Leptoquarks in Flavour Physics

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Abstract. While the LHC has not directly observed any new particle so far, experimental results from LHCb, BELLE and BABAR point towards the violation of lepton flavour universality in $b \rightarrow s\ell^+\ell^-$ and $b \rightarrow c\ell\nu$. In this context, also the discrepancy in the anomalous magnetic moment of the muon can be interpreted as a sign of lepton flavour universality violation. Here we discuss how these hints for new physics can also be explained by introducing leptoquarks as an extension of the Standard Model. Indeed, leptoquarks are good candidates to explain the anomaly in the anomalous magnetic moment of the muon because of an m_t/m_μ enhanced contribution giving correlated effects in Z boson decays which is particularly interesting in the light of future precision experiments.

1 Introduction

So far the LHC has not directly observed any particles beyond the ones in the Standard Model of particle physics (SM). While in the SM the Higgs boson couplings to fermions are the only source of lepton flavour universality violation (LFUV), in the past years several hints for additional LFUV have been accumulated. The ratios of semi-leptonic B decays

$$R(K^{(*)}) = \text{Br}[B \rightarrow K^{(*)}\mu^+\mu^-] / \text{Br}[B \rightarrow K^{(*)}e^+e^-],$$

$$R(D^{(*)}) = \text{Br}[B \rightarrow D^{(*)}\tau\nu] / \text{Br}[B \rightarrow D^{(*)}\ell\nu],$$

$$R(J/\Psi) = \text{Br}[B_c^+ \rightarrow J/\Psi\tau^+\nu] / \text{Br}[B_c \rightarrow J/\Psi\mu^+\nu],$$

show sizeable deviations from the SM predictions. Considering $b \rightarrow s\ell^+\ell^-$ transitions, $R(K)$ [1] and $R(K^*)$ [2] show a combined significance for LFUV at the 4σ level [3–7]. If we also take into account all other $b \rightarrow s\mu^+\mu^-$ observables, in several scenarios the global fit prefers new physics (NP) above the 5σ level [8]. In $R(D^{(*)})$ BaBar [9], BELLE [10, 11] and LHCb [12, 13] found a significance for LFUV of about 4σ [14]. In this context it is interesting to mention that LHCb recently measured a deviation of about 2σ in $R(J/\Psi)$ [15]. This is consistent with the anomaly in $R(D)$ and $R(D^*)$. The tension in the anomalous magnetic moment of the muon (a_μ) between measurement [16] and SM prediction is at the 3σ level [17, 18]. Also this discrepancy can be interpreted as a sign of LFUV even though the anomalous magnetic moments are already in the SM flavour non-universal: If we assume that NP coupled with the same

strength to electrons and to muons, a_e would be more sensitive for NP. Since no deviation from the SM prediction in a_e has been observed so far, the tension in a_μ can be interpreted as another sign for LFUV induced by NP.

Motivated by these anomalies, we study leptoquarks (LQ) which provide a possible solution of them. Firstly we concentrate on each anomaly itself and discuss which LQ representations suit best for an explanation and consider correlated effects in other observables. Finally, we will investigate if we can explain the described anomalies simultaneously.

2 a_μ

In order to explain the discrepancy in a_μ , a rather large effect of the order of the SM weak interaction contribution is required. Among the set of new particles that can give the desired effect, LQ are interesting candidates [19–23]. Even though the LQ must be rather heavy due to LHC constraints (above 1 TeV), one can still get relevant effects in a_μ . For some representations of LQ, the amplitude can be enhanced by a factor $m_t/m_\mu \simeq \mathcal{O}(10^3)$ or $m_b/m_\mu \simeq \mathcal{O}(10)$ compared to the SM.

To achieve an enhancement of factor m_t/m_μ , the LQ must couple to left- and right-handed top or anti-top quarks simultaneously. However, not all LQ representations have this feature. Among the 10 scalar and vector LQ representations generating lepton-quark interaction terms that are invariant under the SM gauge group [24], only two scalars can possess this enhancement: An SU(2) singlet Φ_1 and an SU(2) doublet Φ_2 with quantum numbers

$$Q(\Phi_1) : \left(3, 1, -\frac{2}{3}\right), \quad Q(\Phi_2) : \left(\bar{3}, 2, -\frac{7}{3}\right). \quad (1)$$

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Figure 1. Feynman diagrams that contribute to a_μ and $Z \rightarrow \ell_i^+ \ell_f^-$. The crosses on the fermion lines stand for chirality flips, involving a top mass.

These representations couple to the fermions of the SM as follows

$$\mathcal{L}_{int} = (\lambda_{fi}^{1R} \bar{u}_f^c \ell_i + \lambda_{fi}^{1L} \bar{Q}_f^c i \tau_2 L_i) \Phi_1^\dagger, \quad (2)$$

$$\mathcal{L}_{int} = (\lambda_{fi}^{2RL} \bar{u}_f L_i + \lambda_{fi}^{2LR} \bar{Q}_f i \tau_2 \ell_i) \Phi_2^\dagger. \quad (3)$$

Q and L are SU(2) doublets, u and ℓ are SU(2) singlets and c denotes charge conjugation. f and i are flavour indices. The Feynman diagrams involving Φ_1 and Φ_2 are shown left in Fig. 1.

For simplicity, we only consider couplings of top quarks to muons and set $\lambda_{32}^{1L,1R}$ and $\lambda_{32}^{2RL,2LR}$ equal to $\lambda_{\mu}^{L,R}$. Besides the contribution to a_μ , we also obtain correlated effects in $Z \rightarrow \mu^+ \mu^-$ (see the right Feynman diagram in Fig. 1), in $b \rightarrow s \nu \bar{\nu}$ (for Φ_1) and in $b \rightarrow s \mu^+ \mu^-$ (for Φ_2). Fig. 2 shows the allowed regions in $\lambda_{\mu}^L - \lambda_{\mu}^R$ parameter space for a LQ with mass of 1 TeV, to respect constraints from direct searches. For $Z \rightarrow \mu^+ \mu^-$ the expected bounds from GigaZ [25] and TLEP [26] are shown as well. Additionally, for Φ_1 the expected BELLE II limit for $B \rightarrow K^{(*)} \nu \bar{\nu}$ is taken into account. Φ_2 gives a $C_9 = C_{10}$ -like contribution to $b \rightarrow s \ell^+ \ell^-$ which provides a slight improvement of 1σ in the global fit.

If we also allow for couplings of the top quark to taus or electrons, lepton flavour violating processes as $\tau \rightarrow \mu \gamma$ or $Z \rightarrow \mu e$ will be possible. A more detailed discussion can be found in Ref. [27].

3 $b \rightarrow s \ell^+ \ell^-$

Dealing with $b \rightarrow s \ell^+ \ell^-$ transitions, one usually works with an effective Hamiltonian of the form

$$H_{\text{eff}}^{\ell_f \ell_i} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{a=9,10} C_a^{fi} O_a^{fi} + C_a'^{fi} O_a'^{fi}, \quad (4)$$

$$O_{9(10)}^{fi} = \frac{\alpha}{4\pi} [\bar{s} \gamma^\mu P_L b] [\bar{\ell}_f \gamma_\mu (\gamma_5) \ell_i], \quad (5)$$

$$O_{9(10)}'^{fi} = \frac{\alpha}{4\pi} [\bar{s} \gamma^\mu P_R b] [\bar{\ell}_f \gamma_\mu (\gamma_5) \ell_i]. \quad (6)$$

Then, for several scenarios with NP in C_9 only, $C_9 = -C_{10}$ or $C_9 = -C_9'$, the global fit prefers NP above the 5σ level [8].

We consider the case where NP contributes as $C_9 = -C_{10}$.

While in the muon channel the preferred value deviates from the SM prediction with a tension of 5σ , in the case with electrons the SM contribution is sufficient to give a good fit to the data. To reach the central value, an $O(10\%)$ NP effect in the muon channel is required. $b \rightarrow s \ell^+ \ell^-$ is suppressed by a loop and a CKM factor because it is a flavour changing neutral current. Therefore, the effect of NP does not have to be very large to account for the data. There are several suggestions to explain the anomaly in $b \rightarrow s \mu^+ \mu^-$ with LQ, see e.g. [28–41].

There are three LQ representations that give a $C_9 = -C_{10}$ -like contribution to $b \rightarrow s \ell^+ \ell^-$

$$\Phi_3 : \left(3, 3, -\frac{2}{3}\right), \mathcal{L}_{int} = \lambda_{fi}^3 \bar{Q}_f^c i \tau_2 (\tau \cdot \Phi_3)^\dagger L_i, \quad (7)$$

$$V_1^\mu : \left(\bar{3}, 1, -\frac{4}{3}\right), \mathcal{L}_{int} = (\kappa_{fi}^{1R} \bar{d}_f \gamma_\mu \ell_i + \kappa_{fi}^{1L} \bar{Q}_f \gamma_\mu L_i) V_1^{\mu\dagger}, \quad (8)$$

$$V_3^\mu : \left(3, 3, \frac{4}{3}\right), \mathcal{L}_{int} = \kappa_{fi}^3 \bar{Q}_f \gamma_\mu (\tau \cdot V_3^\mu) L_i. \quad (9)$$

If we only allow for couplings to muons, these LQ will give tree-level effects in $b \rightarrow s \mu^+ \mu^-$ but contribute at loop-level in other flavour observables. This is why LQ can explain the anomalies in $b \rightarrow s \mu^+ \mu^-$ transitions but are not in conflict with other observables.

Including couplings to electrons, we get additional effects in $b \rightarrow s e^+ e^-$ as well as in the lepton flavour violating processes $\mu \rightarrow e \gamma$ and $b \rightarrow s \mu e$. We can write

$$\text{Br}[\mu \rightarrow e \gamma] \propto \left| \chi C_9^{ee} + \frac{C_9^{\mu\mu}}{\chi} \right|^2, \quad (10)$$

$$\text{Br}[B \rightarrow K \mu e] \propto \left| \frac{C_9^{ee}}{\gamma} \right|^2 + |\gamma C_9^{\mu\mu}|^2, \quad (11)$$

where $\chi = y_{32}/y_{21}$ and $\gamma = y_{21}/y_{22}$, with $y = \lambda$ for scalar LQ and $y = \kappa$ for vector LQ. Note that one can avoid an effect in $\mu \rightarrow e \gamma$ completely if $C_9^{\mu\mu} = -\chi^2 C_9^{ee}$. For real values of χ this means that $\text{sign}[C_9^{ee}] = -\text{sign}[C_9^{\mu\mu}]$. In Fig. 3 you find a detailed analysis for the scalar triplet Φ_3 . For V_1^μ and V_3^μ the situation is quite similar, albeit the blue bands are more narrow. For more information see Ref. [42].

Figure 2. Allowed regions in the λ_μ^L - λ_μ^R parameter space from current limits of LEP and expected future constraints of GigaZ and TLEP with $M_{LQ} = 1$ TeV. Left: SU(2) singlet Φ_1 . Right: SU(2) doublet Φ_2 . Note that if the expected sensitivity of TLEP was reached and no excess in the $Z\mu\bar{\mu}$ -coupling was found, an explanation of the anomaly in a_μ would strongly be disfavoured.

4 $b \rightarrow c\tau\nu$

The transition $b \rightarrow c\tau\nu$ is a charged current process and is therefore generated at tree-level in the SM. Since an explanation of $R(D)$ and $R(D^*)$ requires an $\mathcal{O}(10\%)$ effect, also the NP must contribute at tree-level. Charged Higgses [44–48], W' bosons [31] and LQ [22, 23, 32, 33, 35, 49, 49–54] are NP candidates. However, B_c lifetime [55, 56] and q^2 distributions [57] in combination with direct searches [58] strongly disfavour charged Higgses and W' bosons.

Hence, we are left with LQ. If we want to explain the excess in $R(D)$ and $R(D^*)$ by modifying the couplings to tau neutrinos and/or taus, we also get effects in $b \rightarrow s\tau^+\tau^-$ and $b \rightarrow s\nu\bar{\nu}$. It can be shown in a model independent way that these effects are of the order of 10^3 compared to the SM [33]. This is due to the fact that the processes $b \rightarrow s\tau^+\tau^-$ and $b \rightarrow s\nu\bar{\nu}$ occur at loop-level in the SM, while LQ contribute at tree-level with considerably large couplings in order to explain $R(D^{(*)})$. An $\mathcal{O}(10^3)$ effect is in strong conflict with experimental results of $B \rightarrow K^{(*)}\nu\bar{\nu}$. Hence, a model that explains $R(D)$ and $R(D^*)$ must avoid a major effect in $b \rightarrow s\nu\bar{\nu}$. One possibility is the vector LQ singlet V_1^μ (see Eq. (8)). Another model was proposed in Ref. [59], where instead of V_1^μ two scalar LQ (the SU(2) singlet Φ_1 in Eq. (2) and the SU(2) triplet Φ_3 in Eq. (7)) are required. If Fig. 4 we can see for which parameters we can explain $R(D^{(*)})$ without violating the limits of $b \rightarrow s\nu\bar{\nu}$.

Besides explaining $R(D^{(*)})$, it also enhances $B_s \rightarrow \tau^+\tau^-$ up to a factor 10^3 compared to the SM and therefore lies within experimental reach. The current limit is $\text{Br}[B_s \rightarrow \tau^+\tau^-] < 6.8 \times 10^{-3}$ [60]. Fig. 5 shows the correlation of $R(D^{(*)})$ and $\text{Br}[B_s \rightarrow \tau^+\tau^-]$.

5 Simultaneous Explanation

We may ask if one can explain the three types of anomalies in a_μ , $b \rightarrow s\mu^+\mu^-$ and $R(D^{(*)})$ simultaneously.

If we take the model that we proposed in Sec. 4 and insert a discrete symmetry for the couplings $\lambda_{jk}^{1L} = e^{i\pi j} \lambda_{jk}^3 \equiv \lambda_{jk}^L$ the effect in $b \rightarrow s\nu\bar{\nu}$ will be cancelled exactly. If we include $b \rightarrow s\mu^+\mu^-$, $B \rightarrow D^{(*)}\mu\nu/B \rightarrow D^{(*)}e\nu$ will be affected. However, these observables remain compatible with experiments. Additionally the LFV process $\tau \rightarrow \mu\gamma$ and $b \rightarrow s\tau\mu$ appear. Both processes give constraints on our parameter space. On the left-hand side of Fig. 6 the allowed regions for $M_{LQ} = 1$ TeV are shown, under the assumption that $b \rightarrow s\mu^+\mu^-$ matches the central value of the global fit. As we can see easily, the explanation of $R(D^{(*)})$ requires $\lambda_{33}^L/\lambda_{32}^L > 1$. On the right-hand side of Fig. 6 we need $\lambda_{33}^L/\lambda_{32}^L < 0.6$ to explain a_μ without getting in conflict with experimental constraints of $\tau \rightarrow \mu\gamma$. With this contradiction, we cannot explain all three anomalies simultaneously. However, if we abandon anyone of them, it is possible to explain the other two anomalies. If we abandon the assumption $\lambda_{jk}^{1L} = e^{i\pi j} \lambda_{jk}^3$ one can avoid the discussed constraints and explain all three anomalies.

Another good candidate is the vector LQ singlet V_1^μ because it does not affect the $b \rightarrow s\nu\bar{\nu}$ transitions but gives a $C_9 = -C_{10}$ effect in $b \rightarrow s\ell^+\ell^-$. It can also be used to explain $R(D^{(*)})$. In a_μ we can obtain a m_b/m_μ contribution which is not as large as for the two scalar LQ Φ_1 and Φ_2 (see Sec.2), but still may be significant.

However, one faces the problem that massive vector bosons without a Higgs mechanism are not renormalizable. For $\ell' \rightarrow \ell\gamma$ in Sec. 3 this does not cause a problem because this process is finite in unitary gauge. Recently, models containing renormalizable massive vector LQ were proposed [61–64]. In Ref. [62] a Pati-Salam model in combination with vector-like fermions is phe-

Figure 3. The darker (lighter) red region shows the global fit at 1σ (2σ) for $b \rightarrow se^+e^-$ and $b \rightarrow s\mu^+\mu^-$ transitions. In blue, the allowed region constrained by the current limit $\text{Br}[\mu \rightarrow e\gamma] < 4.2 \times 10^{-13}$ [43] with $\chi = \{1/4, 1, 4\}$ for the scalar triplet Φ_3 with $M_{LQ} = 1\text{TeV}$. The outer (inner) green contour shows the case where $\text{Br}[B \rightarrow K\mu^+\mu^-] = 2 \times 10^{-8}$ (0.2×10^{-8}). For real values of χ only the region with $C_9^{\mu\mu} < 0$ and $C_9^{ee} > 0$ seems to be compatible with experimental limits. Indeed this is also where the central value of the global fit lies. However, if in the future the global fit prefers $C_9^{\mu\mu} < 0$ and $C_9^{ee} < 0$, LQ with real couplings will not be able to explain $b \rightarrow s\ell^+\ell^-$ transitions without violating the constraints from $\mu \rightarrow e\gamma$.

Figure 4. In lighter (darker) blue you see the 1σ (2σ) preferred region of the weighted sum of $R(D)$ and $R(D^*)$, in yellow the allowed region of $b \rightarrow s\nu\bar{\nu}$. $M_{1(3)}$ is the mass of the LQ Φ_1 (Φ_3).

Figure 5. In blue we have the weighted sum of $R(D)$ and $R(D^*)$ and the red line depicts the correlated prediction of $\text{Br}[B_s \rightarrow \tau^+\tau^-]$. The grey region shows the current experimental bounds.

nomenologically consistent and leads to a massive vector LQ. This vector LQ has the properties of V_1^μ in Eq. (8).

6 Conclusion

In these proceedings we reviewed which LQ are good candidates to explain flavour anomalies: For the deviation in a_μ the scalar LQ Φ_1 and Φ_2 give an m_t/m_μ enhanced contribution. This is a useful feature to explain the rather large

discrepancy. Considering $b \rightarrow s\ell^+\ell^-$ transitions, the three LQ representations Φ_3 , V_1^μ and V_3^μ are required by the fit, because they give $C_9 = -C_{10}$. $R(D^{(*)})$ can be explained either by V_1^μ or, as we proposed, by a combination of a scalar LQ singlet Φ_1 and scalar LQ triplet Φ_3 without getting in conflict with $b \rightarrow s\nu\bar{\nu}$ observables. We also showed that this model is able to explain any two of the three anomalies (a_μ , $b \rightarrow s\mu^+\mu^-$ and $R(D^{(*)})$) simultaneously.

Figure 6. Left: In blue we have the weighted sum of $R(D)$ and $R(D^*)$. The contour lines show $\text{Br}[B \rightarrow K\tau\mu] \times 10^6$. Right: The anomaly in a_μ combined with the contour lines depicting $\text{Br}[\tau \rightarrow \mu\gamma] \times 10^8$. In both plots the grey region is excluded by experiments.

Acknowledgments

D.M. thanks the organizing committee, and especially Giancarlo D'Ambrosio, for the invitation and for giving the opportunity to present his work.
D.M. is supported by an Ambizione Grant of the Swiss National Science Foundation (PZ00P2_154834).

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