Present Status of $b \to s \ell^+ \ell^-$ Anomalies

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Abstract

We discuss the observed deviations in $b \to s \ell^+ \ell^-$ processes from the Standard Model predictions and present global fits for the New Physics description of these anomalies. We further investigate the stability of the global fits under different theoretical assumptions and suggest strategies and a number of observables to clear up the source of the anomalies.

Keywords: $B$-Physics, Global Fit, Lepton Flavour Universality Violation

1. Introduction

The angular observables of the $B \to K^* \mu^+ \mu^-$ decay were measured in 2013 by the LHCb collaboration using $1 \text{ fb}^{-1}$ of data [1]. While most of the measured observables agreed with their Standard Model (SM) predictions, the angular observable $P_5'$ was in $3.7\sigma$ tension with respect to the SM prediction, in the $q^2 \in [4.30, 8.63] \text{ GeV}^2$ bin. Assuming the anomaly is not due to an underestimation of the hadronic effects or a statistical fluctuation in the experimental data, global analysis of $b \to s$ data indicated that a New Physics (NP) explanation for this anomaly is in the effective theory language a reduction of about 25% in the Wilson coefficient $\mathcal{C}_9$ [2–6]. In 2014, LHCb presented experimental results for the ratio $R_K \equiv \frac{BR(B^+ \to K^* \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$ in the $q^2 \in [1, 6] \text{ GeV}^2$ bin which was in $2.6\sigma$ tension with the SM prediction [7]. This anomaly which points toward violation of lepton flavour universality can be explained with a reduction in $\mathcal{C}_9$ which is consistent with the NP explanation for the $P_5'$ anomaly [8, 9]. This observable, unlike the $B \to K^* \mu^+ \mu^-$ observables is theoretically very clean. Furthermore, in 2015 the LHCb collaboration measured a number of $B_s \to \phi \mu^+ \mu^-$ observables where the branching ratio in the $q^2 \in [1, 6] \text{ GeV}^2$ bin is in tension with the SM prediction at $3.2\sigma$ [10], which again can be explained with a reduction in $\mathcal{C}_9$ [8]. In 2015, LHCb updated the measurements of $B \to K^* \mu^+ \mu^-$ observables with $3 \text{ fb}^{-1}$ of data where the tension in $P_5'$ (in

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the [4, 6] and [6, 8] GeV² bins) remained although with slightly less significance [11]. In addition, recently the Belle experiment presented a measurement of the angular observables of \(B \rightarrow K^* \ell^+ \ell^-\) [12] which shows a 2σ deviation for \(P_{\perp}^q\) in the \(q^2\) ∈ [4, 8] GeV² bin, which supports the LHCb result.

For the exclusive decays \(B_{(s)} \rightarrow K^*(\phi)\mu^+\mu^-\), where the final state meson is a vector meson, the long-distance contributions of the electromagnetic and semileptonic operators \((O_{7,9,10})\) can be described through seven independent form factors \(V_{A_{0,1,2}}, T_{1,2,3}\). The form factors are usually considered a main source of uncertainty as non-perturbative calculations are required to estimate them. There are further hadronic effects from the four-quark and chromomagnetic operators \((O_{1-6} \text{ and } O_8, \text{respectively})\) accompanied with the exchange of a virtual photon. The matrix elements of these operators cannot all be factorised into form factors, giving rise to non-factorisable corrections. At low \(q^2\), in the heavy quark and large energy limit, these effects are calculable at leading order in \(\Lambda/m_b\) in QCD factorisation and its field-theoretical formulation of Soft-Collinear Effective Theory (SCET). However, higher powers of the non-factorisable effects are not known and further calculations become available can only be "guesstimated" (a partial calculation of the power corrections for the \(B \rightarrow K^* \ell^+ \ell^-\) decay is available through a phenomenological description [13]).

In the low \(q^2\) region the seven a priori independent form factors can be reduced to two soft form factors \(\xi_{\perp,\parallel}\) [14], up to corrections of \(O(\alpha_s)\) and \(O(1/m_b)\), and while the former corrections have been calculated the latter remain unknown. These unknown factorisable power corrections can be guesstimated through dimensional arguments or by fitting ad hoc functions when comparing with the full form factors [15]. Reduction of the seven form factors to two soft form factors makes it possible to construct angular observables which are (soft) form factor independent at leading order [16][17].

One set of such form factor independent observables includes the so-called optimised \((P')\) observables. These observables are specially interesting in the absence of correlations among the form factor uncertainties, since otherwise there can be an overestimation of the theoretical errors.

The two theoretical strategies for \(B_{(s)} \rightarrow K^*(\phi)\mu^+\mu^-\) decays are therefore using the soft form factors (soft FF) or the full form factors (full FF). In either of the approaches the significance of the anomalies is dependent on the estimated size of the power corrections. For the soft FF approach, we estimate the factorisable and non-factorisable power corrections collectively by varying the tranversity amplitudes according to

\[
A_{\perp,\parallel} \rightarrow A_{\perp,\parallel} \times \left(1 + b_i e^{i \delta} + c_i (q^2/6 \text{ GeV}^2) e^{i \delta}\right),
\]

where \(i\) stands for \(\perp,\parallel, 0\), and with \(\theta, \phi \in (-\pi, \pi)\) and \(b_i \in (-0.1, +0.1), (-0.2, +0.2), (-0.3, +0.3)\) ranges and \(c_i \in (-0.25, +0.25), (-0.5, +0.5), (-0.75, +0.75)\) ranges which in the following we refer to as 10, 20 and 30% error for the power corrections, respectively. In the full FF approach only the non-factorisable power corrections are relevant which we consider by multiplying the hadronic part of the tranversity amplitudes by a multiplicative factor similar to the soft FF case with \(b_i \in (-0.05, +0.05), (-0.1, +0.1), (-0.2, +0.2), (-0.6, +0.6)\) and \(c_i \in (-0.125, +0.125), (-0.25, +0.25), (-0.5, +0.5), (-1.5, +1.5)\) for the 5, 10, 20 and 60% error, respectively.

### 2. Model-independent New Physics fits

We perform global fits using SuperIso v3.6 [18–20] by calculating and minimising the \(\chi^2\) in which all the theoretical and experimental correlations are considered [21].

Assuming New Physics to appear only in one operator, a model independent analysis of all the relevant \(b \rightarrow s\) data favours NP models with negative contributions to \(C_9\). The best fit values for various one operator fits are given in Tab. [1] where the full FF approach with 10% power correction error has been considered for the theoretical prediction of the \(B(s) \rightarrow K^*(\phi)\mu^+\mu^-\) observables.

| \(\delta C_9/C_{9,SM}^0\) | b.f. value | Pull_{SM} | 68% C.L. | 95% C.L. |
|----------------------|-----------|------------|----------|----------|
| \(\delta C_9'\) | -0.18 | 3.0σ | [-0.25, -0.09] | [-0.30, -0.03] |
| \(\delta C_9''\) | 0.03 | 1.0σ | [-0.05, +0.12] | [-0.11, +0.18] |
| \(\delta C_{10}/C_{10,SM}^0\) | -0.12 | 1.9σ | [-0.23, -0.02] | [-0.31, +0.04] |
| \(\delta C_{9,SM}^0\) | 0.25 | 2.9σ | [+0.11, +0.36] | [+0.03, +0.46] |
| \(\delta C_{9}''/C_{9,SM}^0\) | -0.21 | 4.2σ | [-0.27, -0.13] | [-0.32, -0.08] |

Table 1: Best fit values and the corresponding 68 and 95% confidence level intervals in the one operator global fit to the \(b \rightarrow s\) data. In the last two rows the fits are done when considering lepton non-universality.

As can be seen from the table, the most probable scenario is for a reduction in \(C_9^0\) in which the SM value is in 4.2σ tension with the best fit value of \(C_9\).

It is also plausible for NP effects to appear in more than one operator. Assuming two operator fits, the results of the fits for the \(\{C_9, C_{10}\}, \{C_9', C_9''\}\) and \(\{C_{9}, C_9''\}\) sets have been shown in Fig. [1] where we considered the
full FF approach with 5, 10 and 20% power correction errors. In all cases $\delta C_9$ has more than 2$\sigma$ tension with the SM. From the left plot in Fig. 1 it is obvious that the best description of the data is when assuming lepton flavour violation, what can also be seen in the last line of Tab. 1.

One can go one step further and consider new physics contributions to several Wilson coefficients at the same time. Fig. 2 shows an example of such a fit for the $\{C_9^e, C_9^\mu, C_{10}^e, C_{10}^\mu\}$ set. Allowing for NP effects in four operators, the constraints on the Wilson coefficients $C_9^e$ and $C_9^\mu$ can be considerably relaxed compared to the two-operator fit and the tension of $\delta C_9^{\text{SM}}$ with SM can be reduced to 1$\sigma$. However, in this case the overall tension on lepton-universality is appearing in the other Wilson coefficients $C_{10}^e$ and $C_{10}^\mu$ which are not shown in the projected plane (see Fig. 2 for more details).

3. Stability of the fits with respect to theoretical assumptions

In order to check the dependence of the model-independent fit on the theoretical assumptions we first compare the fit results for the soft and full FF approaches. In Fig. 3 the two operator fit for $\{O_9, O_{10}\}$ has been shown when using the soft FF approach and assuming 10% power correction error. Fig. 3 should be compared with the left plot in Fig. 1. In both cases, regardless of the theoretical approach used, there is more than 2$\sigma$ tension for $\delta C_9$ with respect to the SM. Moreover, in the full FF approach assuming up to 20% power correction error, the picture remains almost the same indicating that power corrections are the sub-dominant theoretical error.

Interestingly, assuming up to 60% error due to power corrections in the full FF approach the tension is not
results are also rather stable with respect to the form factor uncertainties when doubling them. The $2.6\sigma$ tension of the best fit value is reduced to $2.1\sigma$, and it is only quadrupling the form factor uncertainties which brings the tension below $2\sigma$. For the discussion of the correlations used in the LCSR calculation of the form factors \cite{23} we refer the reader to Ref. \cite{21}.

Similar results are obtained for $|C_9, C'_9|$ and $|C'_9, C'_9|$ fits when assuming the different mentioned theoretical assumptions (see \cite{21}).

\section{Stability of the fits with respect to experimental data and specific observables}

One may check also the influence of a given observable on the fit. To do so, we can remove the observable from the fit and study the consequences. On the upper plot in Fig.\ 
5 the $1$ and $2\sigma$ regions of the $|C_9, C'_9|$ fit have been shown when removing the data on the $S_5$ observable (this is equivalent to removing $P^*_5(=S_5/\sqrt{F_L(1-F_L)})$ for which the largest anomaly is observed). Interestingly, even when removing the data on $S_5$, the best fit value of $\delta C_9$ is still in tension with the SM, implying that it is not only the anomaly in $S_5$ ($P^*_5$) which drives $\delta C_9$ to negative values but this is rather an overall behaviour of the $b \rightarrow s$ data.

On the other hand, the observable which drives the fit to favour lepton flavour universality violation (LFUV) is $R_K$, since the only NP interpretation of the $R_K$ anomaly is through LFUV scenarios (where the Wilson coefficients for the muon and electron sectors are independent of each other). This can be seen in the lower plot in Fig.\ 5 where the $1$ and $2\sigma$ allowed regions are shown when removing the data on $R_K$. In this case the tension of the best fit point with lepton flavour universality is only at $\sim 1\sigma$ level.

The LHCb collaboration analysed the $3\ fb^{-1}$ data on $B \rightarrow K^*\mu^+\mu^-$ with two different methods, the method of moments and the most likelihood method, where the former is less precise but more robust with respect to the latter. In order to see the effect of the different methods on the fit results, the two operator fits using only the data on $B \rightarrow K^*\mu^+\mu^-$ observables have been presented in Fig.6. The tension of the best fit point with SM is less in the case where the experimental results analysed with the method of moments have been used which is mostly due to the larger experimental errors. Here, again, similar results are obtained for $|C_9, C'_9|$ and $|C'_9, C'_9|$ fits (see \cite{21}).

\footnote{The corrections on the amplitude level in the fit to the data and the power correction error in the approach used above are two different quantities. The order of magnitude of both quantities should be similar though.}
5. Strategies to identify the source of the anomalies

In order to identify the source of the observed anomalies, several paths can be undertaken. The most important issue is due to the unknown power corrections, as the significance of the anomalies depends on the assumptions on the power corrections. Going towards an estimate of these corrections would therefore be the first strategy to disentangle the New Physics effects from the hadronic corrections. The challenge here is that these corrections are not calculable in QCDf, although alternative approaches exist based on light cone sum rule techniques. Another interesting proposal in this direction was made very recently [23].

The second strategy would be the cross check with other ratios of decays to muons versus decays to electrons, similar to the $R_K$ ratio. The advantage of such ratios is that they are free from hadronic uncertainties and the deviations cannot be explained by the unknown power corrections. In Table 2, we give predictions for such ratios based on the global fit considering the two operator fit within the $(C_9, C_{10})$ set [21]. It can be seen from the table that in most cases the SM point lies outside the $2\sigma$ region of the indirect predictions. In particular, the ratio in the case of the $A_{FB}$ shows a large deviation, making it a precious observable to cross check with [14].

The third strategy would be to cross check with the measurements in the inclusive decay of $B \to X_s \ell^+ \ell^-$, which is theoretically well-explored. Predictions based on the model independent analysis show that at the future Belle II it will be possible to confirm the NP interpretation of the observed anomalies in the exclusive decays [5, 8, 25].

| Observable | Prediction |
|------------|------------|
| $BR(B \to X_s \mu^+ \mu^-)/BR(B \to X_s \ell^+ \ell^-)_{\nu_{\mu}110(6)GeV}$ | [0.61, 0.93] |
| $BR(B \to X_s \mu^+ \mu^-)/BR(B \to X_s \ell^+ \ell^-)_{\nu_{110(6)GeV}}$ | [0.68, 1.13] |
| $BR(B^0 \to K^{0} \mu^+ \mu^-)/BR(B^+ \to K^{0} \ell^+ \ell^-)$ | [0.65, 0.96] |
| $\langle F_{L}(B^0 \to K^{0} \mu^+ \mu^-)/(F_{L}(B^+ \to K^{0} \ell^+ \ell^-)) \rangle_{\nu_{110}(6)GeV}$ | [0.85, 0.96] |
| $\langle A_{FB}(B^0 \to K^{0} \mu^+ \mu^-)/(A_{FB}(B^+ \to K^{0} \ell^+ \ell^-)) \rangle_{\nu_{110}(6)GeV}$ | [0.87, 1.01] |
| $\langle S_{L}(B^0 \to K^{0} \mu^+ \mu^-)/(S_{L}(B^+ \to K^{0} \ell^+ \ell^-)) \rangle_{\nu_{110}(6)GeV}$ | [0.87, 1.01] |
| $BR(B^+ \to K^+ \mu^+ \mu^-)/BR(B^+ \to K^+ \ell^+ \ell^-)$ | [0.58, 0.85] |
| $\langle F_{L}(B^0 \to K^{0} \mu^+ \mu^-)/(F_{L}(B^+ \to K^{0} \ell^+ \ell^-)) \rangle_{\nu_{110}(6)GeV}$ | [0.998, 0.999] |
| $\langle A_{FB}(B^0 \to K^{0} \mu^+ \mu^-)/(A_{FB}(B^+ \to K^{0} \ell^+ \ell^-)) \rangle_{\nu_{110}(6)GeV}$ | [0.98, 1.01] |
| $\langle S_{L}(B^0 \to K^{0} \mu^+ \mu^-)/(S_{L}(B^+ \to K^{0} \ell^+ \ell^-)) \rangle_{\nu_{110}(6)GeV}$ | [0.98, 1.01] |
| $BR(B^0 \to K^0 \mu^+ \mu^-)/BR(B^+ \to K^0 \ell^+ \ell^-)$ | [0.58, 0.85] |
| $\langle F_{L}(B^0 \to K^{0} \mu^+ \mu^-)/(F_{L}(B^+ \to K^{0} \ell^+ \ell^-)) \rangle_{\nu_{110}(6)GeV}$ | [0.998, 0.999] |

Table 2: Predictions at 95% C.L. for the ratios of $B$ decays with muons in the final state, to electrons in the final state.
6. Conclusions

The latest LHCb results, based on the 3 fb\(^{-1}\) of data set still show some tensions with the SM predictions. Model independent fits point to about 25% reduction in the Wilson coefficient \(C_9\), with New Physics in the muonic contributions being preferred. We have studied the stability of the fits both with respect to theoretical assumptions and with respect to experimental analyses, and showed that doubling the form factor errors and/or increasing the non-factorisable power corrections by up to 60% do not change the fit results dramatically. Nevertheless, the LHCb data can be fitted by a general ansatz for hadronic power corrections, but somehow huge power corrections are needed in the fit within the critical bins.

In addition, we have identified strategies in order to understand the origin of the observed anomalies, based on the LHCb data and on the future Belle II measurements.

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