

# Shedding light on the $b \rightarrow s$ anomalies with a dark sector

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The LHCb collaboration has recently reported on some anomalies in  $b \rightarrow s$  transitions. In addition to discrepancies with the Standard Model (SM) predictions in some angular observables and branching ratios, an intriguing hint for lepton universality violation was found. Here we propose a simple model that extends the SM with a dark sector charged under an additional  $U(1)$  gauge symmetry. The spontaneous breaking of this symmetry gives rise to a massive  $Z'$  boson, which communicates the SM particles with a valid dark matter candidate, while solving the  $b \rightarrow s$  anomalies with contributions to the relevant observables.

## I. INTRODUCTION

Rare decays stand among the most powerful probes of physics beyond the Standard Model (SM). Indeed, most new physics (NP) scenarios suffer from severe constraints due to their potentially large contributions to flavor observables. This has motivated an intense experimental search, with special focus on observables which are strongly suppressed in the SM.

In 2013, the LHCb collaboration reported on the measurement of several observables in processes involving  $b \rightarrow s$  transitions. A significant tension with the SM was found in some cases. These include angular observables in  $B \rightarrow K^* \mu^+ \mu^-$  [1], particularly large in case of the popular  $P'_5$  [2–4], as well as a decrease, with respect to the SM expectation, in several branching ratios [5, 6]. These anomalies received immediate attention in the flavor community, and soon several independent global fits [7–10] showed that the tension could be alleviated in the presence of new physics contributions. Interestingly, in 2014 the LHCb collaboration also found an indication of lepton universality violation in the theoretically rather clean ratio [11]

$$R_K = \frac{\text{BR}(B \rightarrow K \mu^+ \mu^-)}{\text{BR}(B \rightarrow K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036, \quad (1)$$

measured in the low dilepton invariant mass regime, which departs from the SM result  $R_K^{\text{SM}} = 1.0003 \pm 0.0001$  by  $2.6\sigma$  [12]. Again, this led to some excitement in the community, in particular after it was found that this hint is compatible with the previous anomalies in  $b \rightarrow s$  transitions: they can be explained by the same type of NP contributions to muonic operators [13–17]. So far, the discussion has focused on results obtained by LHCb with an integrated luminosity of  $1 \text{ fb}^{-1}$ . The latest chapter of this story is the recent announcement of the LHCb collaboration of new results using the full LHC Run I dataset [18], with an integrated luminosity of  $3 \text{ fb}^{-1}$ , which confirm the robustness of the LHCb data. Indeed, the new results are compatible with those found with  $1 \text{ fb}^{-1}$ , and several theorists have used the new data to update their analyses. According to [19], the hypothesis of non-zero NP contributions

is preferred over the SM by  $3.7\sigma$ ,  $4.3\sigma$  if the 2014 measurement of  $R_K$  is included, whereas the analysis of [20] finds a slightly larger statistical significance for NP (slightly larger than  $4\sigma$ ) even in the absence of  $R_K$ . In any case, assuming that hadronic effects [21, 22] are not behind these anomalies (something impossible in case of  $R_K$ ), there is clear evidence of new physics in  $B$  meson decays. For a complete review of the subject see [17] and references therein.

Several approaches have been considered in order to explain the  $b \rightarrow s$  anomalies. Some papers [23–25] consider generic  $Z'$  bosons with flavor violating couplings. These have been shown to provide a simple way to reconcile theory predictions with experimental data. There are also some works that were built to address the first anomalies but fail to address the lepton universality violating  $R_K$  measurement, see for example Refs. [26, 27] in the context of 331 scenarios or Ref. [28], where 4-quark scalar interactions were considered. Finally, a few recent models can also account for the lepton universality violating  $R_K$  measurement. One finds three types of working models: models with scalar or vector leptoquarks (or similarly, R-parity violating supersymmetry, where the squarks can play the role of the leptoquarks) [14, 29–31], composite Higgs models [25, 32] and models with a  $Z'$ . The latter is generally considered the easiest approach, since the anomalies can be solved with new contributions to vectorial operators. However, to the best of our knowledge, the only (complete) models that have been put forward in order to account for these anomalies using a  $Z'$  are: (1) the one introduced in Ref. [33] (and the Two-Higgs-Doublet version in [34]), which makes use of a  $U(1)_{L_\mu - L_\tau}$  gauge symmetry, and (2) the one proposed in the recent paper [35], which extends the horizontal gauge symmetry to the quark sector.

The existence of dark matter (DM) is a well established evidence of new physics, supported by a plethora of astrophysical and cosmological observations. This motivates further extensions of the SM of particle physics that include valid DM candidates. In DM models, the current Planck  $3\sigma$  limits for the DM relic density,  $0.1118 < \Omega_{\text{DM}} h^2 < 0.1280$  [36], typically imply strong constraints on the mass and couplings of the DM candidate. This, combined with additional constraints (such as those from flavor physics), sometimes leads to very predictive scenarios where the parameter space of the DM model shrinks to small regions compatible with all observations.

We propose a simple model which captures the main in-

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redients required to explain the  $b \rightarrow s$  anomalies and, simultaneously, provides a DM candidate. In order to do so, we extend the SM with a dark sector charged under an additional  $U(1)$  gauge symmetry. The spontaneous breaking of this symmetry gives rise to a massive  $Z'$  boson, which communicates the SM particles with the dark matter particle and solves the  $b \rightarrow s$  anomalies with contributions to the relevant flavor observables. The interplay between DM and flavor physics leads to a very constrained scenario. In particular, achieving the measured DM relic density while providing the required NP contributions to  $B$  meson decays turns out to be very restrictive on the model parameters.

The rest of the paper is organized as follows: in Sec. II we discuss some general aspects about the  $b \rightarrow s$  anomalies and introduce the basic language to be used throughout the paper. In Sec. III we define our model, show how it addresses the  $b \rightarrow s$  anomalies while providing a DM candidate and discuss extensions to generate non-zero neutrino masses. Sec. IV is devoted to the DM phenomenology of our model and the  $Z'$  portal responsible for its production in the early universe. Sec. V is a review of the most relevant constraints in our model, to be considered in Sec. VI, where we present our numerical results. Finally, in Sec. VII we summarize our results, discuss some related aspects and derive some general conclusions.

## II. THE $b \rightarrow s$ ANOMALIES

In this Section we discuss some general aspects about the  $b \rightarrow s$  anomalies. For a complete review of the subject, we refer the reader to [17].

### A. Operators and global fits

The effective Hamiltonian for  $b \rightarrow s$  transitions is usually written as

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

where  $G_F$  is the Fermi constant,  $e$  the electric charge and  $V$  the CKM matrix.  $O_i$  and  $O'_i$  are the effective operators that contribute to  $b \rightarrow s$  transitions, and  $C_i$  and  $C'_i$  their Wilson coefficients. Since the most important anomalies have been found in semileptonic  $B$  meson decays, we will consider the following set of operators,

$$O_9 = (\bar{s}\gamma_\mu P_L b) (\bar{\ell}\gamma^\mu \ell), \quad O'_9 = (\bar{s}\gamma_\mu P_R b) (\bar{\ell}\gamma^\mu \ell), \quad (3)$$

$$O_{10} = (\bar{s}\gamma_\mu P_L b) (\bar{\ell}\gamma^\mu \gamma_5 \ell), \quad O'_{10} = (\bar{s}\gamma_\mu P_R b) (\bar{\ell}\gamma^\mu \gamma_5 \ell). \quad (4)$$

Here  $\ell = e, \mu, \tau$ <sup>1</sup>. It is also customary to split the Wilson coefficients in two parts: the SM contributions and the NP contributions. Since the primed operators,  $O'_9$  and  $O'_{10}$ , do not receive significant SM contributions, this is usually applied only

to the unprimed Wilson coefficients, which can be written as

$$C_9 = C_9^{\text{SM}} + C_9^{\text{NP}}, \quad (5)$$

$$C_{10} = C_{10}^{\text{SM}} + C_{10}^{\text{NP}}. \quad (6)$$

The SM contributions,  $C_9^{\text{SM}}$  and  $C_{10}^{\text{SM}}$ , have been computed by different groups. Assuming that these are the only contributions to the Wilson coefficients, several independent global fits have found a sizable tension with experimental data on  $b \rightarrow s$  transitions. This motivates the addition of NP contributions. When this is done, the global fits are clearly improved. According to [17] (we will mainly consider the results of this global fit), the best improvements are found in two cases:

- **Scenario 1:** NP provides a negative contribution to  $O_9^\mu$ , with  $C_9^{\mu, \text{NP}} \sim -30\% \times C_9^{\mu, \text{SM}}$ , leading to a Wilson coefficient  $C_9^\mu$  significantly smaller than the one in the SM.
- **Scenario 2:** NP enters in the  $SU(2)_L$  invariant direction  $C_9^{\mu, \text{NP}} = -C_{10}^{\mu, \text{NP}}$ , with  $C_9^{\mu, \text{NP}} \sim -12\% \times C_9^{\mu, \text{SM}}$ .

In both cases, the rest of operators involving muons are perfectly compatible with the SM expectations. Similarly, no NP is required for operators involving electrons or tau leptons.

### B. Model building requirements

Once determined the type of contributions to  $C_9$  and  $C_{10}$  a NP model has to induce, one can figure out the main ingredients of a simple working model. Arguably, the simplest one contains the following elements:

- A massive  $Z'$  boson, responsible for the vectorial operators  $O_9$  and  $O_{10}$
- The  $Z'$  must have flavor violating couplings to quarks
- The  $Z'$  must couple differently to electrons and muons

This setup can be easily parameterized by the Lagrangian [17, 37]

$$\mathcal{L} \supset \bar{f}_i \gamma^\mu \left( \Delta_L^{f_i f_j} P_L + \Delta_R^{f_i f_j} P_R \right) f_j Z'_\mu. \quad (7)$$

In order to account for the anomalies, one requires  $\Delta_L^{bs} \neq 0$  and either (1)  $\Delta_L^{\mu\mu} = \Delta_R^{\mu\mu} \neq 0$ , or (2)  $\Delta_L^{\mu\mu} \neq 0$  and  $\Delta_R^{\mu\mu} = 0$ , depending on the scenario one wants to consider. The rest of the  $Z'$  couplings to SM fermions can be set to zero. As we will see in Sec. III, the model we are going to consider belongs to scenario (2). In this case, the quark and lepton currents contributing to  $O_9$  and  $O_{10}$  are both left-handed and one finds at tree-level [17]

$$C_9^{\mu, \text{NP}} = -C_{10}^{\mu, \text{NP}} = -\frac{\Delta_L^{bs} \Delta_L^{\mu\mu}}{V_{tb} V_{ts}^*} \left( \frac{\Lambda_\nu}{m_{Z'}} \right)^2, \quad (8)$$

with

$$\Lambda_\nu = \left( \frac{\pi}{\sqrt{2} G_F \alpha} \right)^{1/2} \simeq 4.94 \text{ TeV}, \quad (9)$$

<sup>1</sup> When referring to operators involving a particular lepton flavor, we will denote it with a superscript, e.g.  $C_9^\mu$  and  $O_9^\mu$ , for muons.

where  $\alpha = \frac{e^2}{4\pi^2}$  is the fine structure constant. Note that  $\Lambda_\nu$  and the CKM elements appear in Eq. (8) in order to normalize the Wilson coefficients as defined in Eqs. (3) and (4).

We now introduce a complete renormalizable model with these properties.

### III. THE MODEL

We extend the SM gauge group with a new dark  $U(1)_X$  factor, under which all the SM particles are assumed to be singlets. The only particles charged under the  $U(1)_X$  group are the following vector-like fermions,

$$Q_L = \left( \mathbf{3}, \mathbf{2}, \frac{1}{6}, 2 \right), \quad Q_R = \left( \mathbf{3}, \mathbf{2}, \frac{1}{6}, 2 \right), \quad (10)$$

$$L_L = \left( \mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2 \right), \quad L_R = \left( \mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2 \right), \quad (11)$$

as well as the complex scalar fields

$$\phi = (\mathbf{1}, \mathbf{1}, 0, 2), \quad \chi = (\mathbf{1}, \mathbf{1}, 0, -1), \quad (12)$$

where we denote the gauge charges under  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$  and the  $SU(2)_L$  doublets can be decomposed as  $Q_{L,R} = (U, D)_{L,R}$  and  $L_{L,R} = (N, E)_{L,R}$ .

Besides canonical kinetic terms, the new vector-like fermions have Dirac mass terms,

$$\mathcal{L}_m = m_Q \bar{Q} Q + m_L \bar{L} L, \quad (13)$$

as well as Yukawa couplings with the SM fermions

$$\mathcal{L}_Y = \lambda_Q \bar{Q}_R \phi Q_L + \lambda_L \bar{L}_R \phi L_L + \text{h.c.}, \quad (14)$$

where  $\lambda_Q$  and  $\lambda_L$  are 3 component vectors. The scalar potential takes the form

$$\mathcal{V} = \mathcal{V}_{\text{SM}} + \mathcal{V}(H, \phi, \chi) + \mathcal{V}(\phi, \chi). \quad (15)$$

Here  $H$  is the SM Higgs doublet and  $\mathcal{V}_{\text{SM}} = m_H^2 |H|^2 + \frac{\lambda}{2} |H|^4$  is the SM scalar potential. The pieces involving the  $U(1)_X$  charged scalars are

$$\mathcal{V}(H, \phi, \chi) = \lambda_{H\phi} |H|^2 |\phi|^2 + \lambda_{H\chi} |H|^2 |\chi|^2 \quad (16)$$

and

$$\begin{aligned} \mathcal{V}(\phi, \chi) &= m_\phi^2 |\phi|^2 + m_\chi^2 |\chi|^2 + \frac{\lambda_\phi}{2} |\phi|^4 + \frac{\lambda_\chi}{2} |\chi|^4 \\ &+ \lambda_{\phi\chi} |\phi|^2 |\chi|^2 + (\mu \phi \chi^2 + \text{h.c.}). \end{aligned} \quad (17)$$

We will assume that the scalar potential is such that only the standard Higgs boson and the  $\phi$  field acquire non-zero vacuum expectation values (VEVs),

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}}, \quad \langle \phi \rangle = \frac{v_\phi}{\sqrt{2}}. \quad (18)$$

Therefore, the  $\phi$  field will be responsible for the spontaneous breaking of  $U(1)_X$ , giving a mass to the  $Z'$ ,  $m_{Z'} = 2g_X v_\phi$ ,

where  $g_X$  is the  $U(1)_X$  gauge coupling, and inducing mixings between the vector-like fermions and their SM counterparts thanks to the Yukawa interactions in Eq. (14). Furthermore, after spontaneous symmetry breaking, the resulting Lagrangian contains a remnant  $\mathbb{Z}_2$  symmetry, under which  $\chi$  is odd and all the other fields are even. Therefore,  $\chi$  is a stable neutral scalar, and thus a potentially valid DM candidate. It is worth noting that the mechanism to stabilize the DM particle does not introduce additional ad-hoc symmetries, but simply makes use of the same  $U(1)_X$  symmetry that is required in order to give an explanation to the LHCb observations. This goal has been achieved by breaking the continuous  $U(1)_X$  symmetry to a remnant  $\mathbb{Z}_2$ , something that can be easily accomplished with a proper choice of  $U(1)_X$  charges [38–40].

Before concluding this section we must comment on  $U(1)$  mixing. It is well known that nothing prevents  $U(1)$  factors from mixing. In the model under consideration, this would be given by the Lagrangian term [41]

$$\mathcal{L} \supset \varepsilon F_{\mu\nu}^X F_X^{\mu\nu}, \quad (19)$$

where  $F_{\mu\nu}^{X,Y}$  are the usual field strength tensors for the  $U(1)_{X,Y}$  groups. In the presence of a non-zero  $\varepsilon$  coupling, kinetic mixing between the  $U(1)_X$  and  $U(1)_Y$  gauge bosons is induced. As a consequence of this, the physical  $Z'$  boson would couple to all particles that carry hypercharge, this is, to all the SM fermions. This would lead to phenomenological problems since couplings to the first generation are strongly constrained. Therefore, we will assume that the tree-level  $\varepsilon$  coupling vanishes. This is easily justified in our model because this term is not induced via renormalization group running if it is zero at some high-energy scale (where one may speculate about a ultraviolet completion). The reason is our choice of the  $U(1)_X$  charges [42]. In addition, we must keep the 1-loop induced  $\varepsilon$  coupling, generated in loops including heavy vector-like quarks and leptons, under control. We find

$$\varepsilon_{1\text{-loop}} \propto \frac{g_{1gX}}{16\pi^2} \log\left(\frac{m_Q}{m_L}\right). \quad (20)$$

Therefore,  $m_Q \sim m_L$  would ensure small  $\varepsilon$  couplings, while allowing large  $g_X$ . Something required by DM constraints (see Sec. IV).

#### A. Solving the $b \rightarrow s$ anomalies

This model solves the  $b \rightarrow s$  anomalies in a similar fashion as the one in Ref. [33]. The  $Z'$  couplings to the SM fermions are generated after their mixing with the corresponding vector-like quarks and leptons, as shown in Fig. 1. Neglecting  $m_{s,b}^2 \ll m_Q^2$  and  $m_\mu^2 \ll m_L^2$ , the resulting  $Z'$  couplings are found to be

$$\Delta_L^{bs} = \frac{2g_X \lambda_Q^b \lambda_Q^{s*} v_\phi^2}{2m_Q^2 + (|\lambda_Q^s|^2 + |\lambda_Q^b|^2) v_\phi^2}, \quad \Delta_L^{\mu\mu} = \frac{2g_X |\lambda_L^\mu|^2 v_\phi^2}{2m_L^2 + |\lambda_L^\mu|^2 v_\phi^2}. \quad (21)$$

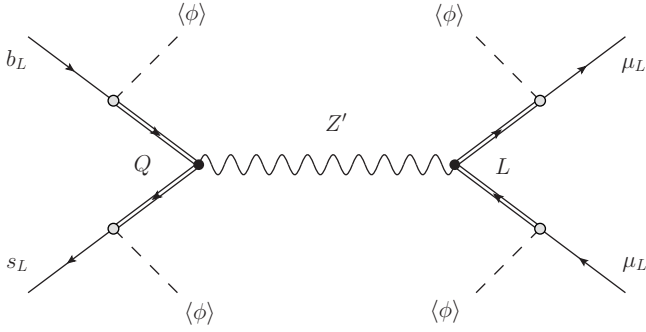


FIG. 1. Generation of  $O_9$  and  $O_{10}$  in our model.

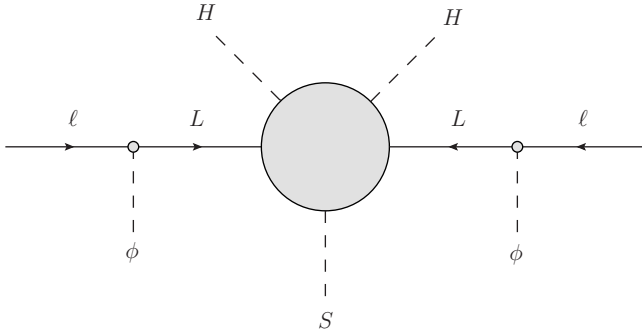


FIG. 2. Non-trivial neutrino mass generation in our setup.  $S$  is a new scalar field with  $U(1)_X$  charge  $-4$ , necessary in order to make the operator gauge invariant.

In case  $\lambda_Q^{s,b} \ll 1$ , the  $Z'$  coupling to a pair of SM quarks can be further approximated to  $\Delta_L^{bs} \simeq g_X v_\phi^2 \frac{\lambda_Q^b \lambda_Q^{s*}}{m_Q^2}$ . These results can be combined with Eq. (8) in order to determine the allowed ranges for the model parameters that explain the  $b \rightarrow s$  anomalies found by LHCb.

### B. Neutrino masses

We can further extend the model to get non-zero masses for the SM neutrinos. This can be done trivially by adding new particles, singlets under  $U(1)_X$ , which mediate the standard mechanisms. For example, the addition of right-handed neutrino singlets,  $\nu_R = (1, 1, 0, 0)$ , allows for the usual type-I seesaw mechanism.

It is, however, more interesting to consider a mechanism that involves the  $U(1)_X$  sector of the model. This can be done by means of the effective operator

$$O_\nu = \frac{1}{\Lambda^5} \ell \ell H H \phi \phi S, \quad (22)$$

as shown in Fig. 2. Here  $S$  is a new scalar field with  $U(1)_X$  charge  $q_S = -4$ , necessary in order to make the operator gauge invariant. An example model that can serve as

ultraviolet completion of  $O_\nu$  is obtained with the addition of the scalar  $S = (1, 1, 0, -4)$ , together with a vector-like (Dirac) fermion  $F = (1, 1, 0, 2)$ . This allows for the Yukawa couplings  $\lambda_S S \bar{F}^c F$  and  $y \bar{L} H F$ , which lead to  $O_\nu$  after integrating out  $F$  and  $L$ . Although  $S$  must get a non-zero VEV in order to break lepton number and generate neutrino masses, we note that our choice  $q_S = -4$  guarantees that the remnant  $\mathbb{Z}_2$  symmetry that stabilizes the DM particle  $\chi$  is preserved.

## IV. DARK MATTER PHENOMENOLOGY

At high temperatures  $\chi$  attains thermal equilibrium in the heat bath through its reactions with the different degrees of freedom to which it couples. At decoupling, the dominant processes determining the DM yield are the following  $2 \leftrightarrow 2$  reactions<sup>2</sup>:

- $HH^\dagger \leftrightarrow \chi\chi^*$  (Higgs portal): processes enabled by the  $\lambda_{H\chi} |H|^2 |\chi|^2$  coupling.
- $\bar{F}F \leftrightarrow \chi\chi^*$ , with  $F$  standing for the SM and the new vector-like quarks and leptons ( $Z'$  portal): the former enabled by  $F_{\text{SM}} - F$  mixing and  $U(1)_X$  coupling, while the latter solely by  $g_X$ .

For very heavy DM with  $m_\chi > m_{Z'}$ , also  $Z'Z' \leftrightarrow \chi\chi^*$  can take place. Depending on the relative size of these processes (pure scalar and  $Z'$ -mediated) one can then distinguish several scenarios. Among them those solely involving  $Z'$ -mediated processes, are—arguably—expected to be dominant (they are driven by a gauge coupling). Interestingly enough, in that case a clear correlation with flavor physics must exist. Note that these processes match those in Fig. 1 if one trades one of the fermion pairs for  $\chi\chi^*$ . Therefore, under the fairly reasonable assumption that the  $Z'$ -mediated processes play a dominant role, an interplay between flavor and DM physics is possible establishing. Thus, in turn, further constraining the flavor-transition parameters through the restrictions imposed by the condition of generating the correct DM relic density (see the useful Ref. [43])<sup>3</sup>.

Although our results rely on MicrOmegas [46], a simple analytical discussion is worth doing. The cross section for the  $\bar{F}F \leftrightarrow \chi\chi^*$  processes can be estimated to be

$$\sigma(s) \sim \left| \Delta_L^{f_i f_j} \right|^2 g_X^2 \frac{1}{s} \frac{m_{Z'}^4}{(m_{Z'}^2 - s)^2 - m_{Z'}^2 \Gamma_{Z'}^2} f(x_f, x_s), \quad (23)$$

where the  $x_i = m_i^2/s$  and  $f(x_f, x_s)$  is a kinematic function. Depending on the relative size of  $m_\chi$  and  $m_{Q,L}$  ( $r = m_\chi/m_{Q,L}$ ), one can distinguish two regimes. For  $r < 1$ , DM annihilation processes involve dominantly SM quarks and leptons ( $b_L, s_L$  and  $\mu_L$ ). In that case, however, the corresponding cross

<sup>2</sup> Note that since  $m_{Z'} > m_\chi$ ,  $Z' \rightarrow \chi\chi^*$  plays a subdominant role.

<sup>3</sup> Further constraints such as direct/indirect detection and collider searches might be also relevant, see [44, 45].

sections are suppressed by chiral/vector-like mixing (see eq. (21)), annihilation is rather inefficient and therefore leads to an overpopulation of  $\chi$  scalars. For  $r > 1$ , processes involving the vector-like fields are also possible, and since they are not suppressed by mixing parameters they can lead to the appropriate DM relic abundance. Note that if the DM and vector-like fermion mass splitting is small, then the cross section will be phase space suppressed:  $f \rightarrow 0$ . In this case, resonant annihilation is needed to efficiently deplete the scalar  $\chi$  population (see Fig. 3). For large mass splittings, in contrast, annihilation is very efficient, and so the correct relic density can be readily obtained. However, reconciling this “scenario” with flavor constraints turns out to be tricky. Avoiding the resonance requires  $m_{Z'} > m_\chi$ , which means  $m_{Z'} \gg m_{L,Q}$ , and a large  $g_X$  close to 1. In that limit,

$$C_9^{\text{NP}} \sim -\frac{\Lambda_v^2}{V_{tb}V_{ts}^*} \frac{\lambda_Q^b \lambda_Q^s}{2m_Q^2}, \quad (24)$$

which for typical vector-like quark masses,  $m_Q \sim \text{TeV}$ , implies large chiral/vector-like quark mixing ( $\lambda_Q^{b,s} \sim 0.05$  couplings) in order to be compatible with the LHCb observations. This, however, is in clear tension with quark flavor constraints (see next section).

In summary, the correct DM relic density can be easily produced within our setup provided  $r \sim O(1)$  and DM annihilation proceeds resonantly. Resonant annihilation can be avoided for  $r \gg 1$ , but finding spots in parameter space consistent with both, DM and flavor constraints seems challenging. The right relic density might as well be produced when  $r < 1$ , but probably this would require being sharply at the  $Z'$  resonance.

## V. CONSTRAINTS

There are constraints on the mass of additional gauge bosons coupled to SM states. The ballpark of these limits is about 2.5–3.0 TeV for  $U(1)$  extensions which predict a coupling of the  $Z'$  to light quarks of  $O(1)$  [47]. However, in our model these couplings are suppressed by the small mixing between the SM quarks and the vector-like states. Thus, we nearly get any constraint on the mass of the  $Z'$  from LHC searches. In addition, we are going to assume in the lepton sector only a sizable mixing for muons with the new states. Therefore, we get also hardly any limit on  $m_{Z'}$  from LEP searches.

Thus, we can safely assume in the following that the  $Z'$  couplings to the first generation of SM fermions can be neglected and evade all LEP and LHC limits. Similarly,  $Z'$  contributions to flavor observables related to the first generation can be safely neglected. Let us now review several relevant constraints in our model.

### A. Collider constraints

The masses of the vector-like quarks have strong bounds from the LHC. Being colored particles, vector-like quarks can be efficiently produced in  $pp$  collisions, which typically pushes their masses towards the TeV scale, see [48] and references therein. Since our setup works with vector-like quarks with masses at or above the TeV scale, these bounds are easily satisfied.

Vector-like leptons can be searched for at the LHC in the standard multi-lepton channels. Using the CMS analysis in [49], based on searches for final states including 3 or more leptons with an integrated luminosity of about  $19.5 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ , Ref. [50] obtained a lower limit on the mass of doublet vector-like leptons of about 460 GeV, in case they decay to electrons or muons, and about 280 GeV, in case they decay to tau leptons. More recently, Ref. [51] considered the analogous ATLAS multi-lepton search [52], with  $20.3 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ , also looking for final states with 3 or more leptons. The results were similar to the ones derived from the CMS analysis, with lower limits on the mass of doublet vector-like leptons of about  $\sim 500 \text{ GeV}$ .

Finally, one can also derive limits from  $Z \rightarrow 4\ell$  searches at the LHC. However, according to [33], these are rather mild, only relevant for  $Z'$  masses below 100 GeV.

### B. Quark flavor constraints

Contrary to the model in [33], where the muonic current contributing to the  $b \rightarrow s$  observables is purely vectorial ( $\bar{\ell}\gamma_\alpha\ell$ ), in our model the current is left-handed and thus contains an axial vector contribution as well ( $\bar{\ell}\gamma_\alpha\gamma_5\ell$ ). This is relevant for the  $B_s \rightarrow \mu^+\mu^-$  decay, especially sensitive to axial-vector currents. Currently, there is a little tension between the SM prediction for the average time-integrated branching ratio,  $\overline{\text{BR}}(B_s \rightarrow \mu^+\mu^-)$ , and the CMS and LHCb measurements. While the SM prediction is found to be  $\overline{\text{BR}}(B_s \rightarrow \mu^+\mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$  [53], the combination of the CMS and LHCb measurements leads to  $\overline{\text{BR}}(B_s \rightarrow \mu^+\mu^-)_{\text{exp}} = (2.9 \pm 0.7) \times 10^{-9}$  [54]. In view of this little deficit, the new  $Z'$  mediated contribution might be potentially welcome.

The  $B_s \rightarrow \mu^+\mu^-$  decay is known for its reach in probing new physics scenarios (see for example the recent papers [55–59]). In the SM, the amplitude is dominated by the axial vector leptonic current, and thus by the  $C_{10}^{\mu}$  Wilson coefficient ( $C_{10}^{\mu, \text{SM}}$ ). Similarly, in the model under consideration, the main NP contribution is given by a modification of  $C_{10}^{\mu}$ . We note that vector contributions vanish for lepton flavor conserving channels. Therefore, our prediction for the average time-integrated branching ratio is simply given by

$$\overline{\text{BR}}(B_s \rightarrow \mu^+\mu^-) = \left| \frac{C_{10}^{\mu, \text{SM}} + C_{10}^{\mu, \text{NP}}}{C_{10}^{\mu, \text{SM}}} \right|^2 \overline{\text{BR}}(B_s \rightarrow \mu^+\mu^-)_{\text{SM}}. \quad (25)$$

Nevertheless, the large experimental error in  $\overline{\text{BR}}(B_s \rightarrow \mu^+\mu^-)$  precludes from obtaining useful bounds. Using the SM

and the experimental average time-integrated branching ratios given above, one finds  $-0.25 < C_{10}^{\mu,\text{NP}}/C_{10}^{\mu,\text{SM}} < 0.03$  (at the  $1\sigma$  level). By combining  $C_{10}^{\mu,\text{NP}} = -C_9^{\mu,\text{NP}}$  with the SM values for  $C_9^\mu$  and  $C_{10}^\mu$ , one finds that in our setup  $C_{10}^{\mu,\text{NP}}/C_{10}^{\mu,\text{SM}} \sim 0.06$ , which is slightly above the  $1\sigma$  limit, and thus perfectly compatible with the experimental measurement of  $\overline{\text{BR}}(B_s \rightarrow \mu^+\mu^-)$  at the  $2\sigma$  level.

Another relevant flavor constraint comes from  $B_s - \bar{B}_s$  mixing, induced at tree-level by  $Z'$  exchange as soon as a non-zero  $\Delta_L^{bs}$  coupling is considered. Allowing for a 10% deviation from the SM expectation in the mixing amplitude,  $|M_{12}/M_{12}^{\text{SM}} - 1| < 0.1$ , one finds [17]

$$\frac{m_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244 \text{ TeV}. \quad (26)$$

### C. Lepton flavor constraints

In principle, the mixings with the vector-like leptons can induce lepton flavor violating (LFV) processes of the type  $l_\alpha \rightarrow l_\beta l_\beta l_\gamma$ , mediated by the  $Z'$  boson. However, one can suppress them with a proper parameter choice. Since all  $b \rightarrow s$  anomalies can be simultaneously explained with (only) new contributions to  $C_9^\mu$ ,  $\lambda_L^\mu \neq 0$  is required, but one can choose  $\lambda_L^{e,\tau} = 0$ . This would eliminate the coupling of the  $Z'$  boson to electrons and tau leptons, and thus all LFV processes mediated by the  $Z'$  boson. This includes LFV in  $B$  decays, recently suggested in [62] and further studied in [31, 63–65].

Besides the anomalies in  $b \rightarrow s$  transitions, the LHC might have found additional hints for new physics. Recently, the CMS collaboration found a  $2.4\sigma$  excess in the  $h \rightarrow \tau\mu$  channel which translates into  $\text{BR}(h \rightarrow \tau\mu) = (0.84_{-0.37}^{+0.39})\%$  [66]. For this result, the collaboration made use of the 2012 dataset taken at  $\sqrt{s} = 8$  TeV with an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . This large Higgs LFV branching ratio cannot be accommodated in our setup, since vector-like leptons are known to be unable to reach such LFV rates in Higgs decays due to limits from the radiative  $\tau \rightarrow \mu\gamma$  decay [50]. However, as suggested in [67, 68] and recently confirmed in several works [34, 69–71], a simple extension with a second Higgs doublet suffices to explain the CMS hint.

Finally, we comment on limits from the (former) non-observation of lepton universality violation. Indeed, very strong bounds have been derived in many scenarios due to the non-observation of lepton universality violating effects in, for example, pion and kaon decays (see for example [72–74]). However, these are absent in our model due to the suppression of the vector-like and first generation SM quark mixing.

### D. Precision measurements

There are several precision measurements in the lepton sector which might be potentially sensitive to the  $Z'$  interactions considered in this model.

First of all, there is the so-called *neutrino trident production* [60]. This is the production of a muon anti-muon pair by

scattering of muon neutrinos in the Coulomb field of a target nucleus. The cross-section gets additional contributions in the presence of a new  $Z'$  boson that couples to the muons, and these can be used to constrain  $\Delta_L^{\mu\mu}$  and  $m_{Z'}$ . The impact of this bound on  $Z'$  models designed to solve the  $b \rightarrow s$  transitions was studied in [33, 34]. Using the CCRF measurement of the trident cross-section [61], one can derive bounds on the mass of the  $Z'$  boson and its coupling to muons. For scenarios with left-handed  $Z'$  coupling to muons, one finds [17]

$$\frac{m_{Z'}}{|\Delta_L^{\mu\mu}|} \gtrsim 470 \text{ GeV}. \quad (27)$$

Finally, there are two other constraints related to precision measurements in leptonic observables:  $(g-2)_\mu$  and the  $Z$  boson couplings to the muon (which are modified at the 1-loop level due to the  $Z'$  interactions). However, in [33] these are found to be relatively mild. For this reason we will not consider them in our numerical analysis.

## VI. NUMERICAL RESULTS

For the numerical analysis we have implemented the model into the `Mathematica` package `SARAH` [76–80] and generated `Fortran` code to link this model to `SPheno` [81, 82]. The big advantage of this setup is that we can cross-check our tree-level approximations with a full numerical calculation. Moreover, based on the `FlavorKit` interface [83], the generated `SPheno` version does not only calculate the tree-level contributions to the Wilson coefficients but also all 1-loop corrections. This way, we can see in what parameter range the tree-level approximation works well and where it breaks down. In general, one can expect loop effects to become important when the mixing between SM quarks and the vector-like states is sizable: this leads to significant changes in the SM-like box and penguin contributions to  $C_9$  and  $C_{10}$ . This alone would not be necessarily a problem. However, the same mixing influences also loop contributions to the other Wilson coefficients, in particular  $C_7$  and  $C_8$ . These effects have to be small in order to satisfy the results of global fits to  $b \rightarrow s$  data. As second step, we used the `CalcHep` [84, 85] output of `SARAH` to implement the model in `MicrOmegas` to calculate the relic density. Interfacing the parameter values between `SPheno` and `MicrOmegas` is done via the `SLHA+` functionality of `CalcHep` [86].

Our main numerical results are summarized in Figs. 3 and 4. In Fig. 3 we show the dark matter relic density in the  $(g_X, m_{Z'})$  plane, together with the ratio  $C_9^{\text{NP}}/C_9^{\text{SM}}$ . The other important parameters entering this calculation have been fixed to

$$\lambda_Q^b = \lambda_Q^s = 0.025, \quad \lambda_L^\mu = 0.5 \\ m_Q = m_L = 1 \text{ TeV}, \quad m_\chi^2 = 1 \text{ TeV}^2$$

First of all, we see that with these parameters the model is perfectly compatible with the constraints discussed in Section V. Furthermore, there is a region for moderately large  $g_X \simeq 0.3$  where the DM constraint can be satisfied and  $C_9^{\text{NP}} =$



## VII. SUMMARY AND DISCUSSION

We have presented a DM model that successfully addresses the anomalies in  $b \rightarrow s$  transitions recently found by the LHCb collaboration. In our setup,  $B$  mesons decay through the  $Z'$  into the dark sector, which mixes with the SM via Yukawa couplings. An interesting connection between DM and flavor physics emerges, leading to a very constrained scenario where the NP masses and parameters are restricted to lie in thin regions of the full parameter space.

The model offers several interesting phenomenological possibilities. Due to the mixing between the SM muons and the vector-like lepton doublet, our model predicts a reduction of the  $h - \mu - \mu$  coupling,  $g_{h\mu\mu}$ , with respect to the SM prediction. The most direct probe of this coupling is, of course, the Higgs boson decay into a pair of muons,  $h \rightarrow \mu^+ \mu^-$ , experimentally very challenging in a hadron collider due to the expected low branching ratio ( $O(10^{-4})$  in the SM). In 2013, the ATLAS collaboration presented results based on an integrated luminosity of  $20.7 \text{ fb}^{-1}$  in collisions at  $\sqrt{s} = 8 \text{ TeV}$ , without any evidence of a signal [75]. For  $m_h = 125 \text{ GeV}$ , they obtained an upper limit on the  $\mu\mu$  signal strength,  $\mu_{\mu\mu} < 9.8$  (at 95% CL). Assuming a SM-like Higgs boson production, this limit translates into  $g_{h\mu\mu} \lesssim 3.1 g_{h\mu\mu}^{\text{SM}}$ . Obviously, our model is well within the limit, since it predicts a reduction of the coupling. Nevertheless, it is worth pointing out that a precise determination of this coupling in a future linear collider would be a strong test of the model <sup>4</sup>.

Let us also comment on the mixings between the vector-like fermions and the SM ones. These are determined by free Yukawa parameters which, in principle, are naturally expected to be of the same order for all SM generations. However, in order to avoid conflict with existing experimental data, one is

forced to strongly suppress the mixings with the first generation, implying  $\lambda_Q^d, \lambda_L^e \ll \lambda_Q^{s,b}, \lambda_L^{\mu,\tau}$ . This might seem like an ad-hoc assumption. However, it just reflects the *constant* need for a theory of flavor, also required to understand the Yukawa structure of the SM <sup>5</sup>.

Finally, one can envisage several phenomenological directions in which this model can be further explored. By allowing for non-zero couplings to first generation quarks and leptons, the impact of the model gets extended to many additional observables of interest. In particular, the LHC would be able to probe the parameter space of the model via the production of the  $Z'$  boson. Furthermore, since the scalar DM carries, at early times, a conserved  $U(1)_X$  charge it will develop an asymmetry, provided chemical equilibrium with the thermal bath is guaranteed. In such a case (asymmetric DM scenario [88]), a link between the baryon and DM asymmetries is something worth exploring.

### NOTE ADDED

An update of the global fit [17] was recently presented in [89]. While this would change slightly the numerical output of our analysis, our conclusions would remain unchanged.

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<sup>4</sup> According to [87], CLIC would be able to measure the  $h - \mu - \mu$  coupling with an uncertainty of about 19%.

<sup>5</sup> We note that although the lepton sector of [33] naturally explains the required hierarchy for the lepton couplings, in the quark sector the situation is exactly the same as in our model.



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