PROCEEDINGS OF SCIENCE

The $B_s^0 \to \mu^+\mu^-$ decay, lepton flavour violation and lepton flavour universality at the LHCb experiment

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Rare decays of b hadrons are sensitive indirect probes of effects beyond the Standard Model. These are processes that are suppressed because they are forbidden at tree level but they can proceed via loops, where new particles can contribute in principle at the same level as the Standard Model. In particular, $b \to s\ell\ell$ processes give access to many observables where effects of new physics can be observed. Recent results on these searches will be presented, including the new measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction, lepton flavour violation and lepton flavour universality measurements performed at the LHCb experiment.

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1. Rare decays

Rare decays are processes that are suppressed in the Standard Model (SM), because they can only proceed via loop diagrams. Typically, they are Flavour Changing Neutral Currents (FCNC), such as $b \to s$ or $c \to u$ transitions, which are forbidden at tree level in the SM. As new particles can enter in the loops at the same level as the SM, these decays are very sensitive to new physics and, as particles in loops are virtual, they can probe higher energy scales than direct searches. Furthermore, they offer a rich environment with a wealth of observables sensitive to new physics: branching fractions, angular observables and ratios between different channels. A consistent pattern of anomalies has been observed which favours Beyond the Standard Model (BSM) scenarios over the SM [1, 2]. Of particular interested are Lepton Flavour Violation (LFV) and Lepton Flavour Universality (LFU) measurements.

LFV is the non-conservation of lepton number, which would produce decays such as $\tau^\pm \to \mu^+\mu^-\mu^\pm$, while LFU is the equality of lepton couplings, that is assumed to be true in the SM and if violated would manifests itself in differences in the branching ratios of decays involving different lepton families. One of the most interesting additions to the SM producing effects in these observables is lepto-quarks [3, 4], which are bosonic particles carrying both lepton and quark quantum numbers.

The following sections present the measurement of the $B^0_s \to \mu^+\mu^-$ branching fractions, and a selection of LFV and LFU measurements performed at the LHCb experiment. The analyses presented in these proceedings are based on a dataset of proton-proton collisions corresponding to up-to 5 fb^{-1} of integrated luminosity collected at center-of-mass energies of 7, 8 and 13 TeV.

2. The $B^0_{d,s} \to \mu^+\mu^-$ decay

The $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays are exceedingly rare decay in the SM as they are FCNCs, which are also CKM and helicity suppressed. For this reason the branching ratios of these decays are predicted to be very small [5]:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9} \text{ and} \tag{2.1}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}. \tag{2.2}$$

On the other hand they can receive even tree level contributions in BSM, which makes them particularly sensitive to new physics. The importance of this measurement is increased by its cleanliness, in fact, since there is a purely leptonic final state, the predictions are not affected by uncertainties due to the description of the hadrons in the final state. LHCb measured the branching fraction of these decays using 4.4 fb^{-1} of luminosity [6], combining four datasets collected at center of mass energies of 7, 8 and 13 TeV between 2011 and 2016. The invariant mass distribution of $B^0_s \to \mu^+\mu^-$ candidates is shown in Fig. 1. In the fit model, in addition to the signal, backgrounds are also considered: decays with mis-identified particles, as $B^0 \to hh$, or partially reconstructed decays with two real muons as $B^+ \to \pi^0\mu^+\mu^-$. The former is potentially the most dangerous background as it peaks under signal mass peak, however only ~ 7 events are expected in the full invariant mass range. The branching ratio of the $B^0_s \to \mu^+\mu^-$ decay is measured to be

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8 \pm 0.6) \times 10^{-9}, \tag{2.3}$$

which is in very good agreement with the SM prediction. For the $B^0 \to \mu^+\mu^-$ decays an excess of less than 3σ is found and therefore a limit is set at $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 3.4\times10^{-10}$ at 95% confidence level.

Even if the branching ratio of $B^0_s \to \mu^+\mu^-$ is SM-like there still is space for new physics. In fact, in the B^0_s system, the light and heavy mass eigenstates are characterised by a sizeable difference in decay widths, $\Delta\Gamma = 0.082 \pm 0.007 ps^{-1}$ and in the SM only the heavy state decays to two muons, but this condition does not necessarily hold in BSM scenarios [7]. The contributions from the two mass states can be disentangled using the effective lifetime defined as $\tau_{\mu^+\mu^-} \equiv \int_0^\infty t\,\Gamma(B_s(t) \to \mu^+\mu^-)\,dt / \int_0^\infty \Gamma(B_s(t) \to \mu^+\mu^-)\,dt$ due to the relation

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B^0_s}}{1-y_s^2} \frac{1+2A_{\Delta\Gamma}y_s + y_s^2}{1+A_{\Delta\Gamma}y_s}, \tag{2.4}$$

where $y_s = \tau_{B^0_s}\Delta\Gamma/2$ is a constant and $A_{\Delta\Gamma}$ is an asymmetry variable which is 1 in the SM but can assume any value in the interval $[-1,1]$ in BSM scenarios.

The effective lifetime is measured using a similar sample as the one used for the branching ratio analysis but with looser particle identification requirements on the muons to favour statistics over purity. Figure 1 shows the distribution of the effective lifetime, where the background is subtracted using the s$\mathcal{P}$lot technique. A fit with an exponential function multiplied by an acceptance function obtained from simulation is performed. The effective lifetime is measured to be $\tau_{\mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05$ ps where the first uncertainty is statistical and the second systematic. Pseudo-experiments generated with extreme values of $A_{\Delta\Gamma}$ are then used to evaluate the compatibility of the result with the different hypotheses. The result is found to be compatible with the SM hypothesis $A_{\Delta\Gamma} = 1$ at 1σ level, while it is compatible at 1.4σ level with the opposite hypothesis.

Finally, a search for the $B^0_s \to \tau^+\tau^-$ decay is performed using 3 fb^{-1} of integrated luminosity collected in 2011 and 2012. This decay is less helicity suppress with respect to the muon one and its branching ratio is predicted to be ~ 100 times larger, which partially recovers for the low efficiency of reconstructing τ decays. For this analysis the τ lepton is reconstructed using its $\tau \to \pi\pi\pi\nu$ decay. No signal is observed and a limit $\mathcal{B}(B^0_s \to \tau^+\tau^-) < 3.0\times10^{-3}$ is set at 95% confidence level.

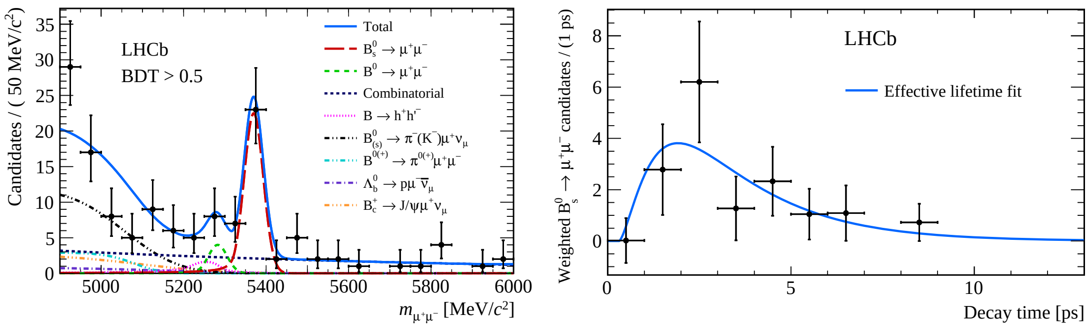

Figure 1: (left) Invariant mass distribution and (right) the effective lifetimes of $B^0_s \to \mu^+\mu^-$ candidates.

3. Lepton flavour universality and lepton flavour violation

Tests of LFU are particularly interesting when using loop decays where new physics can contribute significantly and break the symmetry. These measurements are usually performed using ratios between the branching fractions of decays with just different leptons. In fact, uncertainties due the hadronic part of the decays, which are the main source of theoretical uncertainty, cancel because the same hadronic particles appear of both sides of the ratio.

First of all, LHCb tested LFU between τ and μ leptons by measuring the ratio between the branching fractions of $B^0 \to D^* \mu \nu_\mu$ and $B^0 \to D^* \tau \nu_\tau$ decays, which could proceed via a direct lepto-quark exchange. For this purpose τ was reconstructed using the $\tau \to \mu \nu \nu$ channel, which has the same final state as the muon channel and therefore is chosen because of their similar efficiency. As two neutrinos are present in the final state, there is no clear peak to fit. Therefore, to exploit at best the available information, a template fit is performed on three variables simultaneously: the energy of the muon, $q^2 = (p_B^\mu - p_D^\mu)^2$ and the missing energy estimated using information from kinematical constraints as the flight direction of the muon to the B vertex. The combinatorial background is taken into account using a template obtained from data while templates for backgrounds from partially-reconstructed B decays are obtained from simulation.

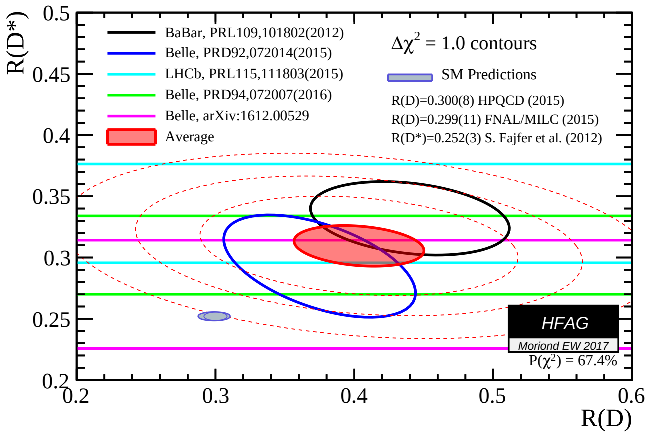

Figure 2: One sigma contour (red) of the combination of the BaBar (black) [8], Belle (green and dark blue) [9, 10] and LHCb (cyan) [11] results for the ratio between the τ and μ channels of $B^0 \to D(D^*)\ell\nu_\ell$ decays, taken from Ref. [12] with the SM prediction from Refs. [13, 14] overlaid in magenta.

The measured value was found to be $0.336 \pm 0.027 \pm 0.030$ [11], compatible with the SM within 2.1σ. As shown in Fig. 2, a combination with the results from Belle and BaBar yields a total 3.9σ [12] deviation from the SM. LHCb is currently improving the measurement by analysing also an independent sample of decays, where τ is reconstructed via the $\tau \to \pi\pi\pi\nu$ channel.

To test LFU between electrons and muons the R_H ratios have been proposed [15], defined as

$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to H\mu\mu)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to Hee)}{dq^2} dq^2}, \tag{3.1}$$

where H, can be a kaon, a K^*, a ϕ or an inclusive strange state.

In particular, LHCb measured the R_K ratio in the $1-6\ \mathrm{GeV}^2/c^4$ region in dilepton invariant mass, q^2, where theory calculations are expected to be most reliable. The quantity measured is actually the double ratio with respect to similar decays where the two leptons come from a J/ψ resonance. These are tree level processes where no new physics is expected and therefore they would not bias the measurement; on the other hand these resonant channels have same final daughters and similar kinematics to the respective rare decays and therefore the double ratio allows to reduce significantly the systematic uncertainties in the efficiency estimation.

The challenge of this analysis are the electronic channels; in fact electron reconstruction is more complex due to multiple scattering and bremsstrahlung radiation. To maximise the yield three trigger categories are considered: events triggered by the electron, by the kaon and by other particles in the event. Furthermore, an algorithm was developed to recover bremsstrahlung photons and correct the electrons momenta; this is done by looking at calorimeter hits around the electrons trajectory.

Assuming LFU holds, the value of the R_H ratios should be close to unity with corrections $O(10^{-3})$ due to the different masses of the leptons. On 3 fb^{-1} of integrated luminosity the R_K ratio was measured to be $0.745^{+0.090}_{-0.074}(\mathrm{stat})^{+0.036}_{-0.036}(\mathrm{sys})$ corresponding to a 2.6σ deviations from the SM [16].

Recently LHCb also measured the R_{K^*} ratio [17] in two q^2 bins: a central q^2 bin [1.1,6] GeV^2/c^4, most sensitive to new physics, and a low q^2 bin [0.045,1.1], where the photon pole dominates and therefore new physics effects are expected to be diluted. The analysis was performed in a similar way to the R_K measurement, exploiting the double ratio with respect to the charmonium channels and using events triggered in three different ways. Fits to the electron channels candidates are reported in Fig. 3, while the results of the analysis are shown in Fig. 4, compared with theoretical predictions and results from other experiments. In the central q^2 bin, in agreement with what found for R_K, a $2.4-2.5\sigma$ deviation (depending on which prediction is used) is observed.

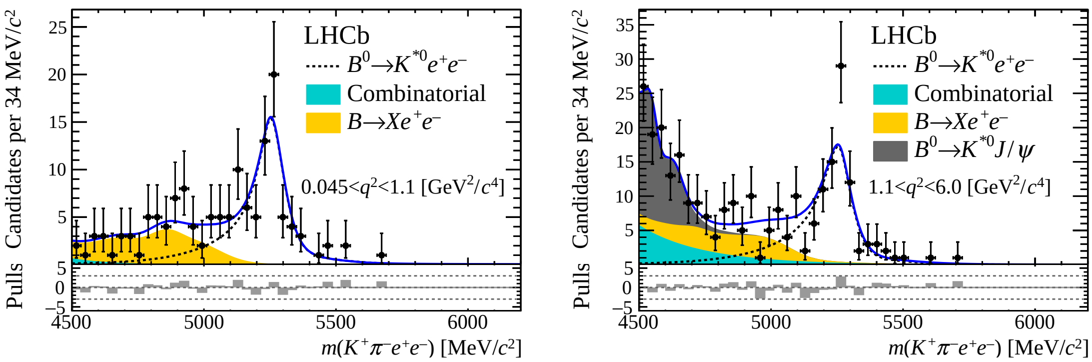

Figure 3: Fit to the 4-body $m(K\pi ee)$ invariant mass of $B^0 \to K^* ee$ candidates in the low- (left) and central (right) q^2 bins. The dashed line is the signal PDF, the shaded shapes are the background PDFs and the solid line is the total PDF.

In several BSM scenarios, such as those including lepto-quarks, links can be drawn between LFU and LFV observables [3]. Therefore it is very important to search for LFV decays to be able to build a consistent picture. Several LFV searches have recently been performed at the LHCb experiment using Run I datasets including decays such as $B^0 \to e\mu$ [20] and $\tau \to \mu^+\mu^-\mu$ [21]. As

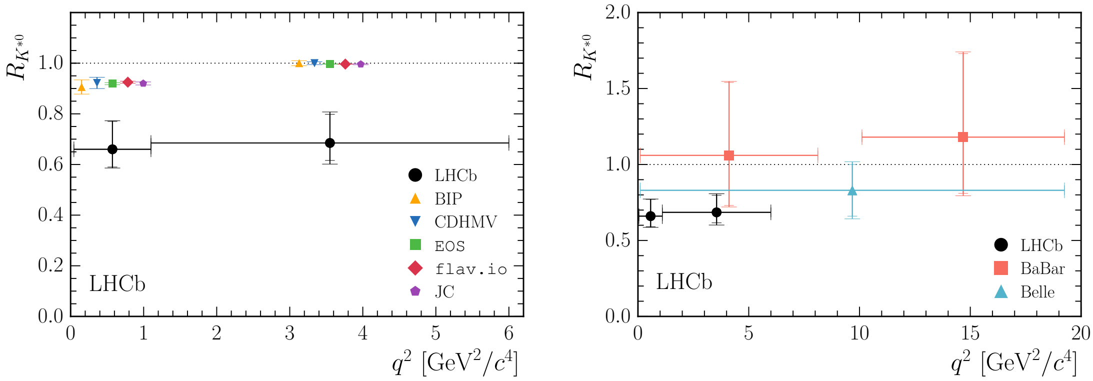

Figure 4: (left) Comparison of the LHCb R_{K^*} measurements with various SM theoretical predictions taken from Ref [17]. (right) Comparison of the LHCb R_{K^*} measurements with previous experimental results from the B factories [18, 19].

no signals are found limits are set on such processes and the analyses are now being updated with the inclusion of Run II datasets.

4. Conclusions

Rare decays represent a rich laboratory to perform precision tests of the SM and probe new physics scenarios. Even if a SM-like $B_s^0 \to \mu^+\mu^-$ branching fraction is found there is still wide space for new physics and of particular interest are LFU observables, where a consistent pattern of deviations from the SM was observed. As the processes here described are loop diagrams with low branching fractions, most of these analyses are limited by statistics and LHCb is committed to update all its result with Run II datasets as well as to analyse new channels, which could include Λ_b and charm rare decays.

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PoS(DIS2017)154