu_{\mu L} - \bar{\tau}\gamma_\alpha\tau - \bar{\nu}_{\tau L}\gamma_\alpha\nu_{\tau L}\right)Z'^\alpha$.
- The gauged $L_\mu - L_\tau$ model is extended by the addition of vector like quarks Q, D and U carrying $+1$ $U(1)'$ charge mix with SM quarks [Altmannshofer et al.]:

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

where the SM singlet scalar field Φ (carries unit $U(1)'$ charge) spontaneously breaks the $U(1)'$ symmetry after acquiring vev v_Φ and gives mass to Z' boson.

- Effective Lagrangian for FCNC Z' couplings to SM quarks are given by:

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

- Assuming the Yukawa couplings are real we get: $g^R_{cc} = g'\frac{Y^2_{Uc}v^2_\Phi}{2m^2_U}$ and $g^R_{ct} = -g'\frac{Y_{Uc}Y_{Ut}v^2_\Phi}{2m^2_U}$. RH tcZ' coupling is proportional to the Yukawa couplings Y_{Uc} and Y_{Ut}. Hence a non zero RH tcZ' coupling induces a RH ccZ' coupling.

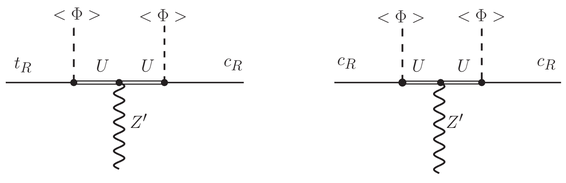

Figure 1: Feynman diagrams that generates effective RH tcZ' and ccZ' coupling.

tZ' Process:

- The process: $pp \to tZ' \to b\nu_\ell\ell^+\mu^+\mu^-$ (tZ' process) and $pp \to \bar{t}Z' \to \bar{b}\bar{\nu}_\ell\ell^-\mu^+\mu^-$ ($\bar{t}Z'$ process).
- The dominant contribution to the tZ' process is via parton level process $cg \to tZ'$, with small contributions from: $gg \to tcZ'$ and $gg \to t\bar{t}Z'$ processes.
- The leading SM background processes are: tZj, $t\bar{t}Z$, $t\bar{t}W$, $WZ+$ light jets and $WZ+$ heavy flavor jets. All the background cross sections are corrected up to NLO QCD cross section except $WZ+$ light jets and $WZ+$ heavy flavor jets which are corrected up to NNLO QCD. We have not multiplied any K factor to the signal.
- The discovery potential of the combined process $tZ' + \bar{t}Z'$:

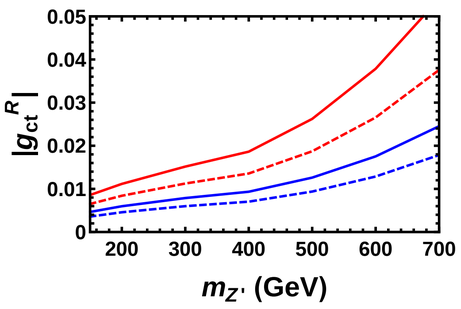

Figure 2: Discovery potential of the combined process $tZ' + \bar{t}Z'$ at 14 TeV LHC. The red solid (blue solid) and red dashed (blue dashed) lines conform the 5σ (discovery) and 3σ contours at 300 fb^{-1} (3000 fb^{-1}) integrated luminosity.

Dimuon process:

- The dominant contribution: $c\bar{c} \to Z'$ with subdominant contributions from $cg \to cZ'$ and $gg \to \bar{c}cZ'$ processes. The SM background processes are: Z/γ^* (DY), $t\bar{t}$, Wt, WW , WZ and ZZ. All the backgrounds cross sections are corrected up to NNLO QCD cross sections. We have not multiplied any K factor for signal. Discovery potential of the dimuon process:

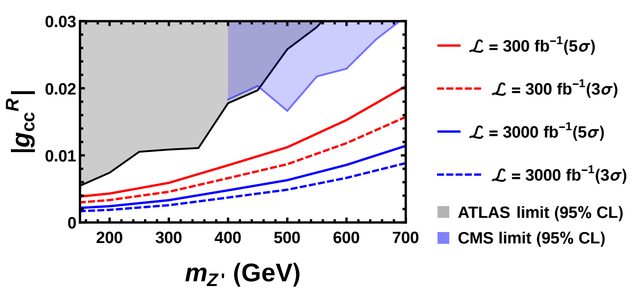

Figure 3: Discovery potential of the dimuon process at 14 TeV LHC. The black and blue shaded regions are excluded from ATLAS and CMS search for heavy resonance in the dimuon final state ($\sqrt{s} = 13$ TeV and 13 fb^{-1} dataset).

Interpretation in the gauged $L_\mu - L_\tau$ model:

- The mixing parameters between vector-like quark U and RH top or charm quark is given by : $\delta_{Uq} \equiv \frac{Y_{Uq}v_\Phi}{\sqrt{2}m_U}$. We allow the mixing parameter $\delta_{Uq} \leq \lambda \simeq 0.23$ (Cabibbo mixing angle). The RH tcZ' coupling is constrained as $|g^R_{ct}| = \frac{m_{Z'}}{v_\Phi}|\delta_{Uc}||\delta_{Ut}| \lesssim 0.013 \times \left(\frac{m_{Z'}}{150\ \text{GeV}}\right)\left(\frac{600\ \text{GeV}}{v_\Phi}\right)$.
- The P_5' and $R_{K^{(*)}}$ anomalies can be explained by $\Delta C_9^\mu = \frac{g^L_{sb}g'}{m^2_{Z'}}$. The upper and lower limits on g^L_{sb} is found to be: $0.7 \times 10^{-4}\left(\frac{m_{Z'}}{150\ \text{GeV}}\right)\left(\frac{|\Delta C_9^\mu|}{(34\ \text{TeV})^{-2}}\right) \lesssim |g^L_{sb}| \lesssim 0.7 \times 10^{-3}\left(\frac{m_{Z'}}{150\ \text{GeV}}\right)$.
- The neutrino trident production and B_s mixing set lower and upper limits on v_Φ respectively: $0.54\ \text{TeV} \lesssim v_\Phi \lesssim 5.6\ \text{TeV}\left(\frac{(34\ \text{TeV})^{-2}}{|\Delta C_9^\mu|}\right)$.
- Discovery contours in the Y_{Uc} vs Y_{Ut} plane:

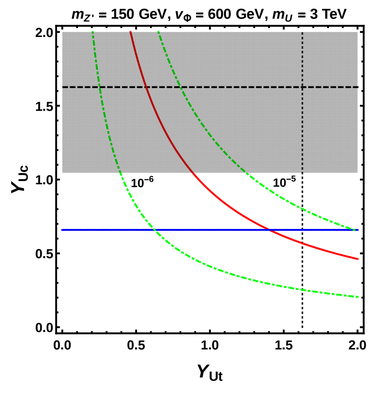

Figure 4: Discovery potential of $tZ' + \bar{t}Z'$ and dimuon processes in Y_{Uc} vs Y_{Ut} plane for a 150 Z' at 14 TeV LHC.

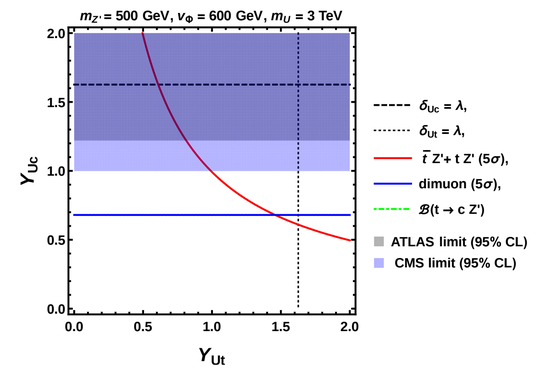

Figure 5: Same figure as the preceding one but for 500 GeV Z'.

- Discovery contours in the integrated luminosity vs m_U plane:

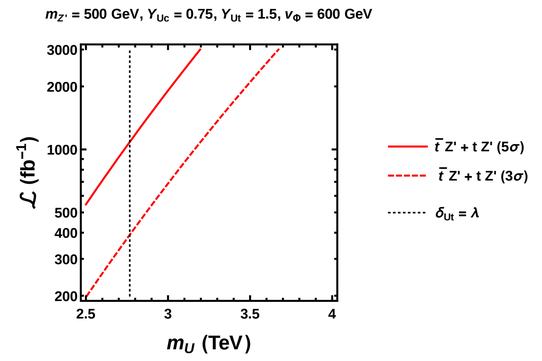

Figure 6: Discovery contours of the $tZ' + \bar{t}Z'$ process for 500 GeV Z'.

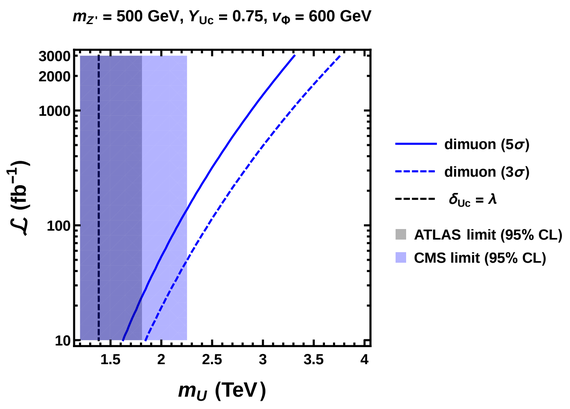

Figure 7: Discovery contours of the dimuon process for 500 GeV Z'.

Summary:

- We have investigated the discovery potential of RH tcZ' coupling at 14 TeV LHC.
- We find that such coupling can be discovered at Run-2 of LHC. We have reinterpreted our results in the gauged $L_\mu - L_\tau$ model, constructed to explain $B \to K^{(*)}$ anomalies.
- A direct consequences of the RH tcZ' coupling is the existence of RH ccZ' and our study suggests this process can be discovered even earlier than tcZ' process.
- RH tcZ' is not well constrained by B and K physics. The tZ' process offers an excellent probe for such couplings.
- Regardless of the future of the $B \to K^{(*)}$ anomalies, our result illustrates that right-handed tcZ' coupling is on the similar footing as current B anomalies and significance of top physics in the flavor program.

Reference:

- Search for tZ' associated production induced by tcZ' couplings at the LHC. Wei-Shu Hou, Masaya Kohda, and Tanmoy Modak arXiv:1702.07275. (Accepted to PRD)