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SELECTED MEASUREMENTS OF RARE DECAYS AT THE LHCb*

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The LHCb spectrometer is specifically designed to study heavy-flavour physics. These proceedings present a selection of rare decays analyses performed with 1 fb^{-1} and 2 fb^{-1} of proton–proton collision data collected at the center-of-mass energies of 7 and 8 TeV, respectively. Rare decays are highly suppressed (or forbidden) in the Standard Model, thus could provide indirect evidence of New Physics. Results of the angular analyses of the $B^0 \to K^{*0}\mu^+\mu^-$, $B^0 \to K^{*0}e^+e^-$, $\Lambda_b^0 \to \Lambda\mu^+\mu^-$, and $B_s^0 \to \phi\mu^+\mu^-$ decays, along with branching fraction measurements for the latter two channels, are summarized. In addition, a test of lepton flavour universality in $B^+ \to K^+\ell\ell$ decays and searches for the lepton flavour violating decays are presented.

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1. Introduction

Rare decays are highly suppressed in the Standard Model (SM), and are thus very sensitive to new physics effects. An excellent example are transitions in which the b quark goes to s quark with the emission of two leptons. Those types of transitions are Flavour Changing Neutral Current (FCNC) processes and can occur in the SM only via loop level processes. FCNC processes are described in effective field theory using an effective Hamiltonian

$$H_{\rm eff} = -\frac{4G_{\rm F}}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i O_i \,,$$

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where C_i are short-distance Wilson coefficients and O_i are long-distance Wilson operators (O_7 is the photon penguin operator, and $O_{9,10}$ are electroweak penguin operators). Another approach to search for effects beyond the SM are searches for lepton flavour violating decays. Lepton flavour violation (LFV) in the neutral lepton sector is present in nature [2], yet it is highly suppressed. Any observation of sizable lepton flavour violation in charged lepton sector would be a clear sign of NP.

A very precise instrument, such as the LHCb detector, is required to measure decays such as aforementioned ones. LHCb is a single-arm forward spectrometer designed to search for indirect evidence of new physics and CP violation in heavy flavour decays [1]. Its excellent vertex and track resolution combined with very good particle identification capabilities make it a very suitable detector for the study of rare decays. A selection of results from these analyses will be discussed in the following sections.

2. Suppressed modes

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

The $B^0 \to K^{*0}\mu^+\mu^-$ decay proceeds through the $b \to s\ell\ell$ FCNC transition (Fig. 1 shows its Feynman diagram), and can be fully described with three helicity angles (θ_l, θ_K, ϕ) and the di-lepton invariant mass squared (q^2).

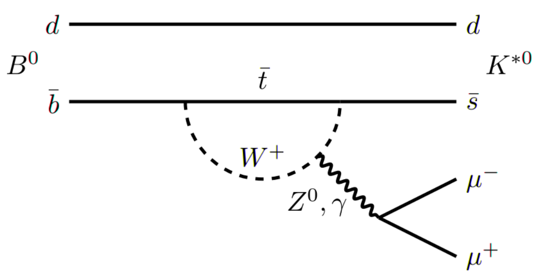

Fig. 1. The Feynman diagram for the $B^0 \to K^{*0}\mu^+\mu^-$ decay.

The differential decay rate includes observables (*e.g.* the longitudinal polarization of the K^{*0} meson $F_{\rm L}$ or forward–backward asymmetries $A_{\rm FB}$) that are dependent on the Wilson coefficients. An additional set of observables, such as $P_5' = S_5/\sqrt{F_{\rm L}(1-F_{\rm L})}$ can be defined, for which the leading form-factor uncertainties cancel [3, 4].

The multivariate selection is used to reduce the combinatorial background, and the $K^+\pi^-\mu^+\mu^-$ invariant mass is used to discriminate between signal and background, resulting in a signal yield of 2398 ± 57 in the B^0 mass window [5450–7000] MeV/c^2. The first full angular analysis of this channel shows 3.7σ (3.4σ) of local (global) deviations from SM predictions. A clear tension in the P_5' distribution can be observed in Fig. 2. The best fit-point to the C_9 Wilson coefficient corresponds to $\Delta\text{Re}(C_9) = -1.04 \pm 0.25$ [5].

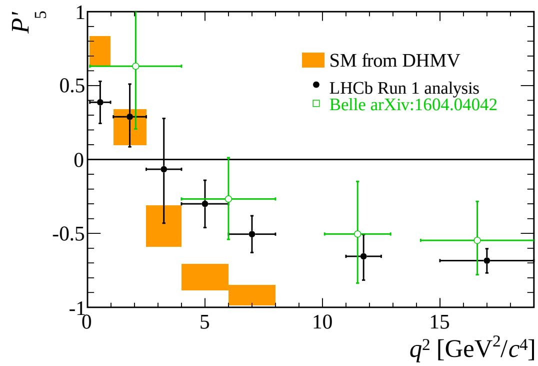

Fig. 2. P_5' distribution in bins of q^2 measured by the LHCb experiment. New Belle result [17] is consistent with the LHCb.

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

An angular analysis of the $B^0 \to K^{*0}e^+e^-$ decay is performed in the low q^2 region between $[0.002, 1.120]$ GeV$^2/c^2$. This analysis is particularly challenging because of the presence of two electrons in the final state. In order to increase the purity of the signal sample, a multivariate selection is applied. A maximum likelihood fit of the angular distribution and of the $K^+\pi^-e^+e^-$ invariant mass is performed leading to a signal yield of 124 events. Moreover, the low q^2 region is sensitive to the C_7 Wilson coefficient. Results are consistent with SM predictions [6].

2.3. Angular and branching fraction analysis of the $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decay

The aim of this analysis is to measure the differential branching fraction in bins of q^2 and to perform the angular analysis of the $\Lambda_b^0 \to \Lambda\mu^+\mu^-$. The polarization of the Λ baryon is preserved in the $\Lambda \to \pi^- p$ decay, enabling access to information complementary to that obtained from B-meson decays. The decay is normalized to $\Lambda_b^0 \to \Lambda\, J/\psi(\to \mu^+\mu^-)$, and Λ candidates are reconstructed with the $\Lambda \to \pi^- p$ decay. The selection is based on a neural network classifier, where proxy simulated $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ Monte Carlo samples are used as a signal, and the upper sideband data is used as a background sample. Regions of q^2 with charmonium resonances are excluded.

The analysis shows several deviations. Firstly, the angular analysis shows tension in the leptonic forward–backward asymmetries in the high q^2 region, SM predictions lie below the measured values. Secondly, there is an inconsistency in the differential branching fraction distribution. The measured differential branching fraction lies below SM predictions at low q^2 (see Fig. 3). Standard Model predictions are above the measured values in several q^2 bins [7].

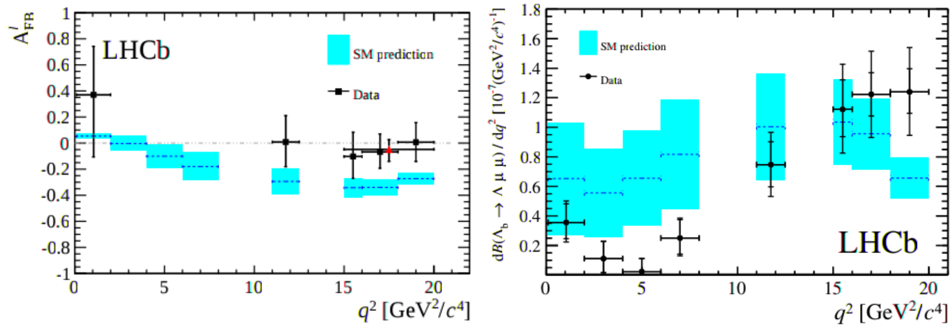

Fig. 3. The leptonic forward–backward asymmetries (left) and the branching fraction (right) distribution in the $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decay.

2.4. *Angular and branching fraction analysis of the $B_s^0 \to \phi\mu^+\mu^-$ decay*

In this analysis, a branching fraction measurement of the $B_s^0 \to \phi\mu^+\mu^-$ channel and the three-dimensional angular analysis in $\cos\theta_\ell$ $\cos\theta_K$, and ϕ in bins of q^2 is performed. The decay channel is experimentally very clean due to the presence of a narrow ϕ meson resonance that decays. The $K^+K^-\mu^+\mu^-$ system is required to have a reconstructed invariant mass in the range of [5261–5800] MeV/c^2 and the mass of the K^+pK^- system is required to deviate less than 12 MeV/c^2 from the known ϕ-meson mass. The combinatorial background is reduced using a Boosted Decision Tree [18].

The analysis of the $B_s^0 \to \phi\mu^+\mu^-$ decay shows a good agreement with the SM in the angular observables (less observables are accessible than in the $B^0 \to K^{*0}\mu^+\mu^-$, since the decay is not self-tagging). However, the branching fraction distribution differs with the SM prediction by 3.3σ in the low q^2 region (see Fig. 4) [8].

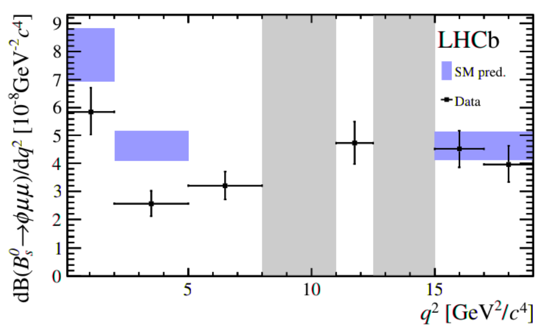

Fig. 4. The differential branching fraction distribution of the $B_s^0 \to \phi\mu^+\mu^-$decay.

2.5. Test of lepton universality in $B^+ \to K^+\ell\ell$ decays

The ratio of branching fractions of the $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ decays is a theoretically very clean observable. The SM gauge bosons couple equally to all lepton flavours, thus this ratio is expected to be equal to

$$R_K = \frac{\mathcal{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{BR}(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}\left(10^{-3}\right) .$$

In order to reduce systematic uncertainties, R_K is measured from the double ratio of branching fractions of $B \to K\ell\ell$ and $B \to K\,J/\psi(\ell\ell)$ decays. In terms of measured yields $\mathcal{N}_X$ and efficiencies ϵ_X, where X stands for a given decay channel, the ratio is given with

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{K^+\,J/\psi(e^+e^-)}}{\mathcal{N}_{K^+\,J/\psi(\mu^+\mu^-)}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{K^+\,J/\psi(\mu^+\mu^-)}}{\epsilon_{K^+\,J/\psi(e^+e^-)}}\right) .$$

The value of the ratio as measured by the LHCb differs from the SM predictions by 2.6σ [9]

$$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat.}) \pm 0.036(\mathrm{sys.})\,.$$

Branching fractions are integrated over the q^2 region [1–6] GeV^2/c^2. Figure 5 shows values of R_K measured by the LHCb [9], Belle [16], and BaBar [15], together with SM predictions. The ratio measured by the LHCb lies below the SM prediction, which is consistent with the BaBar measurement in the lower q^2 region.

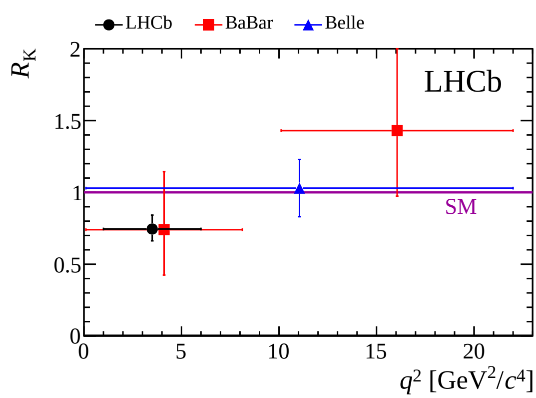

Fig. 5. The R_K distribution in q^2 measured by the LHCb, together with previous results from BaBar and Belle, and with the SM prediction.

3. Lepton flavour violating modes

3.1. Search for the $\tau^- \to \mu^-\mu^+\mu^-$ decay

Lepton flavour violation in the neutral lepton sector is established by the presence of neutrino oscillations. The $\tau^- \to \mu^-\mu^+\mu^-$ decay could proceed through the neutrino oscillation at the penguin level, but the branching fraction of this process is expected to be lower than 10^{-40}, which is beyond any experimental reach [10]. However, many NP models enhance branching fractions of LFV processes, especially for τ decays, given the large mass difference between the tau lepton and the muon. The $D_s^- \to \phi(\to \mu^+\mu^-)\pi^-$ decay is used as a control channel. The LHCb Collaboration sets an upper limit on the branching fraction at the 95% (90%) confidence level to be lower than 4.6 (5.6) $\times 10^{-8}$ [11] (see Fig. 6).

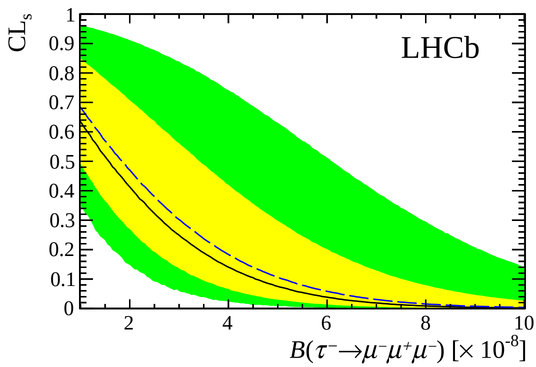

Fig. 6. Distribution of $\mathrm{CL_s}$ values as a function of branching fraction of the $\tau^- \to \mu^-\mu^+\mu^-$decay.

3.2. Search for $B_{s,d} \to e\mu$ decays

The search for lepton flavour violating decays $B_s^0 \to e^\pm\mu^\mp$ and $B^0 \to e^\pm\mu^\mp$ is performed with a 1 fb^{-1} data sample from 7 TeV *pp* collisions. $B^0_{(s)} \to h^+h'^-$ $(h, h' = K, \pi)$ decays are used as control channels, and the $B_s \to e\mu$ branching fraction is computed with respect to that of the $B \to K^+\pi^-$ channel. The observed signal yields are consistent with background expectations for the both decays. The observed limits on branching fractions are $\mathcal{BR}(B_s^0 \to e^\pm\mu^\mp) < 1.1\ (1.4) \times 10^{-8}$ and $\mathcal{BR}(B^0 \to e^\pm\mu^\mp) < 2.8\ (3.7) \times 10^{-9}$ at 90% (95%) confidence level [12] (see Fig. 7).

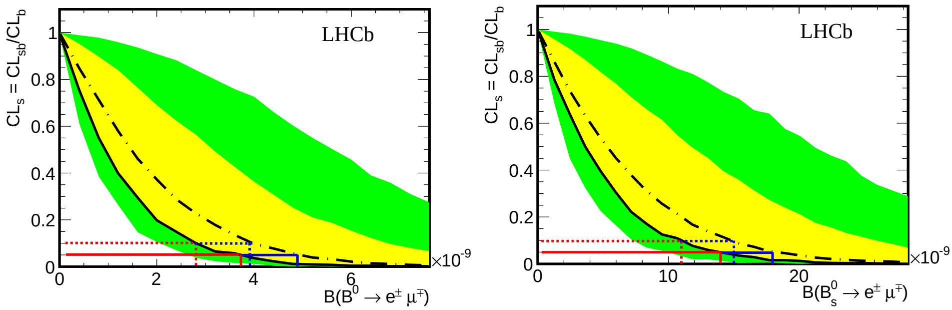

Fig. 7. Distribution of $\mathrm{CL_s}$ values as a function of branching fractions for $B^0 \to e^\pm\mu^\mp$ (left) and $B_s^0 \to e^\pm\mu^\mp$ (right).

4. Summary

These proceedings present studies of rare decays performed by the LHCb experiment. Interesting tensions with SM predictions are observed, such as in angular observables of $B^0 \to K^{*0}\mu^+\mu^-$ decays or in the differential branching fraction measurement of $B_s^0 \to \phi\mu^+\mu^-$ decays. Rare decays are a powerful tool for searching for the new physics effects. While there is no significant evidence of beyond Standard Model physics, the pattern of observed deviations appears to be consistent [13, 14]. Thus, it is necessary to further investigate rare decays to confirm current results.

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