

# $Z'$ models for the LHCb and $g - 2$ muon anomalies

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We revisit a class of  $Z'$  explanations of the anomalies found by the LHCb collaboration in  $B$  decays, and show that the scenario is tightly constrained by a combination of constraints: (i) LHC searches for di-muon resonances, (ii) perturbativity of the  $Z'$  couplings; (iii) the  $B_s$  mass difference, and (iv) electro-weak precision data. Solutions are found by suppressing the  $Z'$  coupling to electrons and to light quarks and/or by allowing for a  $Z'$  decay width into dark matter. We also present a simplified framework where a TeV-scale  $Z'$  gauge boson that couples to standard leptons as well as to new heavy vector-like leptons, can simultaneously accommodate the LHCb anomalies and the muon  $g - 2$  anomaly.

## I. INTRODUCTION

The Standard Model (SM) has been tested at high precision and proven to be the best description of electroweak and strong interactions. However, we have several observational reasons to believe that the Standard Model is incomplete, for example the inference of non-zero neutrino mass and dark matter, the measurement of the muon anomalous magnetic moment and the results of some recent searches for new physics, as well as some more fundamental matters such as the hierarchy problem.

Many SM extensions have been proposed and often share the presence of an extra  $U(1)'$  gauge symmetry. For instance, superstring theory and grand unification theories provide several examples [1–3]. In supersymmetric grand unification theories, the  $U(1)'$  and SM electroweak breaking scales are usually tied to the soft supersymmetry breaking scale [1, 4, 5]. The TeV focused composite Higgs and Little Higgs models naturally have a  $U(1)'$  extension. The recently constructed “Little Flavor” theory [6–8] extends both gauge and fermion generations, connecting them with “Little Higgs”, so as to provide more experimentally allowed flavor off-diagonal options in both the SM and its extensions.

With the advent of the Large Hadron Collider (LHC) those models have been scrutinized, excluding large re-

gions of parameter space [9]. On the other hand, relatively old discrepancies between data and SM predictions (such as the anomalous magnetic moment of the muon ( $g - 2$ ) or anomalies observed in the flavor sector [10–16, 19], new physics searches in di-lepton [20] and diboson channels [20]) promoted some investigations to test whether models of new physics are capable of accommodating them. In this work, we will discuss how one can accommodate the anomalies in a simplified framework, focusing primarily on resolving the flavor anomalies and  $g - 2$ . The latter measurement exhibits  $3.6\sigma$  evidence for new physics contributions to the muon anomalous magnetic moment which has been measured with high precision [21–24]. However, there are sizable uncertainties surrounding the hadronic corrections to  $g - 2$  [25]. Thus, it is naive to take the reported deviation at face value in the light of such large theoretical errors. One could imagine taking different conservative approaches. For instance, one could try to accommodate the measured value at the  $2\sigma$  level, or one could derive limits on the mediator/couplings involved in the  $g - 2$  loop diagram by assuring that the contribution is smaller than the uncertainty in the measurement. Here we will take the former approach and comment on possible bounds if the latter approach had been followed.

Moreover, flavor physics poses some intriguing questions. Rare  $B$  decays mediated by the flavor-changing neutral  $b \rightarrow s$  transition are sensitive probes for beyond the Standard Model (BSM) physics. The decay  $B \rightarrow K^*(\rightarrow K\pi)\mu^+\mu^-$  has a few observable quantities including the branching ratio and the angular distribution of its four-body final state. The measurement has been performed at  $B$  factories [26], Tevatron experiments [27, 28], LHCb [29], ATLAS [29] and CMS [30].

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According to some authors, the LHCb measurements contain deviations from SM expectations which require non-trivial explanation, since several observables in  $B \rightarrow K^*(\rightarrow K\pi)\mu^+\mu^-$  as well as in other decays such as  $B_s \rightarrow \mu^+\mu^-$ ,  $B \rightarrow K\mu^+\mu^-$ ,  $B \rightarrow X_s\gamma$  agree with SM predictions, within uncertainties. Moreover the low value of recent measurements  $R_K = \text{BR}(B \rightarrow K\mu^+\mu^-)/\text{BR}(B \rightarrow Ke^+e^-)$  suggest beyond the standard model lepton non-universality.

Hence, we have exciting and puzzling signals at our disposal but the situation is far from clear, and attempts that account for one anomaly at time in the context of a heavy  $Z'$  boson have been put forth [11, 12, 16–18]. Here we revisit such  $Z'$  scenarios using a search for di-muon resonances from ATLAS and perturbativity of the  $Z'$  coupling, along with updated constraints on the  $B_s$  mass difference to show that a class of  $Z'$  models motivated by the LHCb anomaly are disfavored by data, unless the  $Z'$  is rather heavy and strongly coupled. Solutions are found by suppressing the  $Z'$  coupling to electrons and to light quarks and/or by allowing for a  $Z'$  decay width into dark matter. Values of the  $Z'$  mass,  $M_{Z'} \approx 1.9$  TeV, suggested by the diboson anomaly become allowed.

Lastly, we propose a simplified model capable of simultaneously addressing the discrepant anomalous magnetic of the muon and flavor physics anomalies in a similar vein to Refs. [9, 31–33]. The model evades other existing limits from precision flavor physics while predicting interesting LHC phenomenology.

## II. $B \rightarrow K^*\mu^+\mu^-$ ANOMALY IN $Z'$ MODELS

Recent LHCb measurements of the angular distributions in the  $B \rightarrow K^*\mu^+\mu^-$  decay and the low value of  $R_K = \text{BR}(B \rightarrow K\mu^+\mu^-)/\text{BR}(B \rightarrow Ke^+e^-)$  suggest deviations from Standard Model (SM) expectations [10]. New physics can fit such anomalies, provided that it generates the following effective operator

$$\mathcal{L} \supset \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V_{ts}^* V_{tb} \Delta C_9 (\bar{s}\gamma_\alpha P_L b) (\bar{\mu}\gamma^\alpha \mu) + \text{h.c.}, \quad (1)$$

with coefficient  $\Delta C_9 \approx -1.07 \pm 0.26$  [11, 12, 34, 35].

In order to generate this operator, Ref. [19] considered a ‘toy model’ where the Standard Model is extended by adding a massive  $Z'$  that couples to leptons and to  $\bar{b}s$ . Going to more firm theoretical grounds, we extend the SM gauge group adding one extra abelian factor  $U(1)_X$ , which introduces a massive  $Z'$  boson. If the  $U(1)_X$  charges of the left-handed quark doublets are flavor-dependent, the  $Z'$  acquires flavor-violating coupling to left-handed down quarks, assuming that the CKM matrix mostly comes from rotating down quarks to their mass-eigenstate basis (this is a plausible assumption given that mass hierarchies are large in the up-quark sector than in the down sector, typically leading to smaller mixings). Motivated by these considerations and by Eq. (1) we

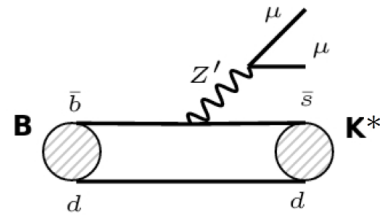


FIG. 1.  $Z'$  contribution to  $B \rightarrow K^*\mu^+\mu^-$  decay

thereby consider the following minimal Lagrangian:

$$\mathcal{L} \supset \frac{Z'^\mu}{2 \cos \theta_W} \left[ g_\mu (\bar{\mu}\gamma_\mu \mu + \bar{\nu}_\mu \gamma_\mu P_L \nu_\mu) + g_t (\bar{t}\gamma^\mu P_L t + \bar{b}\gamma^\mu P_L b) + g_q \sum_q (\bar{q}\gamma^\mu P_L q) + (g_t - g_q)(V_{ts}^* V_{tb} \bar{s}\gamma_\mu P_L b + \text{h.c.}) \right] \quad (2)$$

where  $P_L = (1 - \gamma_5)/2$  projects over left-handed fields and the sum runs over  $q = \{u, d, s, c\}$ . We assumed a common  $Z'$  coupling  $g_q$  to 1st and 2nd generation left-handed quarks (in order to avoid large flavour violation among light quarks), a coupling  $g_t$  to 3rd generation left-handed quarks  $t, b$ , and one vectorial coupling  $g_\mu$  to muons. Then, the coupling to  $\nu_\mu$  arises because of  $SU(2)_L$  invariance, and the coupling to  $\bar{b}s$  (as well as similar terms, that have been omitted) arises after performing the CKM rotation to mass eigenstates in the down sector. Fig. 1 shows a process whereby these effective  $Z'$  couplings can fit the  $B$  anomalies generating the effective operator in Eq. (1) with coefficient

$$\Delta C_9 = -\frac{\pi g_\mu (g_t - g_q)}{2\sqrt{2}G_F M_{Z'}^2 \alpha \cos^2 \theta_W}. \quad (3)$$

### A. Constraints

Here we discuss general limits on neutral vector bosons that are of interest to the LHCb anomaly.

#### 1. $B_s$ mass difference

The existence of a massive  $Z'$  gauge boson alters the prediction of the mass difference ( $\Delta M_{B_s}$ ) of the  $B_s$  meson, whose deviation from the SM expectation can be approximated as [19]

$$\Delta_{B_s} \simeq 3.1(g_t - g_q)^2 \left( \frac{\text{TeV}}{M_{Z'}} \right)^2 \left[ 1 - 0.029 \ln \frac{M_{Z'}}{\text{TeV}} \right], \quad (4)$$

where  $\Delta_{B_s} \equiv \Delta M_{B_s}^{Z'}/\Delta M_{B_s} - 1$ ,  $M_{Z'}$  is the  $Z'$  mass and  $g_t - g_q$  is the coupling between  $Z'$  and  $b, s$  quarks implied by Eq. (2).

Current measurements impose the upper limit

$$|\Delta_{B_s}| < 8.4\% \quad (5)$$

at 95% confidence level [36]. The resulting bound is shown in Fig. 3, and is slightly stronger than in Ref. [19], where the outdated bound  $|\Delta_{B_s}| < 20\%$  was used.

Having assumed that first generation quarks have a common  $Z'$  charge, the ratio between the  $Z'$  correction to  $\epsilon_K$  and to  $\Delta M_{B_s}$  is comparable to the SM prediction for the same ratio.  $\epsilon_K$  then does not lead to an obviously more stringent constraint than the  $\Delta M_{B_s}$  constraint. Given that  $\epsilon_K$  involves extra model-dependent issues, we ignore it in the following.

## 2. Electro-weak precision data

The  $Z'$  gives rise to various corrections to electro-weak precision observables. Had we considered a  $Z'$  coupled to electrons (with a coupling  $g_e$  comparable to  $g_\mu$ , like in Ref. [19]) observables measured at LEP with per mille precision would have been affected at tree level, giving rise to bounds of the form  $g_e^2 M_Z^2 / M_{Z'}^2 < 10^{-3}$ , too strong for our purposes. We instead assumed a  $Z'$  that does not couple to electrons nor to the Higgs doublet, such that it is very weakly constrained and its phenomenology is similar to the muonphilic  $Z'$  studied in [37].

The only observable affected at tree level is  $\nu_\mu$ /nucleon scattering, measured with per cent accuracy by the NuTeV collaboration, which claimed an anomaly in the (neutral current)/(charged current) ratio of deep inelastic  $\nu_\mu$ -nucleon scattering [38]. If this anomaly is not due to underestimated SM uncertainties, new physics can fit the NuTeV anomaly, provided that it generates the following effective operator [39]

$$\mathcal{L} \supset (-38 \pm 14) \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{Q}\gamma^\alpha Q)(\bar{\nu}_\mu\gamma_\alpha P_L\nu_\mu) \quad (6)$$

where  $Q$  are the  $SU(2)_L$  left-handed quark doublets. Although this operator has a structure analogous to the one suggested by the LHCb anomaly, see eq. (1), the coefficient in Eq. (6) is significantly larger. Thereby the  $Z'$  motivated by the LHCb anomaly generates this operator with a coefficient smaller than what is needed to fit the NuTeV anomaly, at least unless one assumes  $|g_t - g_q| \ll g_q$ . Viewing NuTeV data as a one-sided bound, it is safely satisfied in the parameter region of our model which successfully explains the LHCb anomaly.

The precision observables measured with greater than per-mille accuracy are affected only at the loop level. Among them, the most precise measurements are those in the lepton sector. The  $Z'$  affects the  $Z \rightarrow \mu\mu$  width as well as the relative forward-backward asymmetry, measured at LEP. Given that the bound is relatively weak, it is enough for our purposes to estimate it as

$$\Delta_\mu \sim \frac{g_\mu^2}{(4\pi)^2} \frac{M_Z^2}{M_{Z'}^2} < 10^{-3}. \quad (7)$$

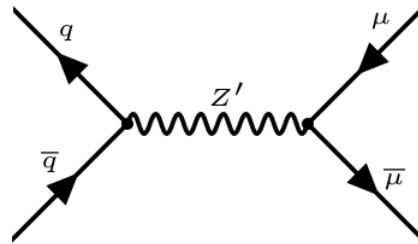


FIG. 2.  $Z'$  contribution to LHC di-muon resonance production.

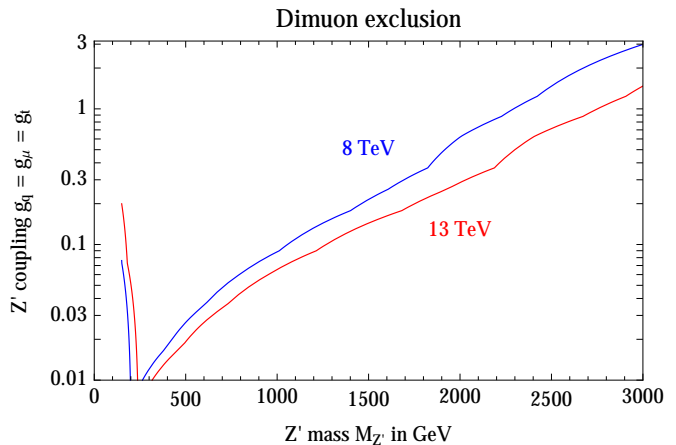


FIG. 3. Upper bound on the  $Z'$  couplings as function of the  $Z'$  mass. We used di-muon resonance search data from an 8 TeV  $20^{-1}$  fb ATLAS analysis [40] and from 13 TeV data.

Furthermore, the anomalous decay moment of the muon (discussed later), and the  $\mu$  decay rate (considered in Ref. [19] as a ‘CKM unitarity bound’) only receive corrections proportional to  $m_\mu^2/M_{Z'}^2$ .

## 3. ATLAS di-muon resonance search

Searches for di-lepton resonances at the LHC have proven to be an excellent probe of models that predict new neutral vector bosons that have sizeable coupling to leptons [42–49]. In particular, bounds on the mediator mass coming from di-lepton searches are more stringent than those from dijets searches in most models due to a reduced background, except for models in which the new neutral vector bosons are leptophobic [50–54]. In order to evaluate the constraints from the  $20 \text{ fb}^{-1}$ , 8 TeV ATLAS data [40] and from 13 TeV first run data [41] with  $3.2 \text{ fb}^{-1}$ . The dilepton invariant mass spectrum is the discriminating factor in both searches, and since no significant deviations from the Standard Model expectation has been observed restrictive bounds were placed. we implemented the model in `Feynrules2.0` [55] and later used `Madgraph5` [56] to simulate signal events. We simulated di-muon pair production with up to one extra jet, and accounted for showering, hadronization, detec-

tion effects and jet clustering using `Pythia8.212` [57] and `Delphes3.0` [58] packages and compared with the background reported in Ref. [40, 41].

Fig. 3 displays the upper bound on  $g_\mu$  as a function of  $M_{Z'}$  for  $g_\mu = g_q = g_t$ . The bound can be rescaled to generic values of the couplings  $g_\mu, g_q, g_t$  taking into account that, in the narrow width approximation, the signal rate scales as

$$\sigma(pp \rightarrow Z' \rightarrow \mu\mu) \propto \frac{g_q^2 g_\mu^2}{g_\mu^2 + 4g_q^2 + 2g_t^2}. \quad (8)$$

#### 4. Perturbativity

Imposing that the gauge coupling of a generic  $Z'$  can be extrapolated up to the Planck energy without hitting Landau poles implies an upper bound on its width

$$\frac{\Gamma_{Z'}}{M_{Z'}} < \frac{\pi}{2} \frac{1}{\ln M_{\text{Pl}}/M_{Z'}} \approx 0.04. \quad (9)$$

This model-independent condition holds because the same diagram generates both the real part of the  $Z'$  propagator (that dictates the renormalization group running) and the imaginary part of the  $Z'$  propagator (that describes the width), with a universal relation among them. New physics at very large energy can affect this bound, making it stronger if extra scalars or fermions charged under the  $U(1)$  are present, and weaker if extra vectors are present such that the  $U(1)$  gets embedded in a non-abelian group.

In the case at hand we have

$$\frac{\Gamma_{Z'}}{M_{Z'}} = \frac{g_\mu^2 + 4g_q^2 + 2g_t^2}{8\pi(2 \cos \theta_W)^2}. \quad (10)$$

This only excludes the upper corners (in red) of the panels in Fig. 4.

Furthermore, as an extra naive and semi-quantitative but reasonable perturbativity condition, we impose that the  $Z'$  gauge couplings to muons,  $g_\mu$ , and to quarks,  $g_q$  (precisely defined by Eq. (2)), must be smaller than  $\approx 1$ . This excludes the region in orange in Figs. 4-5. The reader should keep in mind that this requirement is reasonable but the precise value of the perturbative bound is arbitrary. New physics effects that accommodate the LHCb anomaly can be obtained within the perturbative regime [12]. To the best of our knowledge there is no strongly coupled  $U(1)$  gauge theory that arises naturally, see for instance, Left-Right models [59–63], Little Higgs models [6, 64–66], gauged baryon and lepton number models [51, 53, 67, 68] or 3-3-1 models [69–81].

## B. Combined analysis

We are now ready for a combined analysis.

In Figure 4 we show the region favored at  $\pm 1\sigma$  by the LHCb anomaly (in green), compared to the exclusion bounds discussed before: from  $\Delta M_{B_s}$  (gray regions), from perturbativity (red regions), from di-muon data (magenta regions) and from electroweak precision data (the bounds are so weak that they not appear in the plot). We made plots in the  $(g_\mu, |g_q|)$  plane, assuming  $g_t = 0$  and for a few representative values of  $M_{Z'}$ . In the middle panel we considered  $M_{Z'} = 1.9$  TeV, a value for which a small  $Z' \rightarrow ZZ$  or  $Z' \rightarrow W^+W^-$  decay width (as in [7]) might fit the diboson anomaly [20].

Compared to earlier analyses [19] we used new and updated data, we included di-muon data, we used a different and more solid theoretical framework, we assumed that the  $Z'$  does not couple to electrons (which allows us to fit the  $R_K$  anomaly) and in order to avoid strong electroweak bounds.

These new constraints, and in particular the inclusion of LHC di-muon data, implies that the  $Z'$  models cannot fit the LHCb anomalies, unless the  $Z'$  is heavier than about 2.5 TeV. In such a case, the  $Z'$  should be seen in early run II data. Heavier  $Z'$  bosons need larger gauge couplings, which raises issues with perturbativity.

In view of the strong impact of di-muon data, let us discuss how they can be weakened. The ATLAS di-muon data put limits on the quantity  $\sigma(pp \rightarrow Z') \times \text{BR}(Z' \rightarrow \mu\mu)$ .

One way of weakening the di-muon limits consists in reducing  $\sigma(pp \rightarrow Z')$ , which is proportional to  $g_q^2$ . So far we assumed  $|g_t| \ll |g_q|$  i.e. a  $Z'$  that couples dominantly to light quarks. In the opposite limit  $|g_q| \ll |g_t|$  of a  $Z'$  that couples dominantly to third generation quarks, the  $Z'$  coupling to light quarks is CKM suppressed, and the di-muon bound is no longer constraining. Fig. 4 can be reinterpreted as having  $|g_t|$  (rather than  $|g_q|$ ) on the horizontal axis by just omitting the di-muon bound. Furthermore, in the left panel of Fig. 5 we consider an intermediate situation,  $g_t = -2g_q$ , finding that a  $Z'$  with 1.6 TeV mass becomes allowed.

Another way of reducing the di-muon limits consists in keeping  $g_q$  sizeable and reducing  $\text{BR}(Z' \rightarrow \mu\mu)$ , by assuming that the  $Z'$  has a sizeable branching ratio into Dark Matter particles, as actually predicted in some models [44]. This situation is explored in the middle and right panels of Fig. 5: we see that global solutions are now allowed for  $M_{Z'}$  as light as 1.4 TeV (middle panel). However, in view of the increased total  $Z'$  width, the perturbativity bounds on  $\Gamma_{Z'}/M_{Z'}$  of eq. (9) becomes stronger and start becoming a limiting factor (red regions in Fig. 5).

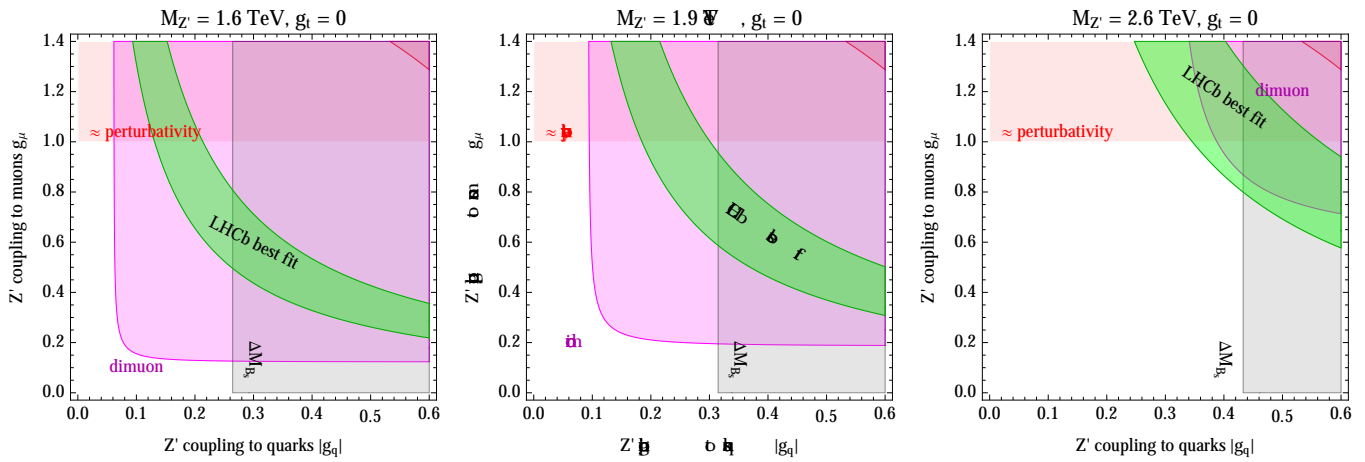


FIG. 4. Region in the plane  $(g_q, g_\mu)$  of  $Z'$  couplings to quarks and to muons that accommodates the LHCb anomaly (in green), superimposed with limits from di-muon data (in magenta), from the  $B_s$  mass difference (in gray) and perturbativity (in red) for different values of the  $Z'$  mass. Electro-weak precision data give a weaker bound on  $g_\mu$  which does not appear in the panels.

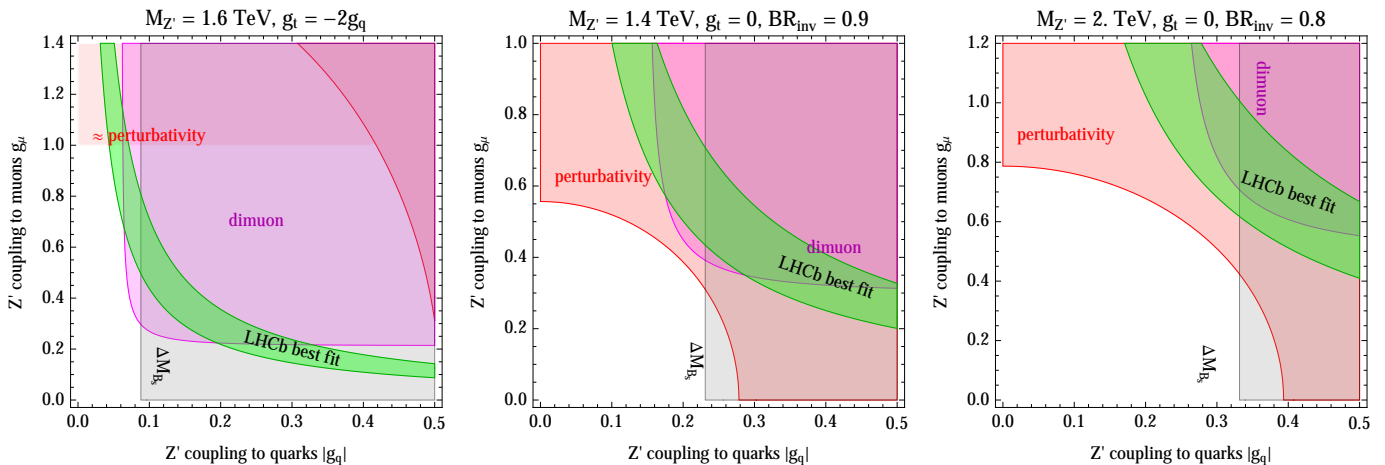


FIG. 5. As in Fig. 4, but adding extra  $Z'$  decay modes into  $t\bar{t}, b\bar{b}$  (left panel) or into invisible modes, such as dark matter (middle and right panels). The presence of extra decay modes suppress the di-muon limits, allowing for global solutions of the LHCb anomalies for lighter values of the  $Z'$  mass.

### III. A NEW SIMPLIFIED MODEL FOR LHCb AND MUON $g - 2$ ANOMALIES

#### A. Framework and Fit to the Anomalies

The muon magnetic moment has been measured in the Brookhaven laboratory, which used a ring of polarized muon beams [23, 24]. The experiment was able to reach a precision with unprecedented sensitivity which intriguingly resulted into a  $3.6\sigma$  excess over the standard model prediction with  $\Delta(g - 2)/2 = (295 \pm 81) \times 10^{-11}$ . Theoretical uncertainties in hadronic corrections (namely hadronic vacuum polarization and light-by-light scattering) blur the significance of the excess, but the  $g - 2$  measurement at Fermilab along with a concerted effort to improve the accuracy of the SM theoretical prediction should decisively clarify the anomaly.

Motivated by this long standing excess and the LHCb anomaly discussed above, we consider a model that extends  $SU(2)_L \otimes U(1)_Y$  with an extra abelian gauge group  $U(1)_X$  and two additional lepton fields: a vector-like lepton electroweak doublet  $(\nu', \ell')$  and vector-like singlet  $\mu'$ . The left-handed part of  $\ell'$ ,  $\ell'_{LH}$ , and the right-handed part of  $\mu'$ ,  $\mu'_{RH}$ , are charged with the quantum numbers  $(2, -\frac{1}{2}, -x)$  and  $(1, -1, -x)$  under  $SU(2)_L \otimes U(1)_Y \otimes U(1)_X$ , respectively. We redefine a SM-like Dirac fermion  $L = (\ell'_{LH}, \mu'_{RH})^T$ .  $L$  can be very heavy since it mostly gets its mass from the vector-like particle mass term  $M_1 \bar{\ell}' \ell' + M_2 \bar{\mu}' \mu'$ . Note that both the SM fermions and new leptons are charged under the new  $U(1)_X$ . For simplicity we assume here that the  $Z'$  gets mass from a different scalar rather than the SM Higgs, so the SM Higgs does not have  $U(1)_X$  charge. This assumption also forbids the new  $Z'$  gauge boson mass eigenstate from mixing with the SM  $Z$  mass eigenstate at tree level. Notice that

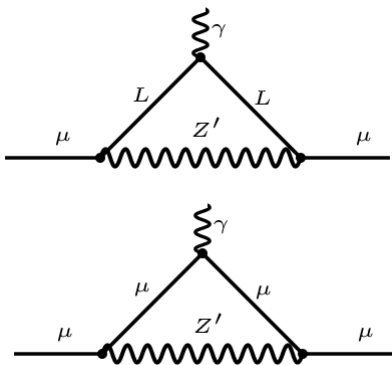


FIG. 6. Diagrams contributing to the muon anomalous magnetic moment. *Upper*: The dominant contribution to  $g - 2$  occurs when both the new charged lepton and the  $Z'$  boson run in the loop. *Lower*: The  $Z'$  correction which is subdominant.

it still allows the new lepton doublet and lepton singlet to have potential Yukawa couplings to the SM Higgs doublet. This leads to deviations in electroweak observables, but these can be easily avoided by a suppression of the vector-like Yukawa couplings.

Consequently, the new charged fermion  $L$  can have a purely vector-like coupling to the  $Z'$  since the left-handed and right-handed fermions have the same  $Z'$  charges and the Lagrangian piece relevant for the muon magnetic moment is

$$\begin{aligned} \mathcal{L}_{\text{eff}} \supset & \bar{\mu}\gamma^\mu (g_v - \gamma_5 g_a) L Z'_\mu + h.c. \\ & + \bar{\mu}\gamma^\mu (g'_{v\mu} - \gamma_5 g'_{a\mu}) \mu Z'_\mu. \end{aligned} \quad (11)$$

In order to account for the LHCb anomaly, a vector coupling to muons is needed. Such a setup can be achieved in several extensions of the SM by simply choosing the left and right-handed field components to transform similarly under the action of  $U(1)_X$  (see Table I of [44] for explicit examples). Under these assumptions, the  $Z'$  possesses only vectorial couplings to the exotic charged lepton and the muon, i.e.  $g_a \equiv 0$ . Notice that there are two diagrams giving rise to corrections to  $g - 2$ , as shown in Fig. 5. One is a diagram containing one new particle only, the  $Z'$ , and another with the exotic charged leptons and the  $Z'$  running in the loop. We have explicitly checked that the  $Z'$  correction to  $g - 2$  is negligible compared to the one involving the new charged lepton. The result is

$$\Delta a_\mu(L) = \frac{1}{8\pi^2} \frac{m_\mu^2}{M_{Z'}^2} \int_0^1 dx \frac{g_v^2 P_v(x) + g_a^2 P_a(x)}{(1-x)(1-\lambda^2 x) + \epsilon^2 \lambda^2 x} \quad (12)$$

where

$$\begin{aligned} P_v(x) &= 2x(1-x)(x - 2(1-\epsilon)) + \lambda^2(1-\epsilon)^2 x^2(1+\epsilon-x) \\ P_a(x) &= 2x(1-x)(x - 2(1+\epsilon)) + \lambda^2(1+\epsilon)^2 x^2(1-\epsilon-x) \end{aligned} \quad (13)$$

where  $M_L$  is the fermion mass running in the loop,  $\epsilon = M_L/m_\mu$  and  $\lambda = m_\mu/M_{Z'}$ . In the  $M_{Z'} \gg M_L$  limit, Eq. (12) becomes

$$\Delta a_\mu(L) = \frac{1}{4\pi^2} \frac{m_\mu^2}{M_{Z'}^2} \left\{ g_v^2 \left[ \frac{M_L}{m_\mu} - \frac{2}{3} \right] + g_a^2 \left[ -\frac{M_L}{m_\mu} - \frac{2}{3} \right] \right\}. \quad (14)$$

It is clear from Eq. (14) that the larger  $M_L$  is, the bigger is the correction to  $g - 2$  from the vectorial coupling. This is due to the fact that there is a necessary mass insertion in the loop correction of  $g - 2$  to flip the chirality. The approximations lose accuracy in the regime where  $M_L$  and  $M_{Z'}$  are comparable and in that case, one should solve Eq. (11) numerically (we did with the help of the Public computer program [82]). In Fig. 7 we present the contribution to the muon anomalous magnetic moment arising from our model for two specific values of the vector coupling,  $g_v = 0.1$  (left panel) and  $g_v = 0.05$  (right panel), respectively, for several  $Z'$  masses. The green band delimits the  $2\sigma$  region that accommodates the muon anomalous magnetic moment. It is clear from Fig. 7 that with TeV scale masses we can accommodate the  $g - 2$  anomaly.

However, in order to simultaneously address the LHCb and  $g - 2$  anomalies, dark matter or visible states should be added in addition to our effective framework. We have shown that the addition of dark matter or other light states to a class of  $Z'$  models opens up a new window to accommodate the LHCb anomaly and the inclusion of an exotic charged lepton that has purely vectorial couplings to the  $Z'$  gauge boson might foot the bill.

Notice that we did not explicitly list couplings between the  $Z'$  gauge boson and the dark matter particle, but this can be easily realised with vector-like Dirac dark fermions, which would play the desired role of relaxing the ATLAS di-muon resonance search constraints. In the left hand panel of Fig. 7,  $Z'$  decays into dark matter are not needed, since the  $Z'$  may decay into new charged leptons instead. The new charged leptons are relatively light with masses of 200 GeV or so, within the reach of the next generation of leptonic colliders. In the right-handed panel of Fig. 7, on the other hand, the  $Z'$  is not heavy enough to decay into the new charged leptons, whose masses are mostly at the TeV scale, to explain muon  $g - 2$  but in agreement with recent collider limits from the LHC [83]. In this case the presence of dark matter or any other light species would be required. We will now turn our attention to existing constraints.

## B. Experimental constraints

As we show above, allowing BSM decay modes of the  $Z'$  allows it to be heavier while still explaining the LHCb anomaly. Allowing the  $Z' L\mu$  coupling allows the  $Z'$  to be heavier while still explaining the  $g - 2$  anomaly. Because the  $Z'$  is allowed to be heavier, other flavor bounds are

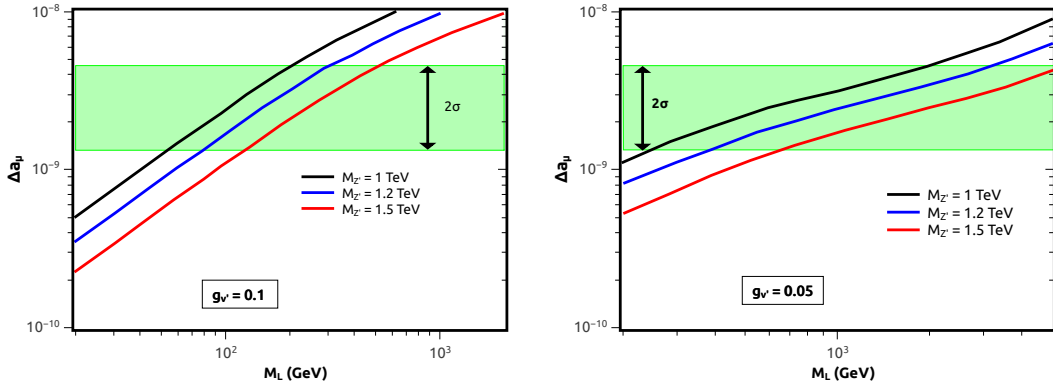


FIG. 7. Correction to the muon magnetic moment arising from the presence of both the  $Z'$  and the new charged leptons. It is clear that for  $g_v = 0.1$ , one needs a relatively light new charged lepton to accommodate  $g - 2$ , whereas for  $g_v = 0.05$ , one can simultaneously address the  $g - 2$  and LHCb anomalies with a TeV scale charged lepton and  $M_{Z'} = 1.2 \sim 1.8$  TeV, whilst remaining compatible with existing limits. A much larger region of parameter space may account for the anomalies once other couplings strengths are used.

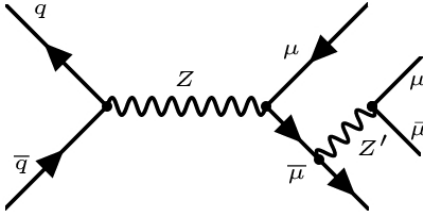


FIG. 8. The  $Z \rightarrow 4\ell$  diagram through a  $Z'$ .

less constraining. Thus, the addition of BSM states to the  $Z'$  leads to a framework that is less constrained.

### 1. $Z \rightarrow 4\ell$

The ATLAS and CMS collaborations measured the branching ratio of the SM  $Z$  decay to four leptons ( $Z \rightarrow 4\ell$ ), finding  $\text{BR}(Z \rightarrow 4\ell) = (4.2 \pm 0.4) \times 10^{-6}$  [84]. This constraint is quite restrictive for our class of  $Z'$  models in the  $M_{Z'} < M_Z$  mass regime [85], which is not the case for our model. The new physics contribution to this process that would arise from replacing the  $Z$  in the second vertex by the  $Z'$  is highly (as shown) is mass suppressed.

### 2. $Z \rightarrow \mu\mu$

The precisely measured  $Z \rightarrow \mu\mu$  decay receives corrections from diagrams with the heavy charged lepton and the  $Z'$  gauge boson running in the loop as shown in Fig. 9. This decay is naturally suppressed due to the TeV scale masses of both charged and  $Z'$  gauge boson.

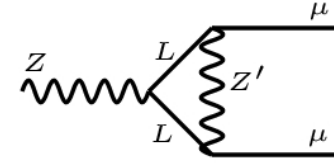


FIG. 9. The  $Z \rightarrow \mu^+\mu^-$  decay diagram via  $Z'$ .

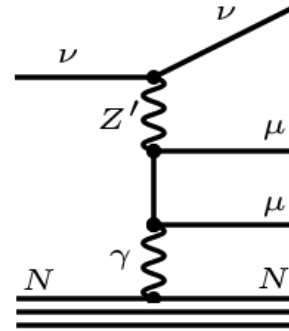


FIG. 10. Neutrino trident process that leads to constraints on the  $Z^\mu$  coupling strength to neutrinos-muons, namely  $M_{Z'}/g_{v\mu} \gtrsim 750$  GeV.

### 3. Neutrino trident

$Z'$  vector fields that only or mostly couple to leptons are constrained by the process shown in Fig. 10 [86]. In the heavy mediator regime, one can write down a dimension six effective Lagrangian operator  $g_{v\mu}^2 (\bar{\mu}\gamma^\mu\mu)(\bar{\nu}\gamma_\mu P_L\nu)/M_{Z'}^2$ , and derive a bound on a function of the coupling and  $Z'$  mass, namely  $M_{Z'}/g_{v\mu} \gtrsim 750$  GeV [86]. This bound is safely obeyed by our model.

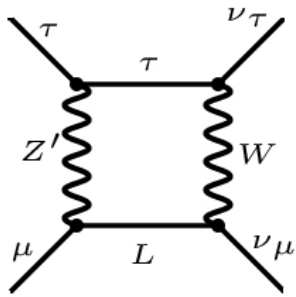


FIG. 11. One of the box diagramd giving a correction to the  $\tau \rightarrow \mu\nu_\tau\bar{\nu}_\mu$  with the new BSM  $Z', L$ .

#### 4. $\tau$ decay

The  $Z'L\mu$  coupling leads to a correction to  $\tau$  decay through the one-loop box diagram in Fig. 11:

$$\frac{\text{BR}(\tau \rightarrow \mu\nu_\tau\bar{\nu}_\mu)}{\text{BR}(\tau \rightarrow \mu\nu_\tau\bar{\nu}_\mu)_{\text{SM}}} \simeq 1 + \delta. \quad (15)$$

Comparing the experimental value [87] with the SM prediction for the tau lifetime [85], we find

$$\delta = (7.0 \pm 3.0) \times 10^{-3}. \quad (16)$$

We can approximate the box diagram contribution from the extra  $Z', L$ , in the  $M_L \sim M_{Z'} \gg M_W$  limit as

$$\delta \sim \frac{g'_v g m_W^2}{4\pi^2 M_{Z'}^2}. \quad (17)$$

The interaction strength between  $W$ ,  $L$  and  $\nu$  is fixed by  $\text{SU}(2)_L$  invariance to be  $g$ , the  $\text{SU}(2)$  gauge coupling strength. For  $g'_\mu \lesssim 0.1$ , our framework satisfies the current upper limits on  $\delta$ .

#### 5. $Z'$ decays into new particles

In our scenario, the  $Z'$  decays SM particles, but also into the new lepton  $L$ , giving rise to the decay channels which include  $Z' \rightarrow \mu L$  and  $Z' \rightarrow LL$ , followed by  $L \rightarrow W\nu_\mu$ . Thus, the  $Z'$  might produce, in addition to di-muon resonances,  $WW$  plus missing transverse momentum ( $\cancel{p}_T$ ), or  $W\mu\cancel{p}_T$  signatures that we plan to investigate in future. The  $W$ 's will then subsequently decay either into either a boosted hadronic  $W$ -jet or into a lepton plus  $\cancel{p}_T$ .

### C. Potential ultra-violet completions

In our simplified framework, we chose the heavy leptons to be vector-like in order to give them large masses, whilst avoiding constraints on fourth generation chiral

particles. The electroweak precision tests are still reasonably well satisfied since contributions from fermions with opposite chirality cancel.

We dub this as an “effective  $Z' + L$ ” setup, as distinct from a conventional minimal  $Z'$  model [88]. The extra lepton fields are introduced to potentially incorporate different flavor scenarios. The couplings in this model (such as family non-universal couplings) can arise in different ways in explicit models [89], vector-like fermion extensions [90], or considering an effective approach where all  $Z'$  couplings are only be generated by higher dimensional operators following the same arguments as in Ref. [91]. We summarize different types of effective couplings between the  $Z'$  and fermions below:

1. SM flavor diagonal and off-diagonal  $Z'$  couplings. They have the potential to explain the LHCb anomaly.
2. SM leptons and BSM lepton  $Z'$  couplings giving rise to the muon anomalous magnetic moment deviations.
3. New heavy lepton couplings to  $Z'$ : these open up new decay channels for  $Z'$  searches, reducing the decay branching ratio to SM fermions and weakening  $Z'$  leptonic resonance searches.

The effective approach allows us to treat all three types of couplings as free parameters, although in most of the UV completed models these parameters will be related. This “effective  $Z'+L$ ” can arise from certain types of “Little Higgs” model, or non-minimal supersymmetry. One of the reasons to have extra vector-like fermions is to decouple the new  $Z'$  from the SM fermions. In the “Little Flavor” [6–8] model,  $[\text{SU}(2) \times \text{U}(1)]^2$  breaks down to a diagonal  $[\text{SU}(2) \times \text{U}(1)]_{\text{SM}}$  subgroup via the little Higgs. The additional  $\text{SU}(2)$  (predicting mixed  $ZWW'$  vertices) can provide a possible explanation for the di-boson anomaly [20]. The SM fermions and extra vector-like fermions are charged under different copies of the original  $[\text{SU}(2) \times \text{U}(1)]$  and end up both charged under  $[\text{SU}(2) \times \text{U}(1)]_{\text{SM}}$ . This leaves the SM couplings of fermions and gauge bosons unaltered, whilst ensuring a skew factor in the BSM couplings of heavy fermions and gauge bosons. A similar mechanism also decouples the Kaluza-Klein resonances of gauge bosons and fermions in Randal-Sundrum models. For more discussion on the effective  $Z'$  couplings, see Ref. [91].

## IV. CONCLUSIONS

We revisited the LHCb anomalies in  $B$  decays in the context of models with an extra  $Z'$  that couples to quarks and muons, finding that such an interpretation is tightly constrained by the ATLAS di-muon resonance search, by the  $B_s$  mass difference, and by perturbativity arguments. We have shown how the LHCb anomaly can be fitted compatibly with all constraints by a  $Z'$  that dominantly



couples to third-generation quarks, or that has a sizeable branching ratio into dark matter or similar species.

and  $g - 2$  anomalies.

## ACKNOWLEDGMENTS

We later proposed an effective  $Z'$  model with extra TeV scale vector-like fermions, finding that it can reconcile both the measurement of  $g - 2$  and the LHCb anomaly while obeying existing limits such as those coming from  $\tau$ -decay, the neutrino trident process and  $Z \rightarrow 4\ell$ . Such  $Z'$  is a viable option to explain the LHCb

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