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Electroweak penguin decays with di-leptons

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Electroweak penguin decays proceed via flavour changing neutral currents that, in the Standard Model (SM), are forbidden at the tree-level and only allowed via higher order loop diagrams. New particles beyond the SM could significantly affect these rare processes, altering their predicted branching fractions and angular distributions. Recent results from the LHCb experiment on semileptonic $b \to s\ell^+\ell^-$ processes are reviewed. While most observables show good agreement with SM predictions, an interesting local deviation is observed in an angular observable of the decay $B^0 \to K^{*0}\mu^+\mu^-$. Recently, also a test of lepton universality using the branching fraction ratio $R_K = \mathscr{B}(B^+ \to K^+\mu^+\mu^-)/\mathscr{B}(B^+ \to K^+e^+e^-)$ has also shown an interesting tension with the SM prediction.

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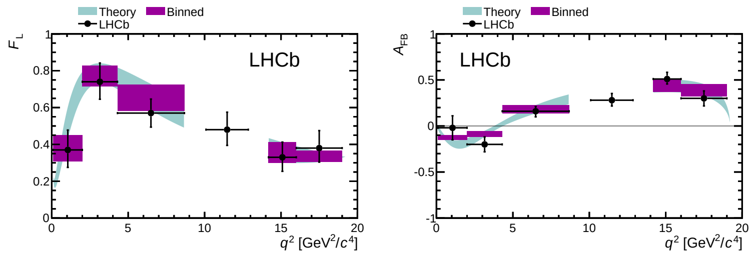

Figure 1: (Left) the longitudinal polarisation fraction of the K^{*0}, F_{L}, and (right) the forward-backward asymmetry A_{FB} with SM predictions [3] overlayed.

1. Introduction

Electroweak penguin decays proceed via flavour changing neutral currents (FCNC) that, in the Standard Model (SM), are only allowed to occur as higher loop-order processes. New heavy particles beyond the SM can significantly contribute to these rare processes and affect both their branching fractions as well as the angular distributions of the final state particles. Semileptonic $b \to s\mu^+\mu^-$ decays provide a clean experimental signature and, due to their sensitivity to non-SM contributions, constitute a cornerstone of the LHCb physics program.

2. Angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$

The decay $B^0 \to K^{*0}\mu^+\mu^-$ exhibits a particularly rich phenomenology due to the many angular observables accessible in this decay mode. The differential decay rate depends on the three decay angles $\cos\theta_\ell$, $\cos\theta_K$ and ϕ and is given by

$$\begin{aligned}\frac{1}{\Gamma+\bar{\Gamma}}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = & \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K \\ & +\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell \\ & -F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ & +S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\ & +\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\ & +S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],\end{aligned} \tag{2.1}$$

where F_{L} denotes the longitudinal polarisation fraction of the K^{*0}, A_{FB} the forward-backward asymmetry of the dimuon system and S_i the remaining CP-averaged angular observables [1]. Using data corresponding to an integrated luminosity of 1 fb^{-1} recorded in 2011, LHCb performed a measurement of F_{L}, A_{FB} and $S_{3,9}$ in bins of q^2, the invariant mass of the dimuon system squared [2]. Figure 1 shows F_{L} and A_{FB} in bins of q^2, together with the SM predictions from Ref. [3] which are in good agreement. Of particular interest is the zero crossing point of A_{FB}, q_0^2, which is precisely predicted in the SM as form-factor uncertainties cancel at leading order. The result of $q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2$ is in good agreement with the SM prediction $q^2_{0,\mathrm{SM}} = 4.36^{+0.33}_{-0.31}\,\mathrm{GeV}^2$ [4].

For the angular observables P_i' that have been proposed in Ref. [5] the form-factor uncertainties cancel at leading order over the full q^2 range. In Ref. [6], LHCb determined the observables

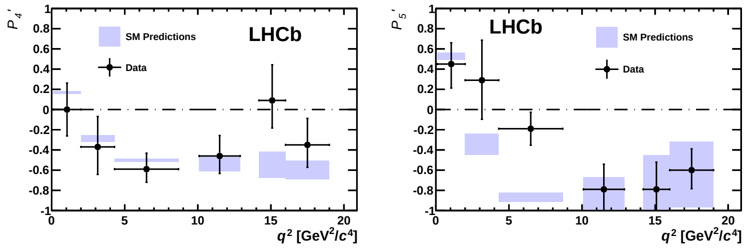

Figure 2: The angular observables (left) P_4' and (right) P_5'. While P_4' shows good agreement with the SM prediction [5], a local deviation with a significance of $3.7\,\sigma$ is observed for P_5' in the q^2 range $[4.3, 8.68]\,\mathrm{GeV}^2/c^4$.

$P'_{4,5,6,8} = S_{4,5,7,8}/\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}$ using a data sample corresponding to an integrated luminosity of $1\,\mathrm{fb}^{-1}$. Figure 2 shows $P'_{4,5}$ with the SM predictions [5] overlayed. While P_4' shows good agreement with the SM prediction, P_5' shows a local deviation corresponding to a significance of $3.7\,\sigma$ in the q^2 range $[4.3, 8.68]\,\mathrm{GeV}^2/c^4$. Accounting for the 24 measurements performed in Ref. [6] the probability to find a deviation of this size or larger is 0.5%. Global fits to the data find that agreement with data can be improved by introducing a non-SM vector current [7, 8, 9, 10] which could be attributed to a Z' boson. The significance of the observed deviation could however be lessened by a different estimate of the form-factor uncertainties [11] or the contribution from $c\bar{c}$ resonances [12]. An updated analysis using the full LHCb Run I data sample, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$, is currently in preparation which will help clarify the situation.

3. $B \to K^{(*)}\mu^+\mu^-$ branching fractions and isospin measurements

Branching fractions of $b \to s\mu^+\mu^-$ processes can also be affected by possible contributions beyond the SM. The LHCb experiment has performed measurements of the branching fractions of the decays $B^0 \to K^{*0}\mu^+\mu^-$ [2], $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ [13], as well as $B_s^0 \to \phi\mu^+\mu^-$ [14]. The differential branching fractions $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$ of the decays $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ are given in Fig. 3. The measured differential branching fractions generally lie below the SM predictions but agree when accounting for the large form-factor uncertainties of the SM predictions [15, 16]. Recently, more precise predictions of $b \to s\mu^+\mu^-$ branching fractions at high q^2 became available from lattice calculations [17, 18]. Interestingly, the data on the branching fractions of $B^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$ at high q^2 hint at a similar, but less significant, deviation of the $b \to s\mu^+\mu^-$ couplings seen for the angular observables of $B^0 \to K^{*0}\mu^+\mu^-$ at low q^2 [19].

The isospin asymmetry A_I is defined as the ratio of branching fractions

$$A_\mathrm{I} = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}. \tag{3.1}$$

The leading form-factor uncertainties cancel for the isospin asymmetries, thereby making them sensitive probes for New Physics. Figure 4 gives the isospin asymmetries for $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$. They are in good agreement with the SM predictions which are $\mathcal{O}(1\%)$ [20, 21, 22]. Tensions with the SM prediction for $A_\mathrm{I}(B \to K\mu^+\mu^-)$ that were hinted at by a previous analysis [23] are not confirmed.

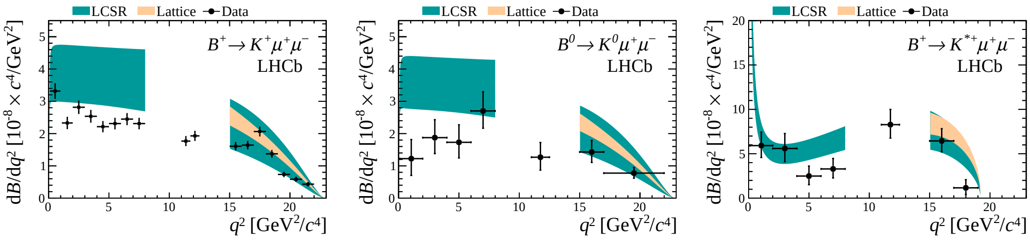

Figure 3: The differential branching fractions of the decays (left) $B^+ \to K^+\mu^+\mu^-$, (middle) $B^0 \to K^0\mu^+\mu^-$ and (right) $B^+ \to K^{*+}\mu^+\mu^-$.

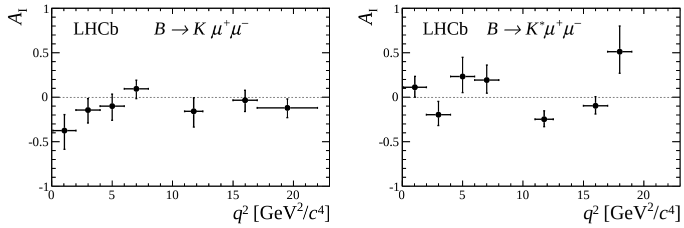

Figure 4: The isospin asymmetry A_{I} for (left) $B \to K\mu^+\mu^-$ and (right) $B \to K^*\mu^+\mu^-$ decays.

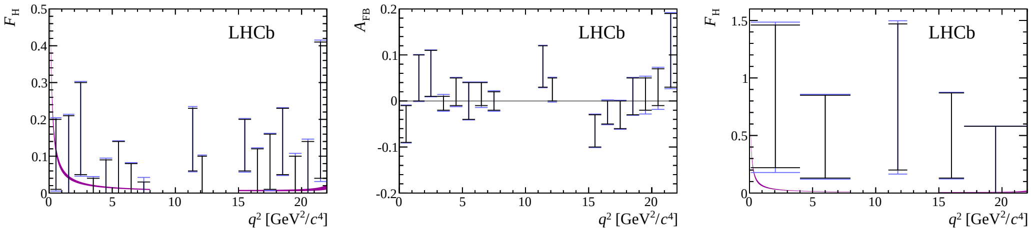

Figure 5: (Left) the flat parameter F_{H} and (middle) A_{FB} for $B^+ \to K^+\mu^+\mu^-$ decays. (Right) the flat parameter F_{H} for $B^0 \to K^0\mu^+\mu^-$ decays. The outer error bars include systematic uncertainties.

4. Angular analysis of $B \to K\mu^+\mu^-$ decays

The differential decay rates of the decays $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0_S\mu^+\mu^-$ depending on the decay angle $\cos\theta_\ell$ are given by

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(B^+ \to K^+\mu^+\mu^-)}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_{\mathrm{H}})(1-\cos^2\theta_\ell) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_\ell, \tag{4.1}$$

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(B^0 \to K^0_S\mu^+\mu^-)}{\mathrm{d}|\cos\theta_\ell|} = \frac{3}{2}(1-F_{\mathrm{H}})(1-|\cos\theta_\ell|^2) + F_{\mathrm{H}}, \tag{4.2}$$

where A_{FB} is the forward-backward asymmetry of the dimuon system and F_{H} the flat parameter, which corresponds to the fractional contribution from (pseudo)scalar and tensor amplitudes to the decay. Since the decay flavour of the decay $B^0 \to K^0_S\mu^+\mu^-$ is unknown from the final state particles, A_{FB} is not accessible for this decay. LHCb performed an angular analysis using the full Run I data sample [24]. The results are given in Fig. 5 and are in good agreement with SM predictions. No hints for large (pseudo)scalar or tensor contributions are seen.

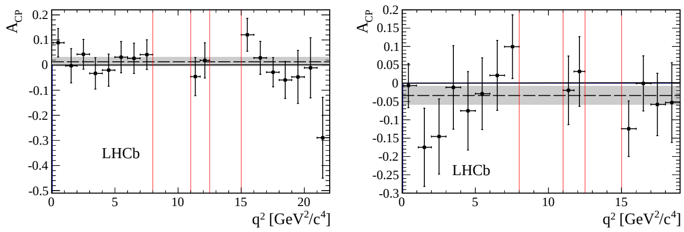

Figure 6: CP-asymmetry $A_{\rm CP}$ for (left) the decay $B^+ \to K^+\mu^+\mu^-$ and (right) the decay $B^0 \to K^{*0}\mu^+\mu^-$ in bins of q^2.

5. CP-asymmetries in $B \to K\mu^+\mu^-$ decays

The direct CP asymmetry $A_{\rm CP}$ is defined as

$$A_{\rm CP} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-) - \Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-) + \Gamma(B \to K^{(*)}\mu^+\mu^-)}, \tag{5.1}$$

and free from form-factor uncertainties. It can therefore be precisely predicted in the SM. For the decay $B^0 \to K^{*0}\mu^+\mu^-$ $A_{\rm CP}$ is $\mathscr{O}(10^{-3})$ [1] but $A_{\rm CP}$ can be up to ± 0.15 in scenarios beyond the SM [25]. LHCb has measured $A_{\rm CP}$ using the full Run I data sample [26]. The results, binned in q^2, are given in Fig. 6 and in good agreement with the SM expectation.

6. First observations of the decays $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ and $B^+ \to \phi K^+\mu^+\mu^-$

Using the full Run I data sample, LHCb has performed the first observations of the $b \to s\mu^+\mu^-$ transitions $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ and $B^+ \to \phi K^+\mu^+\mu^-$ [27]. The decay $B^+ \to K_1(1270)^+\mu^+\mu^-$ is expected to contribute significantly to the $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ final state and is of particular interest since the $K_1(1270)^+$ is an axial-vector [28]. Figure 7 shows the invariant mass distributions of the signal candidates for both decays as well as the differential branching fraction for the decay $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$. The total branching fractions are determined to

$$\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = \left(4.36\,^{+0.29}_{-0.27}\,(\text{stat}) \pm 0.21\,(\text{syst}) \pm 0.18\,(\text{norm})\right) \times 10^{-7},$$
$$\mathscr{B}(B^+ \to \phi K^+\mu^+\mu^-) = \left(0.82\,^{+0.19}_{-0.17}\,(\text{stat})\,^{+0.10}_{-0.04}\,(\text{syst}) \pm 0.27\,(\text{norm})\right) \times 10^{-7},$$

Due to the low statistics, no attempt is made to disentangle the contributions to the $K^+\pi^+\pi^-\mu^+\mu^-$ final state. The $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ branching fraction is lower than, but compatible with, the SM prediction of $\mathscr{B}(B^+ \to K_1(1270)^+\mu^+\mu^-) = (2.3\,^{+1.3}_{-1.0}\,^{+0.0}_{-0.2}) \times 10^{-6}$ [28].

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

Another quantity which is precisely predicted in the SM is the ratio $R_{\rm K}$ defined as

$$R_{\rm K} = \frac{\int_{1\,{\rm GeV}^2/c^4}^{6\,{\rm GeV}^2/c^4} \frac{{\rm d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{{\rm d}q^2}{\rm d}q^2}{\int_{1\,{\rm GeV}^2/c^4}^{6\,{\rm GeV}^2/c^4} \frac{{\rm d}\Gamma[B^+ \to K^+e^+e^-]}{{\rm d}q^2}{\rm d}q^2} \stackrel{\rm SM}{=} 1 \pm \mathscr{O}(10^{-3}) \tag{7.1}$$

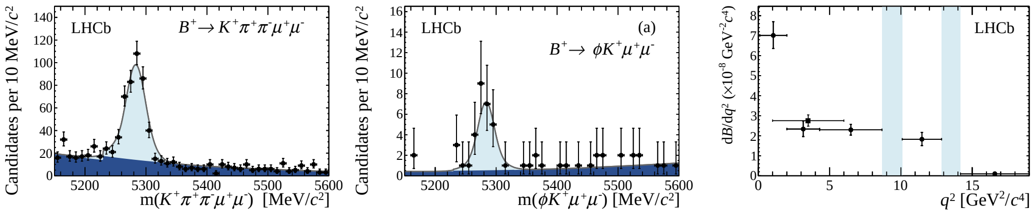

Figure 7: (Left) $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ and (middle) $B^+ \to \phi K^+\mu^+\mu^-$ signal candidates integrated over q^2. (Right) the differential branching fraction for the decay $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$.

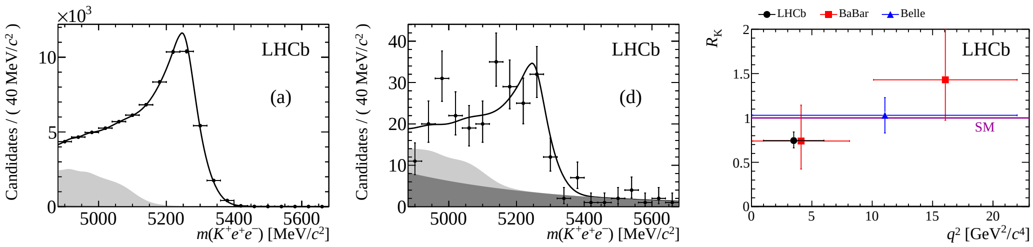

Figure 8: (Left) $B^+ \to J/\psi(\to e^+e^-)K^+$ and (middle) $B^+ \to K^+e^+e^-$ candidates. (Right) the $R_{\rm K}$ value determined by LHCb in comparison with results from the B factories [30, 31]

for the q^2 range $[1,6]\,{\rm GeV}^2/c^4$. Due to universal coupling of the photon and Z^0 to leptons this ratio is close to unity in the SM, with only small effects due to the phase space difference and Higgs penguin contributions. The LHCb experiment measures a value of

$$R_{\rm K} = 0.745^{+0.090}_{-0.074}({\rm stat.}) \pm 0.036({\rm syst.}),$$

which is compatible with the SM prediction at the $2.6\,\sigma$ level [29]. Figure 8 shows $B^+ \to J/\psi(\to e^+e^-)K^+$ and $B^+ \to K^+e^+e^-$ signal candidates as well as the $R_{\rm K}$ value in comparison with results from the B factories [30, 31]. Further analyses of electroweak penguins with electrons in the final state are in preparation to clarify the situation.

8. Conclusions

With its large $b\bar{b}$ production cross section, excellent particle identification capabilities and its precision vertexing and tracking system, the LHCb experiment is ideally suited for the study of electroweak penguin decays. Since they proceed via flavour changing neutral currents these rare decays exhibit high sensitivity to possible contributions beyond the SM. While most observables are in good agreement with SM predictions, interesting tensions are found for the angular observable P_5' in the decay $B^0 \to K^{*0}\mu^+\mu^-$, and for $R_{\rm K}$, the ratio of decay rates $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$. In addition, branching fractions of $b \to s\mu^+\mu^-$ modes tend to lie below SM predictions, which is consistent with the deviation seen in P_5'. An update of the angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ using the full Run I data sample is currently in preparation.

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