$P'_5$ Anomaly for Top: $tZ'$ Production at LHC

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1 Introduction

The “$P'_5$ anomaly”, reported [1, 2] by the LHCb experiment in angular analysis of $B \to K^*\mu^+\mu^-$ decay, has caught a lot of attention lately. One intriguing interpretation is that the $C_9$ Wilson coefficient of the electroweak penguin gets shifted by one unit from Standard Model (SM) expectation, plausibly due to a heavy $Z'$ boson. However, it is of some concern [3] that, increasing data from 1 fb$^{-1}$ [1] to 3 fb$^{-1}$ [2], the experimental significance did not improve. Furthermore, a recent result [4] by the CMS experiment based on 8 TeV data, is quite consistent with SM. Thus, the issue would need the unfolding of LHC Run 2 data, as well as turn-on of Belle II, to clarify.

The $\Delta C_9 \sim -1$ shift has motivated an extension [5] of the so-called gauged $L_{\mu} - L_{\tau}$ model (muon number minus tau number), by adding vector-like $Q$, $D$ and $U$ quarks that carry the extra $U(1)'$ charge, where $Q$ stands for a left- and right- weak doublet while $D$, $U$ are singlets, with obvious notation. By mixing with $b$ and $s$ quarks, the exotic $Q$ and $D$ quarks could generate the desired $\Delta C_9$, implying possible $t \to cZ'$ decay. But since the tree-level $P'_5$ effect corresponds to SM at loop level in strength, $t \to cZ'$ decay is rather suppressed. Interestingly, the mixing of the $U$ quark with right-handed (RH) $t$ and $c$ are not constrained by $B$ physics, but even for this case, $t \to cZ'$ decay is not too promising [6].

Here, we point out [7] an alternative: searching for $cg \to tZ'$ generated by RH $tcZ'$ coupling. Whether $P'_5$ anomaly in $B \to K^*\mu^+\mu^-$ turns out genuine or not, this would be akin to a “$P'_5$ probe” of the top quark itself. We find good discovery potential in the coming future, while the LH $tZ'$ that is related to $P'_5$ would be too weak to observe in direct search at LHC.

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2 Home institute: Department of Physics, National Taiwan University, Taipei 10617, Taiwan.
3 For a U(1) symmetry, one could have just the $U$ quark, with $Q$ and $D$ absent.
2 RH tcZ' and ccZ' Couplings

The $t_R$, $c_R$ quarks mix with $U_L$ by new Yukawa couplings $Y_{Ut}, Y_{Uc}$ to an SM singlet scalar field $\Phi$, which breaks the U(1)' symmetry by $\langle \Phi \rangle = v_{\Phi} \neq 0$. With $Z'$ emitted by the $U$ quark, one could consider an effective and therefore generic coupling

$$- \left( g_{cl}^R \overline{c_R} \gamma^\alpha t_R Z'_\alpha + \text{h.c.} \right),$$

where, specific to the extended $L_\mu - L_\tau$ model, one has

$$g_{cl}^R = \left( g_{tc}^R \right)^* = -g' Y_{Uc}^* Y_{Ut} v_{\Phi}^2 / 2m_U^2,$$

as interpretation. Note that Eq. (2) is nonzero only if $Y_{Uc} \neq 0$. Thus, the model implies a RH $ccZ'$ coupling,

$$g_{cc}^R = -g' |Y_{Uc}|^2 v_{\Phi}^2 / 2m_U^2,$$

hence one could also contemplate a generic coupling

$$-g_{cc}^R \overline{c_R} \gamma^\alpha c_R Z'_\alpha.$$  

Eq. (1) generates the $cg \rightarrow tZ'$ process, where $Z' \rightarrow \mu^+ \mu^-$ with 1/3 branching fraction. We note that

$$\Gamma_{Z'} \simeq m_{Z'}^3 / 4\pi v_{\Phi}^2 \simeq 0.75 \text{ GeV} \left( m_{Z'} / 150 \text{ GeV} \right)^3 \left( 600 \text{ GeV} / v_{\Phi} \right)^2,$$

is in general not long-lived, but also not too broad.

We follow closely a similar study by CMS using 8 TeV data for $tZ$ final state [8], where the signal is $\ell \mu^+ \mu^- + b + \text{missing-}E_T$, with backgrounds from $tZj, ttZ, ttW, WZ + j$, etc. We start by considering two benchmark $m_{Z'}$ values, one below $m_t$ and one above. Events are generated by MadGraph and interfaced with PYTHIA for showering, where Delphes is used for detector simulation. After preselection cuts at generator level on lepton $p_T, \eta$, separation, and jet $p_T$, further selection cuts are applied for refined definition of $\ell \mu^+ \mu^-$, b-jet, lepton $p_T$, top-related “softest lepton” and W-mass etc., and we employ a second $p_T$ jet veto to reduce $ttZ$ and $ttW$ background. Effects of these cuts, such as plots and tables, can be found in Ref. [7]. For signal significance, we use $Z = \sqrt{2 \left[ (S + B) \ln (1 + S/B) - S \right]}$. Assuming $|g_{cl}^R| = 0.01$ and combining the $tZ'$ and $TZ'$ processes, we find 5σ discovery potential for 180 (450) fb$^{-1}$ data at 14 TeV, for $m_{Z'} = 150 (200)$ GeV. This “discoverability” motivates us to extend to full range of $m_{Z'}$ for the discovery reach in $|g_{cl}^R|$.

Eq. (4) motivates “milliweak” Drell-Yan production of $Z'$ from $c\overline{c}$ parton annihilation, $c\overline{c} \rightarrow Z' \rightarrow \mu^+ \mu^-$, which is interesting. For our two benchmark points, we
choose a slightly lower $|g^R_{ct}| = 0.005$ value. We find, through straightforward study and using significance $Z = S/\sqrt{B}$ as usual, $5\sigma$ discovery potential for $110 (170)$ fb$^{-1}$ data at 14 TeV for $m_{Z'} = 150 (200)$ GeV, which seems promising.

Extending the study for discovery reach, we plot $|g^R_{ct}|$ vs $m_{Z'} \in (150, 700)$ GeV in Fig. 1[left] for $tZ'$, and $|g^R_{cc}|$ vs $m_{Z'}$ in Fig. 1[right] for dimuon. For both figures, the upper (lower) solid curves are $5\sigma$ discovery for $300 (3000)$ fb$^{-1}$, while dashed curves stand for $3\sigma$ evidence. For Fig. 1[right], the preliminary dimuon search limits of ATLAS [9] and CMS [10], each with $\sim 13$ fb$^{-1}$ data at 13 TeV, are shown in the figure. Not shown is the improved ATLAS 13 TeV result [11] with 36.1 fb$^{-1}$ data.

From the figures, we see that there is much parameter space to be explored, hence discovery potential, for both $tZ'$ and dimuon processes. For example, if we set the goal of coupling strengths of $|g^R_{ct}|$ down to 0.025 or $|g^R_{cc}|$ down to 0.01, then 300 (3000) fb$^{-1}$ data allows discovery up to 440 (640) GeV. The lesson learned is that HL-LHC might still offer discoveries, that of weaker-coupled (narrow) resonances.

3 Probing Gauged $L_\mu - L_\tau$

Although the couplings $g^R_{ct}$ and $g^R_{cc}$ of Eqs. (1) and (4) can be viewed as generic and independent, let us give a possible physics interpretation of a potential, future discovery at the LHC in the $L_\mu - L_\tau$ model. We introduce the dimensionless ratio

$$\delta_{Uq} = Y_{Uq}v_\Phi/\sqrt{2}m_U, \quad (q = t, c)$$

which is the mixing angle between $U$ and $q = t, c$. The yardstick then is the Cabibbo angle $\lambda \equiv \cos \theta_C \simeq 0.22$. Given that the $U$ quark is quite exotic and heavy, $\delta_{Ut}$ and $\delta_{Uc}$ might not be much larger than $\lambda$, especially for $\delta_{Uc}$.

Motivated by low energy constraints [6], we set $v_\Phi = 600$ GeV, $m_U = 3$ TeV, and plot in Fig. 2 the $5\sigma$ discovery reach in $Y_{Ut} - Y_{Uc}$ plane, for $m_{Z'} = 150$ GeV [left], 500
Figure 2: 5σ discovery reach in $Y_{Ut}$–$Y_{Uc}$ plane at 14 TeV LHC for [left] $m_{Z'} = 150$ GeV and [right] $m_{Z'} = 500$ GeV. Further explanations in text.

GeV [right], where solid curve is for combined $tZ'$ and $\bar{t}Z'$, and horizontal solid line is for dimuon. For both figures, the horizontal dashed line marks $\delta_{Uc} = \lambda$ and vertical dotted line marks $\delta_{Ut} = \lambda$. For Fig. 2[left], the case of $m_{Z'} = 150$ GeV which is below top threshold, the two dash-dot lines are marked by $\mathcal{B}(t \to cZ') = 10^{-6}, 10^{-5}$ [6], while the gray shaded region is excluded by ATLAS preliminary dimuon search at 13 TeV [9] with $\sim 13$ fb$^{-1}$ data; the 36 fb$^{-1}$ result [11] by ATLAS at 13 TeV, not shown, improves limit on $Y_{Uc}$ by $\sim 20\%$. The CMS preliminary 13 TeV result [10] does not probe this low $m_{Z'}$ value. For Fig. 2[right], the case of $m_{Z'} = 500$ GeV which is considerably above top threshold, we note from Eq. (5) that $\Gamma_{Z'} \sim 27$ GeV, and we have adjusted the $m_{\mu\mu}$ mass window to accommodate. The region excluded by CMS preliminary dimuon search at 13 TeV with $\sim 13$ fb$^{-1}$ data is somewhat better than ATLAS. However, the 36 fb$^{-1}$ result [11] by ATLAS at 13 TeV, not shown, is comparable to the CMS preliminary result with smaller dataset. It would therefore be interesting to see the CMS update with full 2015 and 2016 dataset.

A different perspective is to interpret the search as indirect probe of vector-like quark $U$. To illustrate, we take $v_\Phi = 600$ GeV with a mild hierarchical pattern for Yukawa couplings, $Y_{Ut} = 1.5$ and $Y_{Uc} = 0.75$. Note the difference in parameter space from Fig. 2, as we allow $m_U$ to vary. We plot integrated luminosities needed as a function of $m_U$ for 5σ discovery (3σ evidence) of the combined $tZ'$ and $\bar{t}Z'$ process as solid (dashed) lines in Fig. 3, for $m_{Z'} = 150$ GeV [left], 500 GeV [right]. Again, the vertical dotted line marks $\delta_{Ut} = \lambda \simeq 0.22$, decreasing to the right as $m_U$ increases (see Eq. (6)). We see that a discovery, which could happen with $\sim 300$ fb$^{-1}$ or more data (and indication for $m_{Z'} = 150$ GeV case could appear within Run 2), one would be probing $m_U$ above 2.5 TeV. As higher $m_U$ is probed, one probes smaller $\delta_{Ut}$ mixing as
allowed by the higher integrated luminosity, which is indeed analogous with $P_5'$-like sensitivities with number of $B$ mesons.

We give the analogous plots, with $Y_Ut$ now unspecified, for dimuon process in Fig. 4, where now the vertical dashed line marks $\delta_{Uc} = \lambda \approx 0.22$, decreasing to the right as $m_U$ increases. We see that the dimuon search at 13 TeV (shaded regions) by ATLAS and CMS are already probing $m_U$ above 2 TeV, and higher luminosities allow one to probe smaller $\delta_{Uc}$ mixings for heavier $m_U$.

4 Discussion and Conclusion

If mixing angles $\delta_{Uc} \sim \delta_{Ut}$, then dimuons would be more promising. If discovered, one should study $cg \rightarrow cZ'$ with the aid of $c$-tagging, if feasible. For the hierarchical pattern and $\delta_{Uc}/\delta_{Ut} < 0.4$, then $tZ' + \bar{t}Z'$ becomes more promising. If discovered, then the handedness can be studied via angular analysis. Both topics are under investigation. If both $tZ'$ and dimuons are discovered, we could learn the detailed flavor structure. However, if one takes the prejudice that $\delta_{Ut} < \lambda \sim 0.22$ and $\delta_{Uc}/\delta_{Ut} < \lambda$, then the scenario seems out of reach at the LHC. But experimental search should certainly be pursued, as one can consider these as generic processes.

We note that, for LH $g_t'$ coupling that is directly linked to $B \rightarrow K^{(*)}$ anomalies (not just $P_5'$), $tZ'$ would be out of reach even for the HL-LHC, because the effective coupling at the SM loop level makes it too weak to be produced. But maybe one also should contemplate generic $b\bar{b} \rightarrow Z'$? This would enter the $cg \rightarrow cZ'$ program.

In conclusion, we have illustrated the possible emergence of “Top Flavor Physics” with $tZ'$ and $Z' \rightarrow \mu^+\mu^-$ dimuon search at the LHC. The discoverability of this “$P_5'$ of top” could start with Run 2, all the way to the end of HL-LHC. A moral can be
drawn from this: weaker-coupled resonances are probed at Run 2, and by HL-LHC. We should not give up hope for discovery.

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