Associated $Z'$ production in the flavorful $U(1)$ scenario for $R_K(\ast)$

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Abstract

The flavorful $Z'$ model with its couplings restricted to the left-handed second generation leptons and third generation quarks can potentially resolve the observed anomalies in $R_K$ and $R_{K^0}$. After examining the current limits on this model from various low-energy processes, we probe this scenario at 14 TeV high-luminosity run of the LHC using two complementary channels: one governed by the coupling of $Z'$ to $b$-quarks and the other to muons. We also discuss the implications of the latest LHC high mass resonance searches in the dimuon channel on the model parameter space of our interest.
1 Introduction

In the last few years, the LHCb collaboration has reported a number of deviations from $\mu$-$e$ universality in B-meson processes. In particular, the ratios of $\mu^+\mu^-$ to $e^+e^-$ final states in $B \rightarrow K^{(*)}\ell^+\ell^-$ decays: $R_K$ \cite{1} and $R_K^*$ \cite{2} are observed to be smaller than one, each displaying a $\sim 2.5\sigma$ deviation from lepton-flavor universality predicted by the Standard Model (SM). Recent global analyses \cite{3–7}, which also take into account other $b \rightarrow s\ell^+\ell^-$ mediated processes, conclude that the SM is disfavored by the current experimental data with a confidence level exceeding $5\sigma$.

The global fit can be significantly improved if the effective Lagrangian below the weak scale contains new contributions to the 4-fermion operator $(\bar{b}_L\gamma^\rho s_L)(\bar{\mu}_L\gamma^\rho\mu_L)$, in addition to the ones generated by the exchange of SM particles in loops. One option to arrange for these contributions is to assume that the high-energy theory contains a new electrically neutral vector particle $Z'$ coupled to muons and, in a flavor-violating way, to bottom and strange quarks. In this scenario, the 4-fermion operator in question can arise from tree-level $Z'$ exchange. There is already a vast literature discussing $Z'$ models explaining the $b \rightarrow s\ell\ell$ anomalies, see e.g. \cite{8–43}. A generic feature of these models is that the $Z'$ is within the kinematic reach of the LHC and thus can be searched for directly. In particular, these models always predict a non-zero cross section for the quark-level process $b(\bar{b})s(s) \rightarrow Z' \rightarrow \mu\mu$, which leads to the dimuon resonance signature at the LHC. Furthermore, in some models the $Z'$ coupling to $bs$ is correlated with couplings to other quarks, which opens further production channels at the LHC \cite{27,32}.

The goal of this paper is to study new LHC signatures of the $Z'$ boson responsible for the $b \rightarrow s\ell\ell$ anomalies. We consider the model described in Ref. \cite{37} where $Z'$, in addition to the coupling to muons, also possesses a sizable coupling to $b\bar{b}$. This model predicts several new signatures where $Z'$ is produced in association with some SM particles. We focus on two such signatures, which we find especially promising:

- $pp \rightarrow Z' + 1b(2b) \rightarrow \mu^+\mu^- + 1b(2b)$,
- $pp \rightarrow Z'\mu^\pm + E_T \rightarrow 3\mu + E_T$.

For these two processes we study the discovery prospects at the LHC run 3 and the subsequent high-luminosity phase (HL-LHC). We show that the above signature can be observed with the significance exceeding $5\sigma$ in the parameter space of the $Z'$ model favored by the $b \rightarrow s\ell\ell$ anomalies and consistent with all other experimental constraints. The information obtained by studying these two processes is complementary to that conveyed by generic dimuon resonance searches, and will be crucial for the identification of the microscopic model responsible for the $b \rightarrow s\ell\ell$ anomalies.

In what follows, in Section 2 we discuss the model and list the range of couplings of the $Z'$ to muons and $b$-quarks allowed by low-energy precision measurements. In Section 3 we present a detailed analysis of LHC prospects of discovering the $Z'$ in two complementary channels where the $Z'$ is produced in association with SM particles. The production rate of $Z'$ in the two channels is governed by its coupling either to $b$-quarks or to muons and thus they can potentially probe different regions of the allowed parameter space dominated by either of the two couplings. In
Section 4 we compare the sensitivity of these associated $Z'$ production searches with that of the generic dimuon resonance searches. Finally, we summarise and conclude in Section 5.

2 The model

We consider a massive spin-1 boson $Z'$ with coupling to quarks and leptons that can address the $R_K$ and $R_K^*$ anomalies. We work with the setup described in Ref. [37], however in this paper we assume that only the $Z'$ boson can be produced at the energy scale available at the LHC. The relevant BSM interactions pertaining to our collider analysis are encoded in the following Lagrangian:

$$\mathcal{L} \supset Z'_\mu \left( g_{bb} \bar{q}_L \gamma^\mu q_L + g_{bs} \bar{b}_L \gamma^\mu s_L + g_{\mu\mu} \bar{L}_L \gamma^\mu L_L \right), \quad (2.1)$$

where $q_L = (t_L, b_L)^T$, $L_L = (\nu_{\mu L}, \mu_L)^T$. The $Z'$ couplings $g_{bb}$, $g_{bs}$, and $g_{\mu\mu}$ to muons, $s$- and $b$-quarks are in principle free parameters. However, in the setup of [37] in the absence of fine-tuning one expects $|g_{bs}| \sim |V_{ts} g_{bb}|$, where $|V_{ts}| \approx 0.04$ is the 3-2 entry of the CKM matrix. In the following for simplicity we assume $g_{bs} = V_{ts} g_{bb}$, and that $g_{bb}$ and $g_{\mu\mu}$ have the same sign. Thus, the parameter space in our analysis is 3-dimensional, and consists of the 2 couplings $g_{bb}$, $g_{\mu\mu}$ and the $Z'$ mass $M_{Z'}$.

Integrating out the $Z'$ boson generates four-fermion contact interactions in the effective theory below the scale $M_{Z'}$. In particular, a new contribution to the effective interaction $(\bar{b}_L \gamma^\rho s_L)(\bar{\mu}_L \gamma^\rho \mu_L)$ is generated, adding to the SM contribution induced at the loop level. This is the scenario with $C_{NP}^{9\mu} = -C_{NP}^{10\mu}$, using the standard notation of flavor physics. Such a pattern of new physics corrections provides a very good fit to the measured $R_K$, $R_K^*$, and other $b \to s\mu\mu$ observables [3–7]. The best fit of Ref. [5], $C_{NP}^{9\mu} = -C_{NP}^{10\mu} = -0.53 \pm 0.09$, translates into the following constraint on our parameters:

$$\frac{g_{bb} g_{\mu\mu}}{M_{Z'}^2} = \frac{1.00 \pm 0.17}{(6.9 \text{ TeV})^2} \quad @ \text{68\% CL.} \quad (2.2)$$

In the following of this analysis we will assume that the values of the parameters correspond to this best fit within $1\sigma$ uncertainty.

There are further low-energy constraints on these parameters. One is due to four-lepton interactions generated by integrating out $Z'$, which are constrained by the trident muon production in neutrino scattering [44–46]. Using the global fit of Ref. [47] one finds

$$\frac{g_{\mu\mu}^2}{M_{Z'}^2} < \frac{1}{(330 \text{ GeV})^2} \quad @ \text{99\% CL.} \quad (2.3)$$

Another combination of the model parameters is probed thanks to the $Z'$ contribution to the $\Delta F = 2$ operator $(\bar{b}_L \gamma_\rho s_L)^2$, which affects the $B_s$ meson mass difference. The analysis in Ref. [48] translates into the constraint

$$\frac{g_{bb}^2}{M_{Z'}^2} < \frac{1}{(11.5 \text{ TeV})^2} \quad @ \text{99\% CL.} \quad (2.4)$$
Figure 1: The parameter space in the \((g_{\mu\mu}, g_{bb})\) plane for \(M_{Z'} = 200\) GeV preferred at 68% CL by the \(b \to s\ell^+\ell^-\) anomalies (parabolic green band), compared to the regions excluded at 99% CL by trident neutrino production (vertical orange band), and \(B \to D^*\ell\nu\) (horizontal blue band).

An example of the parameter space is shown in Figure 1 for \(M_{Z'} = 200\) GeV. Clearly, fitting the \(b \to s\mu\mu\) anomalies together with the low-energy constraints discussed above leaves a finite interval for the \(Z'\) coupling \(g_{\mu\mu}\) and \(g_{bb}\). The intervals \(g_{\mu\mu}^{\text{min}} \lesssim g_{\mu\mu} \lesssim g_{\mu\mu}^{\text{max}}\) and \(g_{bb}^{\text{min}} \lesssim g_{bb} \lesssim g_{bb}^{\text{max}}\) allowed at 99% CL for the particular values of \(M_{Z'}\) used in our collider analysis are shown in Table 1.

| \(M_{Z'}\) (GeV) | \(g_{\mu\mu}^{\text{min}}\) | \(g_{\mu\mu}^{\text{max}}\) | \(g_{\mu\mu}^{1\sigma}\) | \(g_{bb}^{\text{min}}\) | \(g_{bb}^{\text{max}}\) |
|------------------|------------------|------------------|------------------|------------------|------------------|
| 200              | 0.040            | 0.61             | [0.067,0.078]    | 0.0016           | 0.017            |
| 300              | 0.060            | 0.91             | [0.10,0.12]      | 0.0024           | 0.026            |
| 500              | 0.10             | 1.5              | [0.16,0.20]      | 0.0040           | 0.044            |
| 750              | 0.15             | 2.3              | [0.24,0.32]      | 0.0060           | 0.065            |
| 1000             | 0.20             | 3.0              | [0.32,0.43]      | 0.0080           | 0.087            |

Table 1: Intervals for the couplings \(g_{\mu\mu}\) and \(g_{bb}\) consistent with explaining the \(b \to s\ell\ell\) anomalies, and not excluded at 99% CL by the \(B \to D^*\ell\nu\) and trident constraints. We also show the \(1\sigma\) confidence interval for the coupling \(g_{\mu\mu}\) obtained from the likelihood combining the above mentioned constraints.
3 Collider Analysis

In this section we discuss LHC signatures of a $Z'$ boson with a pattern of couplings to matter motivated by the $b \rightarrow s \mu \mu$ anomalies, as given in Eq. (2.1). One signature, already discussed in several previous works [32, 37], is the resonant dimuon production, $pp \rightarrow Z' \rightarrow \mu^+ \mu^-$. In this scenario, the $Z'$ is predominantly produced at the LHC via the $b \bar{b}$ fusion, with a subleading contribution from the $b \bar{s}$ and $\bar{b} s$ fusion, and it decays to a pair of muons with a branching fraction that is strongly dependent on the couplings $g_{bb}$ and $g_{\mu \mu}$. Another signature is $pp \rightarrow Z \rightarrow 4\mu$ [10, 46, 49], where the $Z$ boson first decays to two muons, and then a $Z'$ (off-shell or on-shell, depending on its mass) is radiated off one of the muons.

The goal of this paper is to explore alternative signatures of the $Z'$ boson at the LHC. We focus on the following two processes:

- $pp \rightarrow Z' + 1b(2b) \rightarrow \mu^+ \mu^- + 1b(2b),$
- $pp \rightarrow Z' \mu^\pm E_T \rightarrow 3\mu^\pm + E_T.$

![Feynman Diagrams](image)

Figure 2: Leading Feynman diagrams for the $Z' + 1b(2b)$ final state.

The leading Feynman diagrams for these processes are shown in Figure 2 and 3. In the first process the $Z'$ boson is radiated off a b-quark, while in the second it is radiated off a muon or a neutrino. In both cases we study the situation where the $Z'$ decays to a muon pair. Consequently, the rate of the first process depends on both $g_{bb}$ and $g_{\mu \mu}$ couplings, while in the second case it
depends only on $g_{\mu\mu}$. Note that, following Eq. (2.2), the magnitude of $g_{bb}$ and $g_{\mu\mu}$ is anti-correlated in our scenario. For this reason, the two processes target complementary regions of the parameter space: the $3\mu^\pm + E_T$ signal is more relevant for larger $g_{\mu\mu}$, while the $\mu^+\mu^- + b$ signal is more relevant for smaller $g_{\mu\mu}$.

We implemented the interactions in Eq. (2.1) in FeynRules [50] so as to generate a MadGraph5 model file. We then generated both the signal as well as SM backgrounds events using MadGraph5_aMC@NLO [51] at the leading order (LO) and at the parton level. For the parton distribution function (PDF) we used the NN23LO1 implementation [52]. The parton level events are passed to PYTHIA 8 [53] for showering and hadronization. Finally, the showered events are passed through the detector level simulation using Delphes3 [54], with the jets reconstructed using the anti-$k_T$ jet algorithm [55]. In our analysis we ignore $Z'$ production proceeding via the $Z'$-b-s coupling, which is suppressed due to the smallness of that coupling in our model, $g_{bs}/g_{bb} \sim |V_{ts}| = O(10^{-2})$.

3.1 $pp \rightarrow Z' + 1b(2b) \rightarrow \mu^+\mu^- + 1b(2b)$ channel

In this channel we consider the production of the $Z'$ boson in $\sqrt{s} = 14$ TeV LHC in association with either one or two $b$-quarks, followed by the $Z'$ decay into a muon pair. The dominant background contributions for this signal arise from the SM processes $pp \rightarrow \mu^+\mu^- + jj$, $pp \rightarrow t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}\mu^+\mu^-\nu_\mu\bar{\nu}_\mu$ and $pp \rightarrow \mu^+\mu^- + 1b(2b)$. Here $j$ denote the light quark partons which can contribute to the background via being mistagged as $b$-jets. For the $\mu^+\mu^-jj$ background the events are matched up to three jets using $k_T$-MLM matching scheme [56,57].

To generate our signal and background events, we employ the following preselection cuts:

$$\Delta R_{jj,b\bar{b},b\ell,j\ell} > 0.4, \quad \Delta R_{\ell\ell} > 0.2, \quad p_T(j,b,\ell) > 10 \text{ GeV}, \quad |\eta_{j,b,\ell}| < 2.5. \quad (3.1)$$

After implementing these cuts, the dependence of the signal cross section on the coupling $g_{\mu\mu}$ is shown in Figure 4 for $M_{Z'} = 200$, 500 and 1000 GeV. In our simulations, for a given $g_{\mu\mu}$ and $M_{Z'}$, the value of $g_{bb}$ is fixed to the central value determined from Eq. (2.2). The upper and lower ends of each signal cross-section curve are due to the finite allowed range of the couplings $g_{bb}$ and $g_{\mu\mu}$, as shown in Table 1.

We require the final state to be comprised of two oppositely charged muons and one or two $b$-tagged jets with $p_T(b) > 20 \text{ GeV}$. We also impose an electron veto in the final state. The
Figure 4: The signal cross-section as a function of $g_{\mu\mu}$ for the $pp \rightarrow Z'b(b)\mu^+\mu^-b(b)$ process. We show the results for $M_{Z'} = 200, 500$ and 1000 GeV at $\sqrt{s} = 14$ TeV. Each curve is plotted for the corresponding $g_{\mu\mu}$ range taken from Table 1, which is determined by flavor and trident constraints.

requirement of $b$-tagged jets helps to reduce the $\mu^+\mu^-jj$ background. In employ the $p_T$ dependent $b$-tag efficiency ($\epsilon_b$) for the $b$-jets is $\epsilon_b = 0.85 \tanh(0.0025 \, p_T) \left( \frac{25.0}{1 + 0.063 \, p_T} \right)$. The misidentification efficiency functions for the $c$-jets ($\epsilon_c$) and that of the other light quark and gluon jets ($\epsilon_j$) have the form, $\epsilon_c = 0.25 \tanh(0.018 \, p_T) \left( \frac{1}{1+0.0013 \, p_T} \right)$ and $\epsilon_j = 0.01 + 0.000038 \, p_T$ respectively [58].

To further optimize the signal selection cuts, we study the distributions of selected kinematic variables. First, we study the transverse momentum distributions of the two muons. In the signal events these two muons originate from the decay of a heavy $Z'$, while for the standard model background, they originate from the Drell-Yan process, from the decay of $t(\bar{t})$ in top pair production process. For the signal, we show the distributions for two representative mass points $M_{Z'} = 200$ GeV and 500 GeV. Since the muons in the signal come from the decay of a heavy $Z'$, thus they are expected to have high transverse momentum. In comparison, the $p_T$ spectrum of muons for the SM background processes are expected to peak at relatively lower values. In Figure 5, the $p_T$ distributions of the leading ($\mu_1$) and sub-leading ($\mu_2$) muons are contrasted between the signal and the background. We find that cutting on $p_T(\mu_1) > 90$ GeV, and $p_T(\mu_2) > 50$ GeV allows us to efficiently discriminate the signal over the SM background.

We now construct the kinematic variable $R$ defined as a ratio of the missing transverse energy
Figure 5: Normalized transverse momentum ($p_T$) distributions of the leading (left) and sub-leading (right) muons for the signal ($M_{Z'} = 200$ and 500 GeV) and relevant SM backgrounds. The values of $g_{\mu\mu}$ and $g_{bb}$ are 0.20(0.48) and $4.2 \times 10^{-3}(1.10 \times 10^{-2})$ for $M_{Z'} = 200(500)$ GeV, respectively.

For the signal, $E_T$ can come only from $p_T$ mismeasurement of muons and $b$-jets, whereas for the $t\bar{t}$ background, $E_T$ comes from the neutrinos in the leptonic decay of $W^\pm$. In Figure 6 we show the normalized distribution of $R$. For this reason, for the signal, $R$ peaks at a lower value while for the $t\bar{t}$ background the distribution tends to peak at a higher value of $R$. We find that the cut $R < 0.2$ allows one to significantly reduce the $t\bar{t}$ background.

Figure 6: Normalized $R = \frac{E_T}{M_{\mu^+\mu^-}}$ distribution for signal and backgrounds.
Finally we require the invariant mass of the muon pair to be in the window around the $Z'$ peak as dictated by,

$$|M_{\mu^+\mu^-} - M_{Z'}| < 6\Gamma_{Z'}$$

where $\Gamma_{Z'}$ is the width of the $Z'$ resonance. This cut is instrumental in further reducing the $\mu^+\mu^- + 1b(2b)$ and $\mu^+\mu^- + jj$ backgrounds as for these process the invariant mass of the muon pair peaks around the $Z$ boson mass. The invariant mass distributions are depicted in Figure 7.

Figure 7: Normalized invariant mass distributions of the muon-pair for signal and backgrounds.

Table 2 summarizes the cuts discussed above and quantifies the effect of each cut on the signal and dominant backgrounds. Using these results, the signal significance can be determined from the formula [59]

$$S = \sqrt{2 \left[ (S + B)\ln \left(1 + \frac{S}{B}\right) - S \right]} \quad (3.3)$$

where $S(B)$ are the number of signal (background) events after all the cuts. For calculating the significance, the signal and the backgrounds have been multiplied by respective k-factors to account for the next-to-leading-order (NLO) corrections. For the signal and $\mu^+\mu^- + 1b(2b)$ backgrounds we use the k-factor of 1.38 [60], while for $t\bar{t}$ and $\mu^+\mu^- jj$ backgrounds we use the k-factors of 1.40 [61] and 1.15 [62], respectively.

Based on the results in Table 2, we can calculate the signal significance for two particular benchmark points, assuming the integrated luminosity of 300(3000) fb$^{-1}$:

$$M_{Z'} = 200 \text{ GeV}, \quad g_{\mu\mu} = 0.20, \quad g_{bb} = 4.2 \times 10^{-3} : \quad S = 8.5 \ (27),$$
$$M_{Z'} = 500 \text{ GeV}, \quad g_{\mu\mu} = 0.48, \quad g_{bb} = 1.1 \times 10^{-2} : \quad S = 6.1 \ (19). \quad (3.4)$$

These benchmarks highlight the good prospect of observing the $Z'$ in this final state in the coming LHC runs. A broader set of results is shown in Figure 8, where the signal significance for several
representative values of $M_{Z'}$ is plotted as a function of the coupling $g_{\mu \mu}$. One can see that the discovery potential in this final state is more more pronounced for lower $g_{\mu \mu}$ which corres to higher $g_{bb}$. As expected, the discovery potential quickly diminishes with the increasing $M_{Z'}$. Nevertheless, a 5$\sigma$ discovery is possible in this channel for $M_{Z'} \lesssim 500$ GeV with 300 fb$^{-1}$ luminosity at $\sqrt{s} = 14$ TeV LHC, assuming the values of $g_{\mu \mu}$ and $g_{bb}$ preferred by the $b \to s\mu\mu$ anomalies and allowed by low-energy constraints. In the same conditions, a 3$\sigma$ discovery is possible for $M_{Z'} \lesssim 1$ TeV.

### Table 2: The signal and background cross sections for the ($\mu^+\mu^- + 1b(2b)$) process after each cut for $\sqrt{s} = 14$ TeV. The values of $g_{\mu \mu}$ and $g_{bb}$ are 0.20(0.48) and $4.2 \times 10^{-3}(1.10 \times 10^{-2})$ for $M_{Z'} = 200(500)$ GeV, respectively.

| Process                  | Preselection | $p_T(\mu_{1,2}) > 90(50)$ GeV | $R < 0.2$ | $|M_{\mu^+\mu^-} - 200$ GeV$| < 6\Gamma_{Z'}$ | $|M_{\mu^+\mu^-} - 500$ GeV$| < 6\Gamma_{Z'}$ |
|--------------------------|--------------|-------------------------------|-----------|------------------|------------------|
| $t\bar{t}$               | 2602.00      | 409.49                        | 126.63    | 6.12             | 2.49             |
| $\mu^+\mu^- + 1b(2b)$    | 13439.61     | 433.00                        | 207.04    | 2.28             | 0.11             |
| $\mu^+\mu^- + 2j$        | 16312.64     | 1162.65                       | 543.55    | 7.61             | 1.75             |
| Total Background          | 32354.25     | 2005.14                       | 877.22    | 16.01            | 4.35             |
| Signal: $M_{Z'} = 200$ GeV| 3.93         | 2.73                          | 2.55      | 2.01             | -                |
| Signal: $M_{Z'} = 500$ GeV| 1.06         | 1.05                          | 1.02      | -                | 0.76             |

#### 3.2 $pp \to Z'\mu^\pm + \not{E}_T \to 3\mu + \not{E}_T$ channel

We move to discussing another possible signature of the $Z'$ particle: tri-muon plus missing energy final state. This final state in arises when the $Z'$ is radiated from $\mu^\pm$ or $\nu_\mu(\bar{\nu}_\mu)$ in $pp \to W^{\pm*} \to Z'\mu^\pm\nu_\mu(\bar{\nu}_\mu)$, followed by $Z' \to \mu^+\mu^-$ decay. As stated earlier, in this case both production and decay of the $Z'$ is controlled by its coupling $g_{\mu \mu}$ to the lepton sector. Thus this channel is best suited for probing the parameter space region with relatively higher values of $g_{\mu \mu}$.

Similarly to the $\mu^+\mu^- + 1b(2b)$ analysis in the previous subsection, we generate signal events in MadGraph with the following preselection cuts:

$$\Delta R_{jj, bb, b\ell, j\ell} > 0.4, \quad R_{\ell\ell} > 0.2, \quad p_T(j, b, \ell) > 10 \text{ GeV}, \quad |\eta_{j, b, \ell}| < 2.5.$$  \hspace{1cm} (3.5)

In Figure 9 we show the dependence of the leading order signal cross section of the coupling $g_{\mu \mu}$ after imposing the preselection cuts, for three representative values of $M_{Z'} = 200$, 300 and 500 GeV.

For the final state in question we can have the following SM processes that contribute to the background: $WZ + jets$, $ZZ + jets$, $WW+jets$, $t\bar{t}$, $Z +jets$. Out of these, $WZ + jets$ and $ZZ + jets$ are the irreducible backgrounds. $t\bar{t}$ can contribute to the background when each top quark decays leptonically: $t \to b\nu_\mu\mu$, and the third muon arises from the semileptonic decay of one of the $b$-quarks. Other sub-dominant contributions arise from $t\bar{t}V$ ($V = W^\pm, Z$) or $WWZ, WZZ$ channels [63].

To optimize our signal versus background discrimination, we demand our final state to be comprised of exactly three muons with two muons of the same sign and the third muon of the opposite sign along with missing energy ($\not{E}_T$). We also impose a $b$-veto on the final state which
Figure 8: Significance vs. $g_{\mu\mu}$ for $M_{Z'} = 200(8a)$, $300(8b)$, $500(8c)$, $750(8d)$ and $1000(8e)$ GeV for $\mu^+\mu^- + 1b(2b)$ channel at $\sqrt{s} = 14$ TeV. The dashed lines represent the error band in Significance curves after including systematics $\sim 10\%$ in the background estimates. The dark shaded region is the one allowed at $1\sigma$ CL by combining the constraints from $B$-meson anomalies, neutrino trident and $B \to D\nu l$.

helps us to reduce the $t\bar{t}$ background. For the two opposite sign dimuon pairs in the final state,
we require their invariant masses, $M_{1\text{OSD}}, M_{2\text{OSD}}$ to satisfy

$$M_{1\text{OSD}} < 75 \text{ GeV} \quad \text{or} \quad M_{2\text{OSD}} > 105 \text{ GeV}.$$\hfill (3.6)

This helps to exclude the background contribution where the opposite sign muon pair(s) arise from $Z$ resonance. We also impose $M_{1\text{OSD}} > 12 \text{ GeV}$ to suppress the Drell-Yan background [63]. With the above criteria, the dominantly surviving background contribution comes from $WZ$+jets.

In our analysis we assume that the $Z'$ mass is greater than the $Z$ and $W^\pm$ boson masses. Thus, the muons in the signal are expected to have higher $p_T$ than those coming from the decay of the $Z$ or $W^\pm$ bosons in the SM backgrounds. The comparative distributions of the transverse momenta of the the leading ($\mu_1$), sub-leading ($\mu_2$) and sub-sub-leading muons ($\mu_3$) in the final state for the signal and backgrounds are shown in Figure 10. To enhance the signal over background ratio we impose the following cuts

$$p_T(\mu_1) > 100 \text{ GeV}, \quad p_T(\mu_2) > 70 \text{ GeV}, \quad p_T(\mu_3) > 40 \text{ GeV}.$$\hfill (3.7)

Finally, in Figure 11 we compare the $E_T$ distributions of signal and the $WZ$+jets background. The missing energy for the background comes from the leptonic decay of the $W^\pm$ boson in $WZ$+jets or from mismeasurement of leptons or jets in the Drell-Yan process. As a result, the distribution of $E_T$ peaks at around half of the $W^\pm$ mass for the background, whereas for the signal it is shifted towards higher values. In our analysis we impose the cut $E_T > 60 \text{ GeV}$ which provides an optimal cut capturing the relatively long tail in the signal and avoiding the peak in the $WZ$+jets background.

Figure 9: Signal cross-section at $\sqrt{s} = 14 \text{ TeV}$ for $3\mu + \not\!E_T$ channel as a function of $g_{\mu\mu}$ for $M_{Z'} = 200, 300$ and $500 \text{ GeV}$. 

![Signal cross-section plot](image-url)
Figure 10: Normalized transverse momentum ($p_T$) distributions of the leading (10a), sub-leading (10b) and sub-sub-leading (10c) muons for the $3\mu + \not{E}_T$ final state. Signal distributions are for $M_{Z'} = 200$ GeV, $g_{\mu\mu} = 0.20$, $g_{bb} = 4.2 \times 10^{-3}$, and for $M_{Z'} = 500$ GeV, $g_{\mu\mu} = 0.48$, $g_{bb} = 1.10 \times 10^{-2}$). We also show the analogous distributions for the $WZ$ background.

We summarize the above discussed cut flow in Table 3 for our two representative benchmark points. Given these results, we can calculate the signal significance for our 2 benchmark points, assuming the integrated luminosity of 300(3000) fb$^{-1}$:

$$M_{Z'} = 200 \text{ GeV}, \quad g_{\mu\mu} = 0.20, \quad g_{bb} = 4.2 \times 10^{-3} : \quad S = 1.6 \quad (5.0),$$

$$M_{Z'} = 500 \text{ GeV}, \quad g_{\mu\mu} = 0.48, \quad g_{bb} = 1.1 \times 10^{-2} : \quad S = 0.4 \quad (1.3). \quad (3.8)$$

The projected significance for our analysis in the $3\mu + \not{E}_T$ channel as a function of the coupling $g_{\mu\mu}$ is portrayed for $M_{Z'} = 200(12a)$, 300(12b) and 500(12c) GeV in Figure 12. For the significance calculation signal and background have been scaled by k-factors of 1.25 [64] and 1.83 [65] respectively. Note that in this case, and unlike in the previously discussed $\mu^+\mu^- + 1b(2b)$ channel,
Figure 11: Normalized missing energy ($E_T$) distribution for the $3\mu + E_T$ final state. We show the distribution for the signal for $M_{Z'} = 200$ GeV, $g_{\mu\mu} = 0.20$, $g_{bb} = 4.2\times10^{-3}$, and for $M_{Z'} = 500$ GeV, $g_{\mu\mu} = 0.48$, $g_{bb} = 1.1 \times 10^{-2}$. We also show the analogous distributions for the $WZ$ background.

Table 3: Effective cross-section at $\sqrt{s}=14$ TeV for both signal and background for ($3\mu + E_T$) channel after each cut described in the next. The signal benchmarks correspond to the couplings $g_{\mu\mu} = 0.20$, $g_{bb} = 4.2\times10^{-3}$ for $M_{Z'} = 200$ GeV, and $g_{\mu\mu} = 0.48$, $g_{bb} = (1.10 \times 10^{-2})$ for $M_{Z'} = 500$ GeV.

the significance increases with increasing $g_{\mu\mu}$. This demonstrates the complementarity of the two final states discussed in this paper.

4 Comparison with dimuon searches

Our $Z'$ model leads to additional LHC signatures besides those studied in Sections 3.1 and 3.2. One is the 4 muon final state produced in the process $pp \rightarrow Z \rightarrow 4\mu$ where the Z boson decays to a muon pair and an on-shell or virtual $Z'$ is radiated off a muon and subsequently decays into pair of muons. This is however relevant only for fairly low $Z'$ masses, $5 \lesssim M_{Z'} \lesssim 70$ GeV [10,46,49], which are outside of our direct interest in this paper. For a heavier $Z'$, the strongest constraints comes from dimuon resonance searches, $pp \rightarrow Z' \rightarrow \mu^-\mu^+$ [32, 41]. In our scenario, $Z'$ is dominantly produced through its couplings to bottom quarks. Its branching fraction into muons depends on $g_{\mu\mu}$, $g_{bb}$ and $M_{Z'}$, and it is typically significant in the interesting parameter space of the model. Other than to muons, $Z'$ may also decay into top and bottom quarks and into neutrinos, however
Figure 12: Significance in the $3\mu + E_{T}$ channel as a function of $g_{\mu\mu}$ for $M_{Z'} = 200(12a)$, $300(12b)$ and $500(12c)$ GeV for $\sqrt{s} = 14$ TeV. The dashed lines represent the error band for the significance curves after including systematics $\sim 10\%$ in the background estimates. The dark shaded region is the one allowed at 1$\sigma$ CL by combining the constraints from $B$-meson anomalies, neutrino trident and $B \rightarrow D \nu l$.

these channels are less competitive. In particular, we have verified that the constraints from dijet resonance searches at the LHC [66, 67] are much weaker than those we obtain from the dimuon resonance searches.

Figure 13 illustrates constraints on the parameter space of the model from dimuon resonance searches. The blue band shows the range of $g_{\mu\mu}$ excluded at 95% CL by the ATLAS analysis at 13 TeV with 139 fb$^{-1}$ of data [68, 69]. We show the exclusion region for $M_{Z'} = 300$ GeV and 500 GeV, assuming the coupling $g_{bb}$ is determined by the central value of the best fit to the $b \rightarrow s\ell\ell$ anomalies in Eq. (2.2). We can see that the regions with smaller $g_{\mu\mu}$ (hence larger $g_{bb}$) are disfavored; in particular the region preferred by the global fit to low-energy data is excluded by the LHC. Nevertheless, an important chunk of the parameter space remains allowed at 2$\sigma$ by all existing LHC and low-energy analyses. Those region will be probed in the future LHC runs.

Furthermore, from Figure 13 we learn that the dimuon and $2\mu + b$ searches probe similar regions of the parameter space, and they exhibit a similar sensitivity. This is not an accident, as the two
signals are closely related, and there is an overlap between the dimuon resonance and the $2\mu + b$ signal regions. We note however that dimuon resonances are predicted by multiple new physics scenarios. Conversely, observing a signal in the $2\mu + b$ channel would be a spectacular confirmation that the newly found resonance could explain the $b \to s\ell \ell$ anomalies.

On the other hand, in Figure 13 we observe that the $3\mu + E_T$ process probes a complementary region of the parameter space compared to the $2\mu + b$ channel or generic dimuon resonance searches. Combining information from all of these channels will allow one to completely exclude the parameter space of our model with $M_{Z'} \lesssim 500$ GeV. Heavier $Z'$ resonances may escape discovery at the LHC in the parameter space preferred by the $b \to s\ell \ell$ anomalies.

![Figure 13](image_url)

Figure 13: The parameter range of our model excluded at 95% CL by the ATLAS dimuon resonance search [68, 69] at $\sqrt{s} = 13$ TeV with 139 fb$^{-1}$ (light blue band) for $M_{Z'} = 300$ GeV (13a) and $M_{Z'} = 500$ GeV (13b). This is compared with the signal significance expected in the $2\mu + 1b(2b)$ (red) and $3\mu + E_T$ (blue) channels for the same collision energy and luminosity. The brown region is preferred at 1σ CL by combining the constraints from $b \to s\ell \ell$ anomalies, the neutrino trident production, and $B \to D(\ast)\ell\nu$ processes.

## 5 Summary and Conclusions

In this work we have analyzed the LHC discovery prospects of a new massive spin-1 particle ($Z'$) in a model explaining the $b \to s\ell^+\ell^-$ anomalies. We focused on the model proposed in Ref. [37] where tree-level exchange of the $Z'$ contributes to $b \to s\mu^+\mu^-$ processes, and can explain in particular the apparent violation of lepton flavor universality encoded in the $R_{K(\ast)}$ observables. In this model the $Z'$ has sizable couplings to left-handed bottom quarks and muons, as well as their $SU(2)_W$ partners. Therefore it can be produced on its own via $b\bar{b}$ fusion and decay into a muon pair, showing up at the LHC as a dimuon resonance. In addition, the $Z'$ can be produced in association with another SM particle when it is radiated off a bottom, top, muon, and neutrino legs. While the dimuon resonance signature has been previously studied in this context, the associated production is less
explored. In this paper we identified two promising signatures of the associated $Z'$ production: $pp \to Z' + 1(2)b$ with $Z'$ radiated of a bottom quark, and $pp \to Z' \mu^\pm + E_T$ with $Z'$ radiated of a muon or a neutrino. In both cases we focused on $Z'$ decays to $\mu^+\mu^-$. The interesting parameter space of our model can be succinctly characterized by two variables: the $Z'$ mass $M_{Z'}$, and its coupling to muons $g_{\mu\mu}$. The coupling to b-quarks $g_{bb}$ is approximately fixed by the previous two via Eq. (2.2) as a result of fitting the $b \to s\ell^+\ell^-$ anomalies. From Eq. (2.2) $g_{bb}$ and $g_{\mu\mu}$ are anti-correlated. We find that the $pp \to Z' + b$ channel is sensitive to lower values of $g_{\mu\mu}$, as the $Z'$ production cross section is proportional $g_{bb}^2$. This feature is the same as for $Z'$ produced alone, and we find that these two production mechanisms offer a comparable sensitivity to the parameter space of the model. Conversely, $pp \to Z' \mu^\pm + E_T$ is sensitive to larger $g_{\mu\mu}$ as the $Z'$ production cross section is proportional $g_{\mu\mu}^2$. Taken together, the two associated production channels offer a good and complementary sensitivity to a wide range of the parameter space explaining the $b \to s\ell^+\ell^-$ anomalies for $200 \lesssim M_{Z'} \lesssim 500$ GeV.

6 Acknowledgement

NG would like to acknowledge the Council of Scientific and Industrial Research (CSIR), Government of India for financial support. NG and SD would like to thank Abhaya Kumar Swain for useful discussions. This work was supported in part by the CNRS LIA (Laboratoire International Associé) THEP (Theoretical High Energy Physics) and the INFRE-HEPNET (IndoFrench Network on High Energy Physics) of CEFIPRA/IFCPAR (Indo-French Centre for the Promotion of Advanced Research). A.F. is partially supported by the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements No 690575 and No 674896. DKG wishes to acknowledge the hospitalities of the LPT Orsay where this project was initiated and the Theoretical Physics Department, CERN, Switzerland, where part of this project was completed.
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