Minimal flavor-changing $Z'$ models and muon $g - 2$ after the $R_{K^*}$ measurement

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Abstract: There has been a steady interest in flavor anomalies and their global fits as ideal probes of new physics. If the anomalies are real, one promising explanation is a new $Z'$ gauge boson with a flavor-changing coupling to bottom and strange quarks and a flavor-conserving coupling to muons and, possibly, electrons. We point out that direct production of such a $Z'$, emerging from the collision of $b$ and $s$ quarks, may offer a complementary window into these phenomena because collider searches already provide competitive constraints. On top of that, we analyze the same $Z'$ scenario in relation to another long-standing discrepancy between theory and experiment that concerns the anomalous magnetic moment of the muon. By scanning the allowed $Z'$ coupling strengths in the low-mass region, we assess the compatibility of the signals from LHCb with the $Z'$ searches in the high energy LHC data and the measurements of the anomalous magnetic moments of the involved leptons. We also argue that observations of the latter can break the degeneracy pattern in the Wilson coefficients $C_9$ and $C_{10}$ presented by LHCb data. The $Z'$ model we consider is compatible with the new measurement of $R_{K^*}$, therefore it can potentially account for the long-standing deviations observed in $B$-physics.
1 Introduction

Processes involving flavor-changing neutral currents are sensitive probes of new physics. In the Standard Model (SM), transitions such as $b \to s \ell^+ \ell^-$ are loop-suppressed, but new particles can contribute at tree-level. The possible impact of new particles on these processes is usually analyzed by integrating out the heavy degrees of freedom and working with the effective Hamiltonian. For $b \to s$ transitions we have,

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \sum_i (C_i O_i + C'_i O'_i) + H.c.,$$

which is expressed in terms of the effective operators $O_i$, $O'_i$ and the Wilson coefficients $C_i$, $C'_i$. Several anomalies with respect to SM predictions have been measured, typically at the $2\sigma$ level, but with increasing statistical significance. One notable anomaly of lepton flavor universality is the measured ratio of branching fractions $R_K = \frac{B(B^+ \to K^+ \mu^+ \mu^-)/B(B^+ \to K^+ e^+ e^-)}{\simeq 0.745}$ [1], as well as the recent measurement of $R_{K^*} = B(B^0 \to K^{*0} \mu^+ \mu^-)/B(B^0 \to K^{*0} e^+ e^-) \sim 0.7$ by LHCb [2], which has already prompted several studies [3–10]. Angular observables have become a popular testing ground, and recent updates [11, 12] have confirmed previous measurements in the decay $B^0 \to K^{*0} \mu^+ \mu^-$. Including other transitions and a large number of observables, global fits to the anomalies seem to be converging on preferred sets of Wilson coefficients [13–15]. However, it is not yet entirely clear which of these sets could be responsible for the anomalies. For example, refinement of the hadronic uncertainty in these analyses is an ongoing theoretical issue.

The general features of a $Z'$ gauge boson [16] make it a good choice to generate $b \to s \ell^+ \ell^-$ transitions, as underlined by many previous studies [17–32]. In this work, we follow a complementary approach and consider what else can be gained from colliders and other low-energy experiments. Specifically, we examine the sensitivity of the Wilson coefficients to constraints from the direct production of a suitable $Z'$ gauge boson that can also explain
the discrepancy between the measured value of the muon magnetic moment and the SM prediction.

We will focus here on scenarios in which the supposed new physics contributions affect exclusively $C_9^\ell$ and $C_{10}^\ell$, for $\ell = \mu, e$. These coefficients are among those currently favored by global fits to the anomalies [13], as well as by a recent analysis [4], which examines compatibility with $R_K$ and the new measurement of $R_K^{*}$. The relevant operators are

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \quad \text{and} \quad O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell).$$

(1.2)

Another motivation for this choice is that although the measurements of $R_K^{*}$ and $R_K$ suggest there is new physics which discriminates between muons and electrons, the LHCb data currently exhibit an interesting degeneracy in $C_9^\ell$ and $C_{10}^\ell$ based on their statistical pulls [4]: we argue that such degeneracy can be broken by analyses of the magnetic moments of the involved leptons in scenarios where the considered $Z'$ boson is well below the TeV scale. In addition, our analysis will show that the LEP bounds strongly disfavor scenarios where the speculated $Z'$ boson couples purely to electrons, besides quarks.

After introducing the adopted framework and detailing our methodology in Section 2, we present the results of our analysis in Section 3. Our conclusions are offered in Section 4.

## 2 A simple $Z'$ model

We assume a general interaction of a $Z'$ boson with quarks $\bar{s}b$ and leptons $\bar{\ell}\ell$ described by the Lagrangian

$$\mathcal{L} \supset \frac{g_2}{2c_W} Z'_\alpha \left\{ [\bar{s}\gamma^\alpha (g_L^\ell P_L + g_R^\ell P_R) b + h.c.] + \bar{\ell}\gamma^\alpha (g_V^\ell + \gamma_5 g_A^\ell) \ell \right\},$$

(2.1)

where $\ell = \mu, e$. The companion interactions with neutrinos and up-type quarks are allowed by the SM gauge symmetry and may offer interesting features which, however, we do not pursue in this work. The quark flavor-violating couplings $g_L^\ell$, $g_R^\ell$ and the lepton flavor-conserving couplings $g_V^\ell$, $g_A^\ell$ are normalized relative to $g_2/(2c_W)$ from the Standard Model for convenience, $c_W$ being the cosine of the Weinberg angle.

After integrating out the $Z'$ and performing tree-level matching, the Wilson coefficients bounded by the LHCb results are related to the $Z'$ couplings by

$$\frac{\alpha^2}{16\pi^2} V_{tb} V_{ts}^* \cdot \left\{ C_{9}^\ell, C_{10}^\ell \right\} = \frac{M^2_{Z'}}{2M_{Z'}^2} \cdot \left\{ g_9^\ell g_V^\ell, g_9^\ell g_A^\ell \right\}. $$

(2.2)

The Wilson coefficient $C_9^\ell$ encapsulates the vectorial couplings between the $Z'$ and leptons, whereas $C_{10}^\ell$ contains the axial couplings. As we can see, despite its simplicity, the $Z'$ model at hand can potentially account for deviations from lepton flavor universality.

The $Z'$ contributions to the magnetic moment of a charged lepton $\ell = \mu, e$ are given by

$$\Delta_{g-2}^\ell = \frac{1}{12\pi^2} \left( \frac{g_2 g_V^\ell}{2c_W} \right)^2 \frac{m_{\ell}^2}{M_{Z'}^2},$$

(2.3)
for $C_9$ scenarios, and by
\[
\Delta_{g-2} = -\frac{5}{12\pi^2} \left( \frac{g_2 g_A}{2 c_W} \right)^2 \frac{m_t^2}{M_{Z'}^2},
\] (2.4)
for $C_{10}$ scenarios, where $M_{Z'}$ is the mass of $Z'$. In our analysis we will refer to the following values for the measured discrepancies of the involved lepton magnetic moments: $\Delta_{g-2}^e = (-10.5 \pm 8.1) \times 10^{-13}$, $\Delta_{g-2}^\mu = (290 \pm 90) \times 10^{-11}$ [33, 34].

The parameters to be scanned over are $M_{Z'}$ and the set of couplings
\[
g_L^q, g_R^q, g_V^\ell, g_A^\ell,
\] (2.5)
which are for instance subject to the LHC dilepton searches that provide upper bounds on the production cross section times branching ratio as a function of $M_{Z'}$, $\sigma_{\ell\ell} \equiv \sigma(pp \to Z') \cdot \mathcal{B}(Z' \to \ell^+\ell^-)$. Using the interaction Lagrangian above with specified input values of the $Z'$ mass and couplings, we numerically simulate the dilepton searches [35] yielding the constraint
\[
\sigma_{\ell\ell}^{\text{sim}}(M_{Z'}, g_L^q, g_R^q, g_V^\ell, g_A^\ell) \leq \sigma_{\ell\ell}^{\text{exp}}(M_{Z'}),
\] (2.6)
where $\sigma_{\ell\ell}^{\text{sim}}$ is the result of our simulation, after the usual kinematical cuts, and $\sigma_{\ell\ell}^{\text{exp}}$ is the experimental upper bound.

The most stringent limits on the couplings of the $Z'$ to electrons originate from LEP electroweak precision measurements [36]. Integrating out the $Z'$ in our model generates the effective four-fermion operators
\[
\mathcal{L}_{\text{eff}} \supset \frac{1}{2} \left( \frac{g_2}{2 c_W} \right)^2 \left( \frac{g_V}{M_{Z'}} \right)^2 (\bar{\ell} \gamma_\mu \ell)(\bar{\ell} \gamma^\mu \ell),
\] (2.7)
and
\[
\mathcal{L}_{\text{eff}} \supset \frac{1}{2} \left( \frac{g_2}{2 c_W} \right)^2 \left( \frac{g_A^q}{M_{Z'}} \right)^2 (\bar{\ell} \gamma_\mu \gamma_5 \ell)(\bar{\ell} \gamma^\mu \gamma_5 \ell),
\] (2.8)
which are constrained by measurements of $e^+e^- \to e^+e^-$ cross sections at LEP. The upper limits on the magnitudes of the electron-$Z'$ couplings are
\[
|g_V^\ell| \leq \frac{2 c_W}{g_2} \frac{M_{Z'}}{20.6 \text{ TeV}} \quad \text{and} \quad |g_A^\ell| \leq \frac{2 c_W}{g_2} \frac{M_{Z'}}{10.1 \text{ TeV}},
\] (2.9)
which respectively hold in the case of vectorial and axial couplings.

We scan the allowed range of couplings for two different masses of $Z'$, with the values $M_{Z'} = 200$ GeV, 500 GeV for scenarios involving muons, and $M_{Z'} = 250$ GeV, 500 GeV for those involving electrons. Our simulations were performed using MadGraph-aMC5@NLO [37] and we validated our code in the special case of a sequential $Z'$ against the simulated cross section reported in Ref. [35] as a function of $M_{Z'}$.

In our analyses we consider also the constraint from $B_s^0 - \bar{B}_s^0$ oscillations in terms of the measured mass difference $\Delta M_s$ given by [38]
\[
\frac{\Delta M_s}{\Delta M_s^{\text{SM}}} \approx 1 + \frac{M_{Z'}^2}{M_{Z'}^2} \left[ (g_L^q)^2 + (g_R^q)^2 - 9.7(g_L^q)(g_R^q) \right] \left( \frac{g_2^2}{16\pi^2} (V_{ts}^* V_{tb})^2 s_0 \right)^{-1},
\] (2.10)
where the contribution from the second term on the right-hand side is bounded by experiment to be in magnitude below the 10% level. The SM loop function is $S_0 \simeq 2.3$.

As for the low-energy observations, including recent measurements by LHCb, we remark that a comprehensive statistical analysis of the Wilson coefficients would involve about 100 observables and a careful treatment of about 100 nuisance parameters. This is so technically challenging that instead approximate “fast-fit” techniques are favoured (see e.g., [4, 5]), although they require considerable computing resources. Since a comprehensive analysis is beyond the purpose of this paper, we adopt a pragmatic approach to understand the impact of the latest data. We perform an independent fit of the Wilson coefficients to LHCb measurements of $R_{K^*}$ [2] and $R_K$ [1], Belle measurements of $D'_4$ and $D'_5$ [39], and LHCb measurements of $B(B_s^0 \to \mu^+\mu^-)$ and $B(B^0 \to \mu^+\mu^-)$ [40]. Recent studies [5, 7] performed global frequentist statistical analysis, whereas [8] performed a global Bayesian analysis with a subset of nuisance parameters and data with HEPfit [41]. Our methodology and its results are detailed in the next section.

3 A first analysis

We calculated the profile likelihood with MultiNest [42] interfaced with a modified version of flavio [13]. Confidence intervals were found by Wilks’ theorem (see [43] for conventions and definitions). All nuisance parameters ($m_b, m_c$, CKM matrix elements and form factors) were fixed to their central values. Wilson coefficients were varied between $-5$ and $5$. We find reasonable agreement for best-fits, confidence intervals and significances with similar flavio results with Markov Chain Monte Carlo algorithms and fast-fit techniques for nuisance parameters [4]. We estimate the significance of the preference for new physics versus the SM to be about $4.5\sigma$, in agreement with recent literature [3–5, 7, 8], but, as in the literature, there are important caveats about systematic uncertainties.

Since it is a product of our MultiNest fit, we note that data favour the $C_{\mu 9}$ model by a Bayes factor of about $10^4$ versus the SM and about 10 versus $C_{\mu 10}$, as well as versus $C_{e 9}$ or $C_{e 10}$. Since, however, we omitted important nuisance parameters that may alleviate tension in the SM, $10^4$ should be regarded as an upper bound to the Bayes factor versus the SM (and is, of course, sensitive to priors). A Bayes factor preference for $C_{\mu 9}$ versus electron Wilson coefficients was also noted in an earlier study of $R_K$ [44].

The results we obtained are presented in Figure 1, whereas Table 1 proposes the results from Ref. [4] for comparison. We find that the two analyses are in reasonable agreement given that the fits take into account different sets of observables.

We focus now on the constraints that collider and low energy experiments impose on the scenarios we delineated.
Figure 1. Best-fits to $b \to s\ell^+\ell^-$ anomalies for the indicated Wilson coefficients.

| Coeff. | best fit | $1\sigma$ CL | $2\sigma$ CL |
|--------|----------|--------------|--------------|
| $C_9^\mu$ | $-1.59$ | $[-2.15, -1.13]$ | $[-2.90, -0.73]$ |
| $C_{10}^\mu$ | $+1.23$ | $[+0.90, +1.60]$ | $[+0.60, +2.04]$ |
| $C_9^e$ | $+1.58$ | $[+1.17, +2.03]$ | $[+0.79, +2.53]$ |
| $C_{10}^e$ | $-1.30$ | $[-1.68, -0.95]$ | $[-2.12, -0.64]$ |

Table 1. The values obtained for the Wilson coefficients from a fit to $b \to s\ell\ell$ anomalies in Ref. [4].
Figure 2. Experimental constraints on the scenario where the $Z'$ only couples to electrons. The shaded regions correspond to the allowed regions of parameter space. Upper panels: $C^e_9$ is non-zero and generated by a $Z'$ with mass 250 GeV (left) and 500 GeV (right). Lower panels: $C^{e}_{10}$ is non-zero and generated by a $Z'$ with mass 250 GeV (left) and 500 GeV (right).

3.1 Scenarios with $C^e_9$ or $C^{e}_{10}$ only

We present in Figure 2 the results obtained for the scenario where new physics effects arise from the coupling of $Z'$ to electrons, and the relative effects are fully encapsulated in the Wilson coefficient $C^e_9$ (top panels), or $C^{e}_{10}$ (bottom panels). The different shaded areas indicate allowed regions of parameter space after taking into account the various constraints.

The green area represents the region allowed by the ATLAS $Z'$ searches in the dielectron channel. The blue band represents the values of the coupling selected by the LHCb measurements of the indicated Wilson coefficient. We refer here to the values for the $2\sigma$ credible regions from our analysis presented in Figure 1. The red band illustrates instead the region of the parameter space allowed by the constraints on the mass difference $\Delta M_s$.

As mentioned before, we also checked that the $Z'$ contribution to the electron $g - 2$ does not spoil the current agreement between theory and experiment. A plot of the new contribution to this quantity is presented in Figure 3 as a function of $M_{Z'}$ for different values of the relevant coupling. The results in the top panel holds for the scenario where all the new physics effects are contained in $C^e_9$, the bottom one for the case of $C^{e}_{10}$. We can see that values of $M_{Z'} \lesssim 50$ GeV would negatively impact on the prediction for the anomalous magnetic moment of the electron.

We remark that these scenarios where the $Z'$ only couples to electrons, besides quarks,
are strongly constrained by the bounds from LEP-II [36]. The gray shade in Figure 2 denotes the area of the parameter space that evades the latter. We can see that the scenario with non-zero $C_9^e$ generated from a vector coupling is more tightly constrained than $C_{10}^e$ by LEP electroweak precision measurements and $B_s^0 - ar{B}_s^0$ oscillations. Indeed in the case of non-zero $C_{10}^e$ a larger region of the parameter space is still allowed by all the considered experimental limits. A $Z'$ boson with axial vector couplings would also induce a negative contribution to the $g - 2$ of the electron, and is therefore amenable to reducing the tension between the measurements and the SM prediction. Although in the simple models we are considering this contribution is not substantial, we remark that the preference for $C_{10}^e$ based on $g - 2$ is consistent with the picture emerging from the other constraints analysed.

3.2 Scenarios with $C_9^\mu$ and $C_{10}^\mu$ only

We present in Figure 4 the analogous results obtained for the case in which, besides quarks, the speculated $Z'$ couples exclusively to muons.

Again we show in the top panel the case where new physics affects $C_9^\mu$ only, and the bottom panels cover the complementary case of $C_{10}^\mu$. As before, the green area represents the region of the parameter space allowed by the ATLAS $Z'$ searches, here for the dimuon

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{The $Z'$ contribution to the anomalous magnetic moment of the electron. The green and yellow bands represent the 1$\sigma$ and 2$\sigma$ confidence levels for the discrepancy between the measurement and the SM prediction. The top panel is for the scenario where all the new physics effects are contained in $C_9^e$, the bottom one for the case of $C_{10}^e$.}
\end{figure}
Figure 4. Experimental constraints on the scenario where the $Z'$ only couples to muons. The shaded regions correspond to the allowed regions of parameter space. Upper panels: $C_9^\mu$ is non-zero and generated by a $Z'$ with mass 200 GeV (left) and 500 GeV (right). Lower panels: $C_{10}^\mu$ is non-zero and generated by a $Z'$ with mass 200 GeV (left) and 500 GeV (right).

The blue band represents the values of the coupling selected by the LHCb measurements of the indicated Wilson coefficient, according to the $2\sigma$ credible intervals shown in Figure 1. The red band is the region of the parameter space allowed by the constraints on the mass difference $\Delta M_s$. We remark that LEP measurements do not constrain the couplings in these scenarios.

The $Z'$ contribution in the $C_9^\mu$ scenario can help to bridge the discrepancy between the measured value of the muon magnetic moment and the SM prediction. As we can see in Figure 5, the $Z'$ contribution is potentially able to reduce such a discrepancy below the $1\sigma$ level for moderate values of the $Z'$-muon couplings for $Z'$ masses up to about 250 GeV. The solid black line in this region with $g^\mu_V = 3$ and $M_{Z'} \simeq 200$ GeV is compatible with the parameter space selected by the LHCb data. In this case, the physical coupling $g^\mu_V (g_2/2c_W) \simeq 0.3\sqrt{4\pi}$ is large, but marginally within the perturbative regime. The corresponding region in Figure 4 is allowed, when the top left panel is extrapolated to $g^\mu_L \simeq 10^{-4}$.

As for the $C_{10}^\mu$ case (not shown), the presence of a $Z'$ in the low-mass range can only worsen the theory prediction as the relative contribution, of negative sign, further lowers the value of the latter.
Figure 5. The $Z'$ contribution to the anomalous magnetic moment of the muon. The green and yellow bands represent the 1σ and 2σ confidence levels for the discrepancy between the measurement and the SM prediction.

4 Conclusions

In this paper we considered four different new physics scenarios which could explain the anomalous $B$-physics results from LHCb and argued that measurements of the anomalous magnetic moments of muon and electron could break the degeneracy in the $C_9^{\mu(e)}-C_{10}^{\mu(e)}$ Wilson coefficients.

We find that a $Z'$-boson which couples only to electrons can produce the correct values for $R_K$ and $R_{K^*}$, but such a scenario is strongly constrained by the precision measurements from LEP. However, if the $Z'$ coupling to $e^+e^-$ is purely axial, the allowed region of parameter space is larger. Such an axially coupled $Z'$ also generates a negative contribution to the anomalous magnetic moment of the electron and could therefore potentially accommodate both anomalies.

We also considered scenarios where the $Z'$-boson couples only to muons. In this case, a vectorial coupling to the $Z'$ is favoured by the Bayesian approach employed for the performed fit. Such a scenario produces also a positive contribution to the $g-2$ of the muon and therefore could help to alleviate the tension between the $g-2$ measurement and the SM prediction. This scenario can also explain the LHCb anomalies while avoiding all the remaining constraints from high energy searches, provided the vectorial coupling to muons is large ($g_\mu^V > 0.1$). An axial coupling of the $Z'$ to muons can also explain the LHCb results, but increases the disagreement of the $g-2$ with measurements.

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References

[1] LHCb collaboration, R. Aaij et al., Test of lepton universality using $B^+ \to K^+ \ell^+ \ell^-$ decays, *Phys. Rev. Lett.* 113 (2014) 151601, [1406.6482].

[2] CMS collaboration, S. Bifani, Search for new physics with $b \to s \ell^+ \ell^-$ decays at LHCb, *CERN Seminar, 18 April 2017*.

[3] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias and J. Virto, Patterns of New Physics in $b \to s \ell^+ \ell^-$ transitions in the light of recent data, 1704.05340.

[4] W. Altmannshofer, P. Stangl and D. M. Straub, Interpreting Hints for Lepton Flavor Universality Violation, 1704.05435.

[5] G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre et al., Flavour anomalies after the $R_K^*$ measurement, 1704.05438.

[6] G. Hiller and I. Nisandzic, $R_K$ and $R_{K^*}$ beyond the Standard Model, 1704.05444.

[7] L.-S. Geng, B. Grinstein, S. Jäger, J. Martin Camalich, X.-L. Ren and R.-X. Shi, Towards the discovery of new physics with lepton-universality ratios of $b \to s \ell \ell$ decays, 1704.05446.

[8] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini et al., A leptoquark model to accommodate $R_{K^0[K^*]}^\exp < R_{K^0[K^*]}^\text{SM}$ and $R_{K^0[K^*]}^\exp < R_{K^0[K^*]}^\text{SM}$, 1704.05835.

[9] A. Celis, J. Fuentes-Martín, A. Vicente and J. Virto, Gauge-invariant implications of the LHCb measurements on Lepton-Flavour Non-Universality, 1704.05672.

[10] ATLAS collaboration, Angular analysis of $B^0 \to K^* \mu^+ \mu^-$ decays in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Tech. Rep. ATLAS-CONF-2017-023, CERN, Geneva, Apr, 2017.

[11] CMS collaboration, Measurement of the $P_1$ and $P_5^*$ angular parameters of the decay $B^0 \to K^0 \mu^+ \mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV, Tech. Rep. CMS-PAS-BPH-15-008, CERN, Geneva, 2017.

[12] CMS collaboration, Measurement of the $P_1$ and $P_5^*$ angular parameters of the decay $B^0 \to K^0 \mu^+ \mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV, Tech. Rep. CMS-PAS-BPH-15-008, CERN, Geneva, 2017.

[13] W. Altmannshofer, C. Niehoff, P. Stangl and D. M. Straub, Status of the $B \to K^* \mu^+ \mu^-$ anomaly after Moriond 2017, 1703.09189.

[14] S. Descotes-Genon, J. Matias and J. Virto, Understanding the $B \to K^* \mu^+ \mu^-$ Anomaly, *Phys. Rev.* D88 (2013) 074002, [1307.5683].

[15] S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, Global analysis of $b \to s \ell \ell$ anomalies, *JHEP* 06 (2016) 092, [1510.04239].

[16] P. Langacker, The Physics of Heavy $Z'$ Gauge Bosons, *Rev. Mod. Phys.* 81 (2009) 1199–1228, [0801.1345].

[17] S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, On the impact of power corrections in the prediction of $B \to K^* \mu^+ \mu^-$ observables, *JHEP* 12 (2014) 125, [1407.8526].

[18] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski and J. Rosiek, Lepton-flavour violating $B$ decays in generic $Z'$ models, *Phys. Rev.* D92 (2015) 054013, [1504.07928].

[19] A. J. Buras, F. De Fazio and J. Girrbach, The Anatomy of $Z'$ and $Z$ with Flavour Changing Neutral Currents in the Flavour Precision Era, *JHEP* 02 (2013) 116, [1211.1896].
[20] R. Gauld, F. Goertz and U. Haisch, *On minimal $Z'$ explanations of the $B \to K^* \mu^+ \mu^-$ anomaly*, *Phys. Rev. D* **89** (2014) 015005, [1308.1959].

[21] A. J. Buras and J. Girrbach, *Left-handed $Z'$ and $Z$ FCNC quark couplings facing new $b \to s \mu^+ \mu^-$ data*, *JHEP* **12** (2013) 009, [1309.2466].

[22] R. Gauld, F. Goertz and U. Haisch, *An explicit $Z'$-boson explanation of the $B \to K^* \mu^+ \mu^-$ anomaly*, *JHEP* **01** (2014) 069, [1310.1082].

[23] A. J. Buras, F. De Fazio and J. Girrbach, *331 models facing new $b \to s \mu^+ \mu^-$ data*, *JHEP* **12** (2013) 009, [1309.2466].

[24] B. Allanach, F. S. Queiroz, A. Strumia and S. Sun, *$Z'$ models for the LHCb and $g-2$ muon anomalies*, *Phys. Rev. D* **93** (2016) 055045, [1511.07447].

[25] A. Crivellin, G. D'Ambrosio and J. Heeck, *Explaining $h \to \mu^+ \tau^-$, $B \to K^* \mu^+ \mu^-$ and $B \to K \mu^+ \mu^-/B \to K e^+ e^-$ in a two-Higgs-doublet model with gauged $L_\mu - L_\tau$, Phys. Rev. Lett.* **114** (2015) 151801, [1501.00993].

[26] A. Crivellin, G. D'Ambrosio and J. Heeck, *Addressing the LHC flavor anomalies with horizontal gauge symmetries*, *Phys. Rev. D* **91** (2015) 075006, [1503.03477].

[27] G. Bélanger, C. Delaunay and S. Westhoff, *A Dark Matter Relic From Muon Anomalies*, *Phys. Rev. D* **92** (2015) 055021, [1507.06660].

[28] E. Megias, M. Quiros and L. Salas, *Lepton-flavor universality violation in $R_{D_{(s)}^\ast}$ and $R_K$ from warped space*, [1703.06019].

[29] E. Megias, G. Panico, O. Pujolas and M. Quiros, *A Natural origin for the LHCb anomalies*, *JHEP* **09** (2016) 118, [1608.02362].

[30] E. Megias, M. Quiros and L. Salas, *$g-2$ from Vector-Like Leptons in Warped Space*, [1701.05072].

[31] I. García García, *LHCb anomalies from a natural perspective*, *JHEP* **03** (2017) 040, [1611.03507].

[32] A. Carmona and F. Goertz, *Lepton Flavor and Nonuniversality from Minimal Composite Higgs Setups*, *Phys. Rev. Lett.* **116** (2016) 251801, [1610.07658].

[33] G. F. Giudice, P. Paradisi and M. Passera, *Testing new physics with the electron $g-2$*, *JHEP* **11** (2012) 113, [1208.6583].

[34] F. Jegerlehner and A. Nyffeler, *The Muon $g-2$*, *Phys. Rept.* **477** (2009) 1–110, [0902.3360].

[35] ATLAS collaboration, *Search for new high-mass resonances in the dilepton final state using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Tech. Rep. ATLAS-CONF-2016-045, CERN, Geneva, Aug, 2016.

[36] DELPHI, OPAL, LEP Electroweak, ALEPH, L3 collaboration, S. Schael et al., *Electroweak Measurements in Electron-Positron Collisions at $W$-Boson-Pair Energies at LEP*, *Phys. Rept.* **532** (2013) 119–244, [1302.3415].

[37] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, [1405.0301].

[38] W. Altmannshofer and D. M. Straub, *New Physics in $B \to K^* \mu \mu$?*, *Eur. Phys. J.* **C73** (2013) 2646, [1308.1501].
[39] Belle collaboration, S. Wehle et al., \textit{Lepton-Flavor-Dependent Angular Analysis of $B \rightarrow K^* \ell^+ \ell^-$}, \textit{Phys. Rev. Lett.} \textbf{118} (2017) 111801, [1612.05014].

[40] LHCb collaboration, R. Aaij et al., \textit{Measurement of the $B^0_s \rightarrow \mu^+ \mu^-$ branching fraction and effective lifetime and search for $B^0 \rightarrow \mu^+ \mu^-$ decays}, 1703.05747.

[41] J. de Blas et al., $\texttt{HEPfit}$: \textit{a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models}, \texttt{.}

[42] F. Feroz, M. P. Hobson and M. Bridges, \textit{MultiNest: an efficient and robust Bayesian inference tool for cosmology and particle physics}, \textit{Mon. Not. Roy. Astron. Soc.} \textbf{398} (2009) 1601–1614, [0809.3437].

[43] A. Fowlie and M. H. Bardsley, \textit{Superplot: a graphical interface for plotting and analysing MultiNest output}, \textit{Eur. Phys. J. Plus} \textbf{131} (2016) 391, [1603.00555].

[44] D. Ghosh, M. Nardecchia and S. A. Renner, \textit{Hint of Lepton Flavour Non-Universality in B Meson Decays}, \textit{JHEP} \textbf{12} (2014) 131, [1408.4097].