PROCEEDINGS OF SCIENCE

Observables and anomalies in $B \to K^{(*)}\ell^+\ell^-$ decays

Sam Cunliffe[*†]
Imperial College London, London, United Kingdom
E-mail: samuel.cunliffe09@imperial.ac.uk

Recent analyses of $B \to K^{(*)}\ell^+\ell^-$ processes at LHCb are in tension with Standard Model predictions. Some phenomenological interpretations suggest a contribution from a new vector particle. These results are difficult to account for within supersymmetric models. However, other phenomenological analyses suggest the data may be described by strong interaction effects that were assumed to be small when producing the Standard Model predictions. A pedagogical introduction to the observables in question is presented, alongside experimental considerations. This is followed by a brief overview of the phenomenological results.

Frontiers of Fundamental Physics 14
15-18 July 2014
Aix Marseille University (AMU) Saint-Charles Campus, Marseille, France

[*] Speaker.
[†] On behalf of the LHCb collaboration

PoS(FFP14)109

1. Rare flavour-changing neutral currents as a probe of new physics

Rare flavour-changing neutral current (FCNC) processes are sensitive to contributions from new physics particles. In the Standard Model of particle physics (SM), FCNCs are forbidden at low order ('tree level' diagrams) and proceed via higher order ('loop') diagrams involving virtual particles. Figure 1 shows the leading order diagram for the FCNC $B^0 \to K^{(*)0}\mu^+\mu^-$ process in the SM and an example diagram where supersymmetric particles contribute.[1] Virtual particles in a field theory are not produced on their mass shell, therefore studies of FCNC processes such as these are sensitive to masses much higher the mass of the B meson. It can also be larger than the energy-scale of collisions at the LHC. In the diagrams in Fig 1, the quark-level transition is a $b \to s\ell\ell$ process. The scope of this document is restricted to $b \to s\ell\ell$ observables, although many others are of interest [1, 2]. All of the measurements presented here have been performed with data collected by the LHCb detector [3].

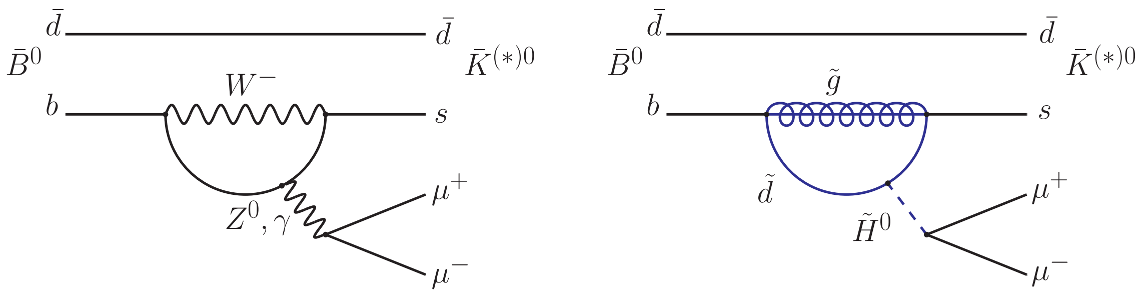

Figure 1: The leading order diagram for $B^0 \to K^{(*)0}\mu^+\mu^-$ in the Standard Model (left) and an example of the process propagated by supersymmetric particles (right).

2. Definitions of observables, and the operator-product expansion

Since FCNCs are sensitive to virtual contributions from broad classes of new particles, they are not normally analysed within any specific theory, rather within a model-independent effective field theory formalism. The effective field theory formalism is the so-called 'operator-product expansion' (OPE). In the OPE, the SM loop order diagrams and all possible new particle contributions are recomputed with effective operators, $\mathscr{O}_i$ and corresponding Wilson Coefficients, C_i. The Hamiltonian for $b \to s\ell\ell$ processes is given by

$$\mathscr{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_{i=0}^{10}\left(C_i\mathscr{O}_i + C_i'\mathscr{O}_i'\right) + \text{h.c.}, \tag{2.1}$$

where $C_i'\mathscr{O}_i'$ denote right handed Wilson Coefficients and operators. The operators $\mathscr{O}_{1-6}$ correspond to 4-quark operators, the operator $\mathscr{O}_7$ corresponds to a radiated photon, $\mathscr{O}_8$ to a radiated gluon, $\mathscr{O}_9$ to a vector current, and $\mathscr{O}_{10}$ to an axial-vector current. Mathematical definitions and more detail may be found in Ref. [4], for example.

[1] Throughout this document (as is conventional in other literature) K^* is used as shorthand for $K^*(892)$, the notation $K^{(*)}$ implies the kaon or the exited $K^*(892)$ in the final state.

The OPE is then used to calculate physical observables in terms of the C_i. Unfortunately, non-perturbative effects from quantum chromodynamics are still present in the effective theory. Thus hadronic form-factors for $B\to K^{(*)}$ still contribute and bring theoretical uncertainty to the predictions for observables. There is a further convention in that the C_i are usually written in terms of the SM prediction and a possible new physics contribution ($C_i^{\rm NP}$),

$$C_i = C_i^{\rm SM} + C_i^{\rm NP}. \tag{2.2}$$

In general terms, the efforts of the $b\to s\ell\ell$ theory community are devoted to the following three main areas. Firstly to defining observables where the effect of hadronic uncertainty is minimal, and sensitivity to the $C_i^{\rm NP}$ is maximal. Secondly to accurate assessment of the remaining hadronic uncertainty in predictions. And finally to phenomenological interpretation of experimental results usually by fits for C_i.

3. Isospin asymmetry of $B\to K^{(*)}\mu^+\mu^-$ decays

The isospin asymmetry, $A_{\rm I}$, is an observable defined as the rate-asymmetry between the neutral and charged $B\to K^{(*)}\mu^+\mu^-$ modes,

$$A_{\rm I} = \frac{\mathscr{B}\left[B^0\to K^{(*)0}\mu^+\mu^-\right] - \frac{\tau_{B^0}}{\tau_{B^+}}\mathscr{B}\left[B^\pm\to K^{(*)\pm}\mu^+\mu^-\right]}{\mathscr{B}\left[B^0\to K^{(*)0}\mu^+\mu^-\right] + \frac{\tau_{B^0}}{\tau_{B^+}}\mathscr{B}\left[B^\pm\to K^{(*)\pm}\mu^+\mu^-\right]}. \tag{3.1}$$

In the above, the branching fractions, $\mathscr{B}$, are scaled by the ratio of lifetimes, τ, in order to obtain the rate. In the SM, $A_{\rm I}$ is predicted to be very close to zero and is sensitive to $C_8^{\rm NP}$ [5].

The measurement of $A_{\rm I}$ [6] involves reconstructing four final states; $B^\pm\to K^\pm\mu^+\mu^-$, $B^0\to K^{*0}\mu^+\mu^-$ (with $K^{*0}\to K^\pm\pi^\mp$), $B^0\to K^0_S\mu^+\mu^-$, and $B^\pm\to K^{*\pm}\mu^+\mu^-$ (with $K^{*\pm}\to K^0_S\pi^\pm$); where the last two require that the $K^0_S\to\pi^+\pi^-$. In fact, the design of the LHCb detector means that K^0_S reconstruction is an experimental challenge and the efficiency must be determined for tracks in two different regions of the detector. However, the dominant systematic uncertainty is from the $\mathscr{B}\left[B\to J/\psi K^{(*)}\right]$, where $J/\psi\to\mu^+\mu^-$, modes used to normalise the branching fractions.

The isospin asymmetry is measured by LHCb in regions of squared dimuon invariant mass (q^2). The results are shown in Fig. 2. Whilst there is some weak tension at low q^2, no significant deviation from the SM prediction is observed.

4. Angular analysis of $B^0\to K^{*0}\mu^+\mu^-$ decays

Further observables are measured by performing an angular analysis of $B^0\to K^{*0}\mu^+\mu^-$ decays (where the $K^*\to K^\pm\pi^\mp$). Angular observables in general, are sensitive to the Lorentz structure of new physics which is expressed through $C_{7,9,10}^{\rm NP}$. In an angular analysis, the angular distribution is fit to data. For $B^0\to K^{*0}\mu^+\mu^-$, the distribution is written in terms of three angles $\{\theta_\ell, \theta_K, \phi\}$ as a sum over angular terms,

$$\frac{{\rm d}^4\Gamma}{{\rm d}q^2{\rm d}\cos\theta_\ell{\rm d}\cos\theta_K{\rm d}\phi} = \sum_{i=0}^{9} J_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi). \tag{4.1}$$

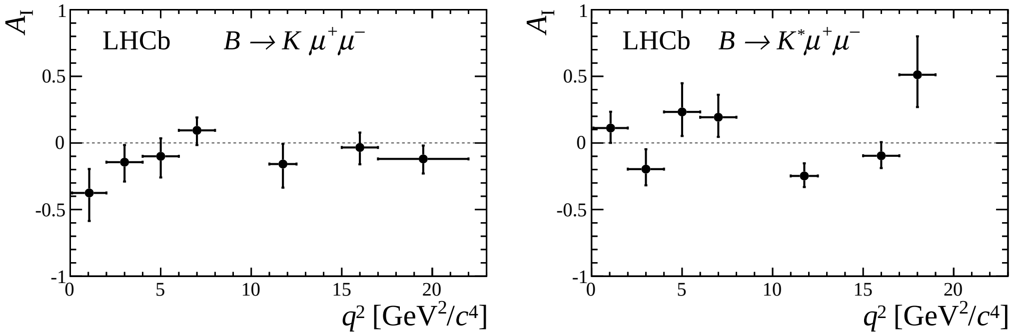

Figure 2: From [6]. The results of measurements of A_I in regions of squared dimuon invariant mass (q^2) for the kaon mode (left) and the excited $K^*(892)$ mode (right). The resonant $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ decays corresponding to $q^2 \in [8, 11]\,\mathrm{GeV}^2/c^4$ and $q^2 \in [12.5, 15]\,\mathrm{GeV}^2/c^4$ are excluded. Results are compatible with the Standard Model prediction of zero.

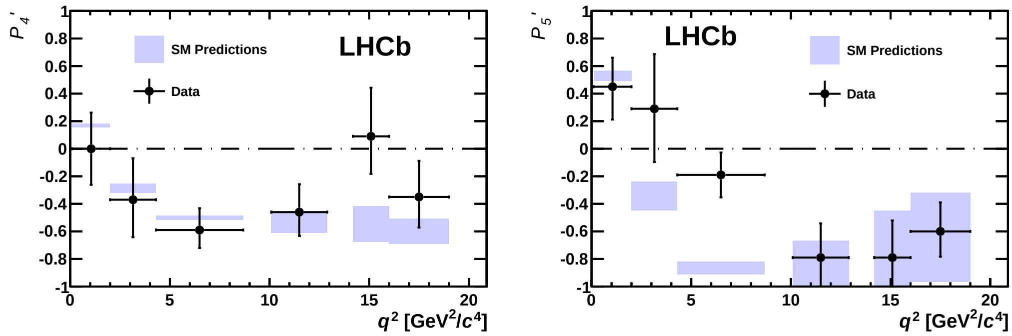

Figure 3: From [9]. Measurements of two of the P_i observables from the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ decays. The value of P_5' in the region of squared dimuon invariant mass $q^2 \in [4.3, 8, 0]$ shows a 3.7σ local deviation from the SM prediction [8] which is shown in blue.

In the above equation, the f_i are the principle angular moments, and $J_i(q^2)$ are bilinear combinations of the polarisation amplitudes which are written in terms of $C_{7,9,10}$ and the $B \to K^*$ form-factors. More details may be found in Refs. [4, 7].

There are several sets of observables that may be derived from the J_i terms. One choice of parametrisation results in a set of observables P_i [8]. The set of P_i observables is designed to be largely form-factor independent.

The experimental angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays [9] relies upon a correction to account for the non-uniform geometry and trigger which biases the angular distribution. This correction is derived using a large sample of phase-space simulated $B^0 \to K^{*0}\mu^+\mu^-$ decays. The angular distribution is fitted in bins of q^2, and the resulting measurement of the P_i observables yields a local deviation of 3.7σ in the observed P_5' in the region $q^2 \in [4.3, 8.0]\,\mathrm{GeV}^2/c^4$. The deviation is with respect to the SM prediction presented in Ref. [8] and is shown in Fig. 3.

4.1 Phenomenological interpretations

Following this measurement, several groups performed global phenomenological fits to the C_i.

PoS(FFP14)109

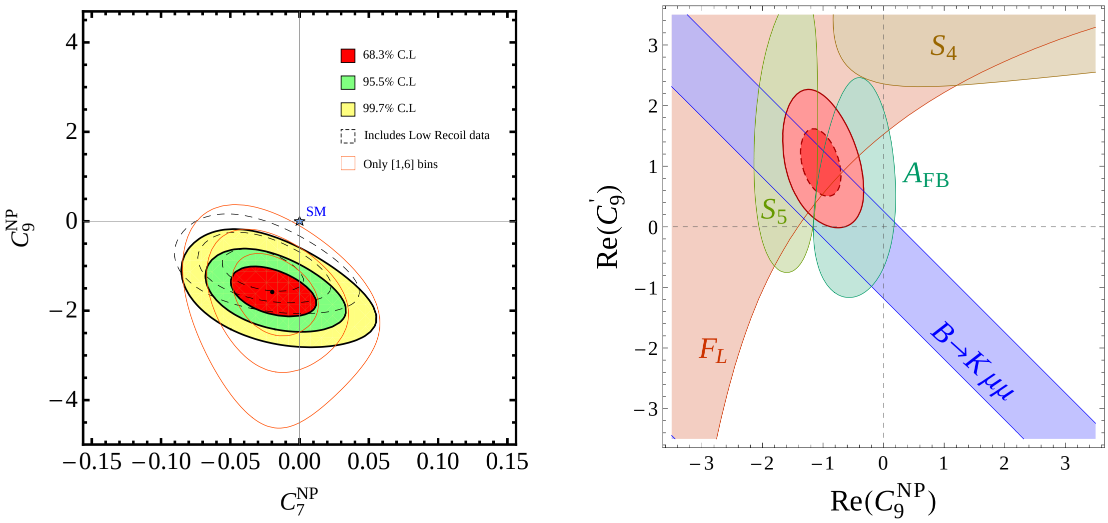

Figure 4: From [10] (left) and [11] (right). The results of global fits presented as likelihood contours for values of modifications to the Wilson Coefficients, C_i^{NP}.

The analyses in Refs [10, 11, 12] were performed by independent groups, choosing differing definitions of the angular observables and with different choices of other experimental inputs. Figure 4 shows examples of the results from Refs [10, 11]. All three analyses indicate a similar tension from the SM in C_9, the Wilson Coefficient corresponding to the vector $b \to s\ell\ell$ vertex. They indicate that this deviation could be explained by an additional vector boson Z' contributing to these decays.

Some authors suggest that the theoretical uncertainties associated to the treatment of the form-factors a low q^2 in Ref. [8] have been underestimated [13]. More recently the effect of resonances in the dimuon spectrum [14] has been shown to have unexpected effects which might be able to explain the anomaly [15].

5. Lepton-universality in $B \to K\ell^+\ell^-$ decays

If phenomenological interpretations of the P_5' result are to be believed, then there is the question of whether the Z' couple universally to leptons [16]. A conceptually simple observable is the ratio of the $B^\pm \to K^\pm\mu^+\mu^-$ to $B^\pm \to K^\pm e^+e^-$ decay rates,

$$R_K = \frac{\mathscr{B}[B^\pm \to K^\pm\mu^+\mu^-]}{\mathscr{B}[B^\pm \to K^\pm e^+e^-]}. \tag{5.1}$$

The SM Higgs boson, which would not respect lepton universality since muons are more massive than electrons, contributes very weakly. Indeed, the SM prediction is $R_K = 1 + O(m_\mu^2/m_b^2)$ if $q^2 > 1\,\mathrm{GeV}^2/c^4$ [17].

The measurement of R_K [18] is experimentally challenging.[2] The electron mode relies on the LHCb calorimeter resolution and the electrons produce copious bremsstrahlung photons at

[2]Supplementary figures at [https://cds.cern.ch/record/1711787/].

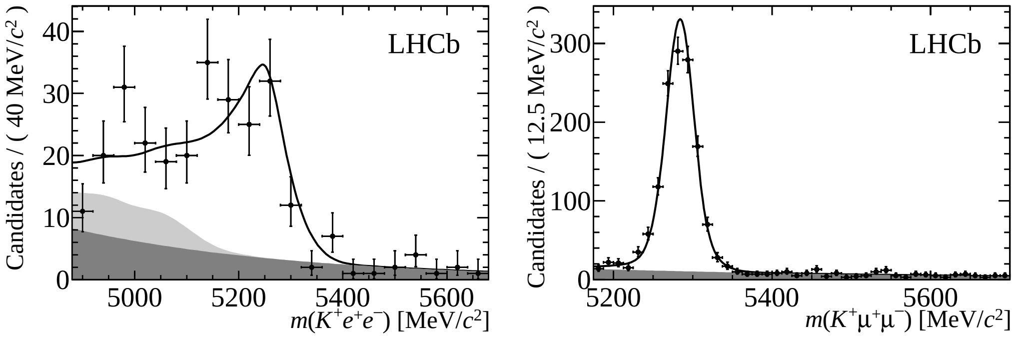

Figure 5: From [18]. Fitted invariant mass distributions of $B^\pm \to K^\pm e^+e^-$ (left) and $B^\pm \to K^\pm \mu^+\mu^-$ (right). The experimental challenge is accounting for the bremsstrahlung photons, which widen the peak in the left plot relative to the peak in the right plot. The light grey component in the left plot is included to account for partially reconstructed decays of the type $B \to K^\pm X e^+e^-$.

these energies. The dominant systematic effect in this measurement is the modelling of the electron modes. The fitted invariant mass distributions are shown in Fig. 5. Processes of the type $B \to K^\pm X e^+e^-$ where X represents some particle that is not reconstructed, form a potentially dangerous background. A component for these backgrounds is added to the fit. The uncertainty in the shape of the probability distribution function, due to these ‘partially reconstructed’ backgrounds contributes to the systematic uncertainty due to modelling. The value of R_K is found to be

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \tag{5.2}$$

in the range $q^2 \in [1,6]\,\mathrm{GeV}^2/c^4$, where the first uncertainty is statistical and the second systematic. This measurement is 2.6σ from the SM prediction.

5.1 Phenomenological interpretations

Since the conference and preparation of these proceedings, some new phenomenological analyses have been performed. The work presented in Refs [19, 20] similarly indicate tension in C_9^{NP}. The tension in R_K may also be due to scalar operators but is less favoured once other FCNC constraints, particularly from the observation of the decay $B_s^0 \to \mu^+\mu^-$ [21, 22], are taken into account [19].

6. Conclusions and summary

To summarise, the study of $B \to K^{(*)}\ell^+\ell^-$ processes is interesting because of virtual contributions from particles in theories of physics beyond the SM. The measured observables for these processes must be chosen carefully to minimise the effect of hadronic uncertainty. Such observables are usually cast in an effective theory with Wilson Coefficients and operators for the effective $b \to s\ell\ell$ vertices. The measurements of three such observables using LHCb data have been presented. Experimental results are combined by performing global fits to Wilson Coefficients which give information related to the broad class of new physics particles that may be contributing. Recent measurement of angular observables by the LHCb collaboration has brought fits of Wilson

Coefficients into tension with the SM. Although there is some question as to the treatment of the form-factor uncertainties, contributions from a new vector Z' could explain this tension. There is also some tension in the measured lepton-universality ratio for $B^+ \to K^+\ell^+\ell^-$. During the preparation of these proceedings analyses have been performed which incorporate this measurement, they indicate similar tension in the Wilson Coefficients. Further experimental measurements by the LHCb collaboration with more data will complement the theoretical work to improve understanding of form-factor uncertainties and assess the potential for new physics contributions.

References

[1] G. Isidori and F. Teubert, Eur. Phys. J. Plus **129** (2014) 40, [arXiv:1402.2844].

[2] LHCb collaboration, R. Aaij *et al.* , and A. Bharucha *et al.*, Eur. Phys. J. **C73** (2013) 2373, [arXiv:1208.3355].

[3] LHCb collaboration, A. A. Alves Jr. *et al.*, JINST **3** (2008) S08005.

[4] W. Altmannshofer *et al.*, JHEP **0901** (2009) 019, [arXiv:0811.1214].

[5] J. Lyon and R. Zwicky, Phys. Rev. **D88** (2013) 094004, [arXiv:1305.4797].

[6] LHCb collaboration, R. Aaij *et al.*, JHEP **06** (2014) 133, [arXiv:1403.8044].

[7] J. Matias, F. Mescia, M. Ramon, and J. Virto, JHEP **1204** (2012) 104, [arXiv:1202.4266].

[8] S. Descotes-Genon, T. Hurth, J. Matias, and J. Virto, JHEP **1305** (2013) 137, [arXiv:1303.5794].

[9] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **111** (2013) 191801, [arXiv:1308.1707].

[10] S. Descotes-Genon, J. Matias, and J. Virto, Phys. Rev. **D88** (2013) 074002, [arXiv:1307.5683].

[11] W. Altmannshofer and D. M. Straub, Eur. Phys. J. **C73** (2013) 2646, [arXiv:1308.1501].

[12] R. Gauld, F. Goertz, and U. Haisch, JHEP **1401** (2014) 069, [arXiv:1310.1082].

[13] S. Jäger and J. Martin Camalich, JHEP **1305** (2013) 043, [arXiv:1212.2263].

[14] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **111** (2013) 112003, [arXiv:1307.7595].

[15] J. Lyon and R. Zwicky, [arXiv:1406.0566].

[16] W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Phys. Rev. **D89** (2014) 095033, [arXiv:1403.1269].

[17] G. Hiller and F. Kruger, Phys. Rev. **D69** (2004) 074020, [arXiv:hep-ph/0310219].

[18] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **113** (2014) 151601, [arXiv:1406.6482].

[19] G. Hiller and M. Schmaltz, Phys. Rev. **D90** (2014) 054014, [arXiv:1408.1627].

[20] D. Ghosh, M. Nardecchia, and S. A. Renner, [arXiv:1408.4097].

[21] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **111** (2013) 101805, [arXiv:1307.5024].

[22] CMS Collaboration, S. Chatrchyan *et al.*, Phys. Rev. Lett. **111** (2013) 101804, [arXiv:1307.5025].