Flavor and Dark Matter connection

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Abstract. In recent years, the LHCb collaboration has published results on the measurement of several observables associated to semileptonic $b \rightarrow s$ transitions. Interestingly, various deviations from their expected values in the Standard Model have been found, including some tantalizing hints pointing towards the violation of Lepton Flavor Universality. We discuss New Physics models that address these anomalies and explore their possible connection to the dark matter of the Universe.

Keywords: Flavor, Dark Matter, B-anomalies, New Physics

1 Introduction

One of the most relevant open questions in current physics is the nature of the dark matter (DM) that makes up 27% of the energy density of the Universe [1]. Many ideas and proposals have been put forward, including the possibility that the DM is composed of particles. This popular scenario requires an extension of the Standard Model (SM) with new states and dynamics, since the SM particles do not have the required properties to be a good DM candidate.

Lepton Flavor Universality (LFU) is a central feature in the SM. The fact that gauge bosons couple with the same strength to the three generations of leptons is well rooted in the SM construction and has a strong experimental support. Nevertheless, this expectation is broken in some New Physics (NP) scenarios, and this can lead to clear signatures of physics beyond the SM. In fact, these signatures might have been observed already. Since 2013, the LHCb collaboration has reported on the measurement of several observables associated to semileptonic $b \rightarrow s$ transitions, finding some tensions with the SM expectations, including possible hints of the violation of LFU.

We are interested in NP models that aim at an explanation of the so-called $b \rightarrow s$ anomalies while introducing a dark sector with the ingredients to accommodate the astrophysical and cosmological indications of the existence of DM [2]. Several authors have explored this direction [3–22]. The rest of the manuscript is organized as follows. We review the $b \rightarrow s$ anomalies and provide a model independent interpretation in Sec. [2] Sec. [3] classifies the proposed New Physics explanations to these anomalies with a link to the dark matter problem and presents two example models that illustrate this connection. We finally summarize in Sec. [4]
There are two types of $b \to s$ anomalies: (1) branching ratios and angular observables, and (2) lepton flavor universality violating (LFUV) anomalies.

**Branching ratios and angular observables:** In 2013, the LHCb collaboration reported on the measurement of several observables in the decay $B \to K^*\mu^+\mu^-$ with 1 fb$^{-1}$ of integrated luminosity. Interestingly, several deviations with respect to the SM expectations were found. The most popular one was a $3.7\sigma$ discrepancy in one of the dimuon invariant mass bins in the $P'_{5}$ angular observable $[23]$. Moreover, LHCb also found a systematic deficit in several branching ratios, mainly $\text{BR}(B_s \to \phi\mu^+\mu^-)$ $[24]$. These anomalies were later confirmed with the addition of further data with the presentation by LHCb of new results in 2015, using in this case their full Run 1 dataset with 3 fb$^{-1}$ $[25,26]$.

**LFUV anomalies:** several observables have been proposed in order to test LFU experimentally. In particular, one can consider the $R_{K^*}$ ratios, given by $[27]$

$$R_{K^*} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}.$$  

These observables are measured in specific dilepton invariant mass squared ranges $q^2 \in [q^2_{\text{min}}, q^2_{\text{max}}]$. These ratios are very close to one in the SM, but this prediction can be altered by NP violating LFU. Moreover, hadronic uncertainties are expected to cancel to a high degree. Therefore, a deviation in $R_{K^*}$ would be regarded as a very clear sign of LFUV. Interestingly, several measurements by the LHCb collaboration point in this direction. The measurement of $R_K$ in the region $[1, 6]$ GeV$^2$ was reported in 2014 $[28]$, whereas the measurement of the $R_{K^*}$ ratio in two $q^2$ bins was announced in 2017 $[29]$. These were the results:

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036, \quad q^2 \in [1, 6] \text{ GeV}^2,$$

$$R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024, \quad q^2 \in [0.045, 1.1] \text{ GeV}^2,$$

$$R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047, \quad q^2 \in [1.1, 6.0] \text{ GeV}^2.$$  

When these are compared to the SM predictions $[30]$, one finds deviations from the SM at the $2.6\sigma$ level in the case of $R_K$, $2.2\sigma$ for $R_{K^*}$ in the low-$q^2$ region, and $2.4\sigma$ for $R_{K^*}$ in the central-$q^2$ region.

While the first category, angular observables and branching ratios, might be affected by hadronic uncertainties and the possibility of uncontrolled QCD
effects cannot be discarded, the second one, composed by the $R_K^{(*)}$ ratios, is clean from this issue and can only be explained by NP violating LFU.

In order to interpret these experimental results it is convenient to adopt a language based on effective field theory. The effective Hamiltonian for $b \rightarrow s$ transitions can be written as

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

Here $G_F$ is the Fermi constant, $e$ the electric charge and $V$ the Cabibbo-Kobayashi-Maskawa matrix. The effective operators contributing to $b \rightarrow s$ transitions are denoted by $\mathcal{O}_i$ and $\mathcal{O}'_i$, while $C_i$ and $C'_i$ denote their Wilson coefficients. The operators that turn out to be relevant for the interpretation of the $b \rightarrow s$ anomalies are

$$\mathcal{O}_9 = (\bar{s} \gamma_\mu P_L b) \left( \bar{\ell} \gamma^\mu \ell \right), \quad \mathcal{O}'_9 = (\bar{s} \gamma_\mu P_R b) \left( \bar{\ell} \gamma^\mu \ell \right), \quad (5)$$

$$\mathcal{O}_{10} = (\bar{s} \gamma_\mu P_L b) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right), \quad \mathcal{O}'_{10} = (\bar{s} \gamma_\mu P_R b) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right). \quad (6)$$

Here $\ell = e, \mu, \tau$. Unless necessary, we will omit flavor indices in the Wilson coefficients in order to simplify the notation. It proves convenient to split the Wilson coefficients into their SM and NP pieces, defining

$$C_9 = C_9^{\text{SM}} + C_9^{\text{NP}}, \quad (7)$$

$$C_{10} = C_{10}^{\text{SM}} + C_{10}^{\text{NP}}. \quad (8)$$

Several independent global fits \cite{31,38} have compared a large set of experimental measurements of observables associated to $b \rightarrow s$ transitions to their expected values in the SM, finding a remarkable tension, only alleviated by the introduction of NP contributions. In particular, there is a general agreement on the qualitative fact that global fits improve substantially with a negative contribution in $C_9^{\mu,\text{NP}}$, with $C_9^{\mu,\text{NP}} \sim -25\% \times C_9^{\text{SM}}$. NP contributions in other muonic Wilson coefficients can affect the global fit, but they are sub-dominant compared to $C_9^{\mu,\text{NP}}$. For instance, the addition of NP in the one-dimensional direction given by $C_9^{\mu,\text{NP}} = -C_{10}^{\mu,\text{NP}}$ also serves to improve the fit, and this can be regarded as a hint in favor of purely left-handed NP interactions. Moreover, no hint for NP is found in contributions involving electrons or tau leptons.\footnote{See also \cite{39} for a recent analysis of the $b \rightarrow s$ anomalies based on gauge invariant effective operators.}

3 Model classification

In general, the models explaining the $b \rightarrow s$ anomalies with a link to the dark matter problem can be classified into two categories:

– **Portal models:** in these models the mediator responsible for the NP contributions to $b \rightarrow s$ transitions is also the mediator for the production of DM in the early Universe.
– **Loop models**: in these models the required NP contributions to $b \to s$ transitions are induced via loops containing the DM particle.

There are also some *hybrid models* that share some properties with both categories.

### 3.1 A portal model

We will first discuss the portal model introduced in [3]. An extension of this model that also accounts for neutrino masses has been recently discussed in [40].

| Field Spin $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$ |
|-----------------------------|
| $\phi$ 0 $(1,1,0,2)$ |
| $\chi$ 0 $(1,1,0,-1)$ |
| $Q_{L,R}$ $\frac{1}{2}$ $(3,2,\frac{1}{6},2)$ |
| $L_{L,R}$ $\frac{1}{2}$ $(1,2,-\frac{1}{2},2)$ |

**Table 1.** New scalars and fermions in the model of [3].

The model adds a new $U(1)_X$ factor to the SM gauge symmetry, with its gauge boson denoted as $Z'$ and its gauge coupling as $g_X$. All the SM particles are singlets under this new symmetry, while the new states beyond the SM, the vector-like (VL) fermions $Q$ and $L$ and the complex scalar fields $\phi$ and $\chi$, are charged. Table 1 shows the charges of the new scalars and fermions in the model. In addition to the usual canonical kinetic terms, the new VL fermions $Q$ and $L$ have gauge-invariant mass terms,

$$L_m = m_Q \overline{Q}Q + m_L \overline{L}L. \quad (9)$$

They also have Yukawa couplings with the SM doublets $q$ and $\ell$ and the scalar $\phi$,

$$L_Y = \lambda_Q \overline{Q}_{R} \phi q_L + \lambda_L \overline{L}_{R} \phi \ell_L + h.c. \quad (10)$$

Here $\lambda_Q$ and $\lambda_L$ are 3 component vectors. We will consider that the scalar potential of the model leads to a vacuum expectation value (VEV) for the $\phi$ scalar, $\langle \phi \rangle = \frac{v\phi}{\sqrt{2}}$, breaking $U(1)_X$ spontaneously and inducing a mass for the $Z'$ boson, $m_{Z'} = 2g_X v\phi$. In contrast, the scalar $\chi$ does not get a VEV. This leads to the existence of a remnant $Z_2$ parity, under which $\chi$ is odd and all the other particles are even. This mechanism [41–43] stabilizes $\chi$ without the need of any additional symmetry.

The solution to the $b \to s$ anomalies in this model is diagrammatically shown in Fig. [1]. The Yukawa couplings in Eq. (10) induce mixings between the VL and SM fermions after $U(1)_X$ breaking. This mixing results in $Z'$ effective
couplings to the SM fermions. Since the SM fermions participating in the Yukawa interactions are purely left-handed, the model predicts \( C_{\mu,9}^{\mu, \text{NP}} = -C_{10}^{\mu, \text{NP}} \). It is possible to show that by using \( |\lambda_{Q}^{\mu}| \sim 1 \gg |\lambda_{b,s}^{\mu}| \) one can accommodate the required values for \( C_{\mu,9}^{\mu, \text{NP}} \) and \( C_{10}^{\mu, \text{NP}} \) determined by the global fits to \( b \to s \) data and, at the same time, be compatible with all constraints.

In what concerns to the Dark Matter predictions of the model, we already pointed out that \( \chi \) is automatically stable due to the remnant \( Z_2 \) symmetry that is left after symmetry breaking. Therefore, this is the DM candidate. Its production in the early Universe takes place via \( 2 \leftrightarrow 2 \) processes mediated by the massive \( Z' \) boson. This establishes a link with the \( b \to s \) anomalies and justifies the choice of name portal models for the category represented by this model.

### 3.2 A loop model

We now consider the model introduced in [14], a simple illustration of the category of loop models. In this case, the SM symmetry is extended with a global (not gauge) \( U(1)_X \) symmetry. As in the previous model, all SM fields are assumed to be singlets under this symmetry. In contrast, the new fields, the VL fermions \( Q \) and \( L \) and the complex scalar \( X \), are charged. Table 2 details the new scalar and fermionic fields and their charges under the symmetries of the model.

The Lagrangian of the model contains the same Dirac mass terms as in Eq. (9), as well as the Yukawa couplings

\[
\mathcal{L}_Y = \lambda_Q \bar{Q}_R X q_L + \lambda_L \bar{L}_R X \ell_L + \text{h.c.}
\] (11)
Here $\lambda_Q$ and $\lambda_L$ are 3 component vectors. We consider a vacuum with $\langle X \rangle = 0$. This preserves the global $U(1)_X$ symmetry and stabilizes the lightest state with a non-vanishing charge under this symmetry. Furthermore, the conservation of $U(1)_X$ forbids the mixing between SM and VL fermions.

![Diagram](image)

**Fig. 2.** Generation of $\mathcal{O}_9$ and $\mathcal{O}_{10}$ in the model of [14].

The solution of the $b \rightarrow s$ anomalies comes now at the 1-loop level, as shown in Fig. 2. No NP contributions to $b \rightarrow s$ transitions are generated at tree-level in this model, as can be easily checked. As in the previous case, the left-handed chirality of the fermions involved in the new Yukawa interactions leads to $C^\mu_{9,\text{NP}} = -C^\mu_{10,\text{NP}}$, and one can obtain the required ranges for these Wilson coefficients by properly adjusting the parameters of the model.

Finally, we move on to the Dark Matter phenomenology of the model. Assuming that the lightest state charged under $U(1)_X$ is the neutral scalar $X$, it constitutes the DM candidate in the model. As discussed in detail in [14], the most relevant DM annihilation channels for the determination of the DM relic density are $XX^* \rightarrow \mu^+\mu^-, \nu\nu$, and this is due to the fact that one requires a large $|\lambda^L_{\mu}|$ in order to account for the $b \rightarrow s$ anomalies. Interestingly, the model is also testable in direct DM detection experiments, such as XENON1T.

### 4 Summary

Flavor and Dark Matter may seem two completely independent issues, but they might be connected to the same fundamental physics. In these proceedings we have discussed models that link the solution to the $b \rightarrow s$ anomalies, a subject of great interest in current flavor physics, to the existence of a dark sector. In doing this, these models extend the SM with new ingredients, opening new model building directions that would not be explored in the absence of this connection. It would definitely be fascinating to find a deep bond between these two areas of physics.
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