PROCEEDINGS OF SCIENCE

Electroweak Penguin Decays at LHCb

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Flavour-Changing Neutral-Current processes, such as decays mediated by $b \to s\ell\ell$ transitions, are forbidden at the lowest perturbative order in the Standard Model (SM) and hence might receive comparatively large corrections from new particles in SM extensions. These corrections may affect different observables related to these decays such as branching fractions or angular distributions. In this proceeding, the most recent results from LHCb in the area of $b \to s\ell\ell$ decays will be presented.

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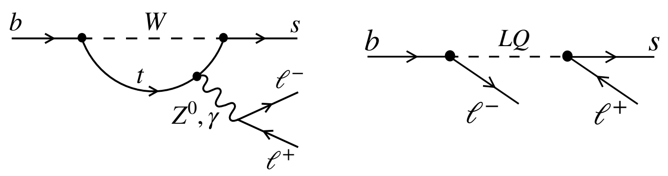
1. Electroweak penguin decays

The effects of mediators from Beyond Standard Model physics, as leptoquarks [1] or new heavy gauge boson as Z' [2] can be studied through high-precision measurements. In this view, processes involving a $b \to s\ell\ell$ transition (Flavour Changing Neutral Current) are of particular interest. They are forbidden at tree level by the Standard Model (SM), meaning they can only happen at higher orders (Figure 1a), and thus with small branching fractions, typically of $O(10^{-7}-10^{-6})$. This allows possible new heavy mediators to enter in their loops and modify their SM amplitudes (Figure 1b).



(a) **(b)**

Figure 1: (a) A SM contribution for $b \to s\ell\ell$ transition, happening via loop and involving the electroweak bosons W, Z and γ. (b) A possible new physics contribution involving a leptoquark (LQ) which could couple directly quarks and leptons with different couplings for different flavour families.

Such types of B-meson rare decays can be described by an effective theory, which includes effective couplings, the so-called *Wilson Coefficients* (WC), and local operators. The study of electroweak penguin decays can give insights on possible modifications of the WCs by mean of new physics, depending on its structure [3].

A large variety of observables is available when looking at electroweak penguin decays, the most studied being:

- **Relative rates** of $b \to s\mu\mu$ and $b \to see$. Ratios of this type are predicted to be equal to one with very high precision, due to the Lepton Flavour Universality of the SM (SM gauge interactions have the same amplitudes for all the lepton families). Such observables are particularly clean, with the theoretical uncertainties coming from the QCD part of the decay cancelling out in the ratio.
- **Angular observables**. New physics can modify the angular distributions of final state particles. Angular observables can be studied by arranging them to reduce uncertainties coming from form factors descriptions. Nevertheless, observables of this type can be polluted by long distance effects (*charm-loop*), hard to predict.
- **Muon branching fractions**, the ones suffering the most from theoretical uncertainties. However, some fully leptonic final state e.g. $B_s^0 \to \mu^+\mu^-$, with their very clean SM predictions ($\sim O(4\%)$ uncertainty), are golden channels to search for new physics.

In the following, an overview of the results in this field provided by the LHCb collaboration will be given. In fact, the LHCb detector is highly suited for this type of decays, being a forward spectrometer with high acceptance of b hadrons produced by the LHC, good particles identification and trigger performances on displaced tracks and excellent tracking efficiency [4].

2. Ratios of Branching Fractions

In order to cancel systematic uncertainties coming from differences in lepton reconstruction, relative rates are experimentally measured as double ratios, as shown in Eq 1.

$$R_X = \frac{BF(B \to X_s \mu^+\mu^-)}{BF(B \to X_s J/\psi(\to \mu^+\mu^-))} \cdot \frac{BF(B \to X_s J/\psi(\to e^+e^-))}{BF(B \to X_s e^+e^-)} \tag{1}$$

where X_s is a generic system containing a strange meson. The possibility of employing the resonant channels (i.e. when the two final state leptons come from a J/ψ resonance) in the ratio, is ensured by the Lepton Flavour Universality of the J/ψ decays.
Several X_s systems have been studied by LHCb, with results summarised below.

- $\mathbf{X_s = K}$ [5] (9fb^{-1} integrated luminosity). The measurement lays at 3.1 standard deviations from the SM predictions and it is compatible with the previous R_K published value obtained with a smaller part of the data collected [6].

$$R_K(1.1 < q^2 < 6\ \text{GeV}^2/c^4) = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{sys}) \tag{2}$$

- $\mathbf{X_s = K^0_S, K^{*+}}$ [7] (9fb^{-1} integrated luminosity) The values agree with the SM predictions at $\sim 1.5\sigma$ level, and with the previous tests of lepton universality

$$R_{K^0_S}(1.1 < q^2 < 6\ \text{GeV}^2/c^4) = 0.66^{+0.20}_{-0.14}(\text{stat.})^{+0.02}_{-0.04}(\text{syst.}), \tag{3}$$

$$R_{K^{*+}}(0.045 < q^2 < 6\ \text{GeV}^2/c^4) = 0.70^{+0.18}_{-0.13}(\text{stat.})^{+0.03}_{-0.04}(\text{syst.}) \tag{4}$$

- $\mathbf{X_s = K^{*0}}$ [8] (3fb^{-1} integrated luminosity) The values show a $2.1 - 2.4\sigma$ tension with the SM, depending on the q^2 range considered:

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } (0.045 < q^2 < 1.1\ \text{GeV}^2/c^4) \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } (1.1 < q^2 < 6\ \text{GeV}^2/c^4) \end{cases} \tag{5}$$

- $\mathbf{X_s = pK}$ [9] (4.7fb^{-1} integrated luminosity). The value is compatible with the SM.

$$R^{-1}_{pK}(0.1 < q^2 < 6\ \text{GeV}^2/c^4) = 1.17^{+0.18}_{-0.16} \pm 0.07 \tag{6}$$

3. Angular distributions

The differential decay rate in bins of q^2 of processes such as $B^{0(+)} \to K^{*0(+)}\mu^+\mu^-$ can be fully described by three angles: $cos(\theta_\ell)$, $cos(\theta_K)$ and ϕ, as defined in [10]. The coefficients of the decay rates are related to WCs, and can be rearranged in a new basis of P'_i operators, specifically constructed in order to reduce QCD uncertainties at leading order. The full set of CP-averaged angular observables are extracted from a multidimensional fit in the angles, $m(K\pi)$ and $m(K\pi\mu\mu)$. Figure 2 shows the values measured for the P'_5 observable by the analysis of the $B^+ \to K^{*+}\mu^+\mu^-$ decays [11], with the full dataset collected. The values are in agreement with what observed in the previous $B^0 \to K^{*0}\mu^+\mu^-$ analysis [12] (with 4.7fb^{-1} of integrated luminosity), confirming a local tensions with the SM predictions of $2.4-2.7\sigma$, depending on the q^2 intervals and the hadronic uncertainties descriptions. LHCb has also recently published the measurement of the angular observables in $B_s^0 \to \phi\mu^+\mu^-$ decays where, given the presence of a flavour symmetric final state, not all the observables are accessible. The results are compatible with the Standard Model predictions. One of the angular variables measured, $F_{\rm L}$, is shown in Figure 2.

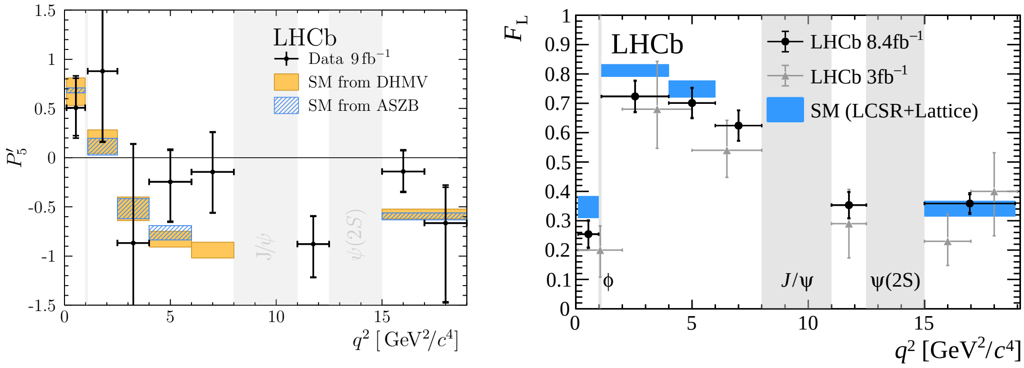


Figure 2: P_5' measured in $B^+ \to K^{*+}\mu^+\mu^-$ decays [11] (left) and $F_{\rm L}$ measured in $B_s^0 \to \phi\mu^+\mu^-$ decays [13] (right), in bins of the di-muon invariant mass. Standard Model predictions are also shown.

4. Differential Branching Fractions

The LHCb collaboration studied the differential branching fractions with respect to the dilepton invariant mass squared (q^2) for several decay modes, namely in $B^{0(+)} \to K^{0(+)}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ [14], in $\Lambda_b^0 \to \Lambda\mu^+\mu^-$[15], in $B^0 \to K^{*0}\mu^+\mu^-$ [16], and more recently in $B_s^0 \to \phi\mu^+\mu^-$ decays [17]. The measured branching fractions appear to be consistently lower than the SM predictions, with the largest discrepancy of $\sim 3.6\sigma$ observed in $1.1 < q^2 < 6.$ GeV for $B_s^0 \to \phi\mu^+\mu^-$decays [17], as shown in Figure 3. However, it is worth to mention that prediction of branching fractions are affected by large theory uncertainties, especially coming from the modelling of the hadronic form factors.
Figure 3 also shows the reconstructed invariant mass of the $K^+K^-\mu^+\mu^-$ system for the $B_s^0 \to f_2'(1525)\mu^+\mu^-$ candidates, studied in the same $B_s^0 \to \phi\mu^+\mu^-$ analysis, leading to the first observation of this decay (9σ), with a branching fraction compatible with the SM prediction: $BF(B_s^0 \to f_2'(1525)\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$.

5. $\mathbf{B^0_{s,d}} \to \mu^+\mu^-(\gamma)$

Fully leptonic final states, such as $B_s^0 \to \mu^+\mu^-$, are further helicity suppressed and have very clean Standard Model predictions (~ few percent) due to the absence of hadrons. Recently, LHCb updated the measurements of the branching fractions of $B_{s,d}^0 \to \mu^+\mu^-(\gamma)$, and of the B_s^0 effective lifetime, using the full dataset collected [18]. No evidence was found for the $B^0 \to \mu^+\mu^-(\gamma)$ decays, and limits were set on $BF(B^0 \to \mu^+\mu^-) < 2.3(2.6) \times 10^{-10}$ and on $BF(B^0 \to \mu^+\mu^-(\gamma)) < 1.5(2.0) \times 10^{-9}$ at 90%(95%) of confidence level. For $B_s^0 \to \mu^+\mu^-$ decays the updated values of branching fractions and the effective lifetime were found to be respectively: $BF(B_s^0 \to \mu^+\mu^-) =$

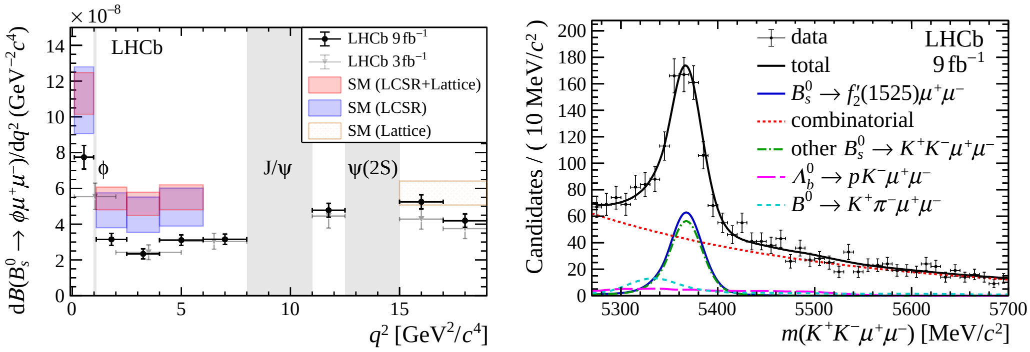


Figure 3: Differential branching ratio measurements, together with SM predictions (left), reconstructed invariant mass of the $K^+K^-\mu^+\mu^-$ system (right), for $B_s^0 \to \phi\mu^+\mu^-$ [17] decays.

$3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9}$ and $\tau_{\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03$ ps, consistent with the Standard Model predictions at 1.5σ.

6. $B^0 \to \phi\mu\mu$

The first limit on $BF(B^0 \to \phi\mu\mu)$ decays was set in a recent LHCb analysis [19], using the full dataset collected. The analysis measured the branching fractions relative to that of $BF(B_s^0 \to \phi\mu\mu)$ setting an upper limit on the ratio of $\mathcal{R} < 4.4 \times 10^{-3}$ at 90% CL.

7. Conclusions

Electroweak penguin decays are ideal probes for New Physics beyond the Standard Model, and LHCb has intensively studied these processes over the past years. Most of the measurements presented are being updated with the full dataset available, in some cases also by employing new analysis strategies (as updating the R_{K^*} result with a combined $R_K - R_{K^*}$ analysis). In addition, new hadronic final states are being studied in ratios of branching fractions (as $R_{K\pi\pi}$, R_ϕ etc.), as well as angular analysis with electrons in the final state. Finally, also innovative approaches are being tested, as fitting directly the Wilson Coefficients through amplitude analysis.
The start of Run3, with the increase of the dataset collected till now, will help in reducing the statistical uncertainties (the dominant sources for the majority of the analysis presented) and the systematics due to data driven models. During these times, LHCb is also undergoing staged upgrades, including the replacement of the vertex and tracking detectors or the removal of the hardware trigger. All of the above will be powerful ingredients to clarify the flavour anomalies that have been puzzling the physics community in the last decade, together with the results of Belle-II.

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References

[1] Hiller, Gudrun and Schmaltz, Martin, *R_K and future $b \to s\ell\ell$ physics beyond the standard model opportunities*, Physical Review D 5 (2014) 90

[2] Falkowski, Adam and Nardecchia, Marco and Ziegler, Robert, *Lepton flavor non-universality in B-meson decays from a U(2) flavor model*, JHEP 11 (2015) 173

[3] Blake, Lanfranchi and Straub, *Rare B decays as tests of the Standard Model*, Progress in Particle and Nuclear Physics 92 (2017)

[4] The LHCb Collaboration, *The LHCb Detector at the LHC*, Journal of Instrumentation, 3 (2008)

[5] The LHCb Collaboration, *Test of lepton universality in beauty-quark decays*, Nature Physics 18, (2022) 277-282

[6] The LHCb Collaboration, *Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$decays*, Phys. Rev. Lett. 122 (2019) 191801

[7] The LHCb Collaboration, *Tests of lepton universality using $B^0 \to K_S^0\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays*, Phys. Rev. Lett. 128 (2022) 191802

[8] The LHCb Collaboration, *Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$decays*, JHEP 08 (2017) 055

[9] The LHCb Collaboration, *Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays*, JHEP 05 (2020) 040

[10] Altmannshofer, Wolfgang and Ball, Patricia and Bharucha, Aoife and Buras, Andrzej J and Straub, David M and Wick, Michael, *Symmetries and asymmetries of $B \to K^*\mu^+\mu^-$ decays in the Standard Model and beyond*, JHEP 01 (2009) 019

[11] The LHCb Collaboration, *Angular Analysis of the $B^+ \to K^{*+}\mu^+\mu^-$ Decay*, Phys. Rev. Lett. 126 (2021) 161802

[12] The LHCb Collaboration, *Measurement of CP-Averaged Observables in the $B^0 \to K^{*0}\mu^+\mu^-$ Decay*, Phys. Rev. Lett. 125 (2020) 011802

[13] The LHCb Collaboration, *Angular analysis of the rare decay $B_s^0 \to \phi\mu^+\mu^-$*, JHEP 11 (2021) 043

[14] The LHCb Collaboration, *Differential branching fractions and isospin asymmetries of $B \to K^{(*)}\mu^+\mu^-$ decays*, JHEP 06 (2014) 133

[15] The LHCb Collaboration, *Differential branching fraction and angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decays*, JHEP 06 (2015) 115

[16] The LHCb Collaboration, *Measurements of the S-wave fraction in $B^0 \to K^+\pi^-\mu^+\mu^-$ decays and the $B^0 \to K^*(892)^0\mu^+\mu^-$ differential branching fraction.*, JHEP 11 (2016) 047

[17] The LHCb Collaboration, *Branching Fraction Measurements of the Rare $B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2^{'}(1525)\mu^+\mu^-$ Decays*, Phys. Rev. Lett. 127 (2017) 151801

[18] The LHCb Collaboration, *Analysis of Neutral B-Meson Decays into Two Muons*, Phys. Rev. Lett. 128 (2022) 041801

[19] The LHCb Collaboration, *Search for the decay $B^0 \to \phi\mu^+\mu^-$*, JHEP 05 (2022) 67

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