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Tests of Lepton Flavour Universality and searches for Lepton Flavour Violation at LHCb

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Rare $b \to s\ell^+\ell^-$ transitions are strongly suppressed in the Standard Model (SM). Leptons from the different families have the same coupling to electroweak bosons in the SM, symmetry that is known as Lepton Flavour Universality. Precise measurements of LFU ratios in $b \to s\ell^+\ell^-$ decays provide, then, a very powerful test of the SM. In the same way, any evidence of a Lepton Flavour Violation (LFV) decay would imply a clear sign of New Physics.

These proceedings present a summary of the latest measurements of LFU tests in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^*\ell^+\ell^-$ decays, with $\ell = e, \mu$, and searches for LFV in $B^0 \to K^{*0}\mu^\pm e^\mp$, $B^0_s \to \phi\mu^\pm e^\mp$ and $B^0 \to K^{*0}\tau^\pm\mu^\mp$ performed at LHCb with the full Run 1 and Run 2 dataset (2011-18, 9 fb^{-1}).

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1. Introduction

Rare $b \to s\ell^+\ell^-$ transitions proceed via Flavour Changing Neutral Currents at loop order in the Standard Model (also called Electroweak Penguin decays), thus they are strongly suppressed. These decays play a crucial role in searches for physics Beyond the Standard Model (BSM) in the flavour sector, since they can get significant contributions from possible New Physics (NP) modifying the decay properties, which may significantly affect observables in experiments.

In recent years the LHCb Collaboration has released some intriguing results in decays involving $b \to s\mu^+\mu^-$ transitions, usually referred as *flavour anomalies.* The measurement of branching fractions in $B \to K^{(*)}\mu^+\mu^-$ and $B^0_s \to \phi\mu^+\mu^-$ decays consistently exhibit values below the Standard Model predictions [1–3]. However, the theoretical predictions of branching fractions haver their precision limited by uncertainties in the hadronic form factors computation. Additionally, the results on angular distributions also present quite significant deviations respect to the theoretical predictions in $B \to K^*\mu^+\mu^-$ and $B^0_s \to \phi\mu^+\mu^-$ decays [4–6], in optimised observables where hadronic uncertainties cancel at first order.

On the contrary, Lepton Flavour Universality (LFU) tests provide a very robust test of the Standard Model. They can be defined as the ratio of branching fractions:

$$R_X({q_{min}}^2, {q_{max}}^2) = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to X\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to Xe^+e^-)}{dq^2}\, dq^2} \tag{1}$$

where q^2 is the squared invariant mass of the dilepton system. In the SM, leptons have the same coupling to the gauge bosons, which has been widely proven experimentally in electroweak boson decays [7]. Therefore, LFU tests result to be very precisely predicted in the theory, where the ratios are expected to be unity with a theoretically uncertainty at the 1% level and differing from unity only due to the different lepton masses [8].

Some BSM models predict a possible breaking of the LFU in $b \to s\ell^+\ell^-$ transitions, which usually couples to the enhancement of forbidden in the SM LFV processes, such as $b \to s\ell\ell'$. Therefore, the experimental search of LFV decays in b hadrons is being widely explored at LHCb.

These proceedings focus on the recent measurements of the LFU ratios R_K and R_{K^*} [9, 10], and searches for the Lepton Flavour Violating Decays $B^0 \to K^{*0}\mu^\pm e^\mp$, $B^0_s \to \phi\mu^\pm e^\mp$ [11] and $B^0 \to K^{*0}\tau^\pm\mu^\mp$ [12], all of them using the full Run 1 and Run 2 dataset (2011-18, 9 fb^{-1})[1].

2. Simultaneous measurement of R_K and R_{K^*}

2.1 LFU and electrons at LHCb

Decays involving electrons in the final state are extremely challenging at the LHCb experiment, and their interaction with the detector is significantly different than for muons. The first difference arises in the hardware trigger (L0), where the thresholds are tighter in the electron trigger than in the muon trigger, due to the larger occupancy of the electromagnetic calorimeter (ECAL) with respect to the muon chambers. Additonally, when the electrons traverse the detector material they emit

[1] K^{*0} refers to the $K^*(892)^0$ resonance, and ϕ to the $\phi(1020)$ resonance if not stated otherwise.

bremsstrahlung photons. In order to correct the radiative energy losses a *Brem Recovery* algorithm is performed by extrapolating the tracks to photon energy deposits in the ECAL. However, at the relevant energy the ECAL resolution is lower than in the tracking detectors, so electrons have poorer momentum resolution than muons and are heavily affected by bremsstrahlung losses, which are only partially recovered [13].

2.2 Analysis Strategy

Lepton Flavour Universality tests in LHCb are performed using a double ratio of the rare decay respect to the resonant mode $B \to J/\psi X$, where the J/ψ tree-level decay to a dielectron or dimuon pair is used as normalisation and calibration channel:

$$R_{K^{(*)}} = \frac{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)} \times \frac{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to e^+e^-))}{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to \mu^+\mu^-))}. \tag{2}$$

This is done in order to cancel out most of the efficiency-related systematic uncertainties, and the method is valid due to the well established lepton flavour universal behaviour of $J/\psi \to \ell^+\ell^-$ decays [14]. Yields ($\mathcal{N}$) are experimentally determined from a mass fit to the invariant mass of the reconstructed B meson, while efficiencies (ϵ) are evaluated using simulated signal samples, which are corrected and calibrated with calibration data samples. In order to disentangle potential New Physics effects, the analysis is divided into two different q^2 regions: a *low* q^2 region from 0.1 to 1.1 GeV^2, and a *central* region from 1.1 to 6.0 GeV^2. This enables to study the possible effect of NP in different regions of q^2.

2.3 Event Reconstruction and Selection

The first stage of the real-time event selection is performed by a hardware trigger, which rejects events having a large detector occupancy and selects the remaining ones that have a muon with high transverse momentum (p_T) relative to the beamline, or an electron with high transverse energy in the ECAL. In order to improve the efficiency (mainly in electron channels), apart from triggering on lepton signal candidates, also signatures independent of signal that fire any of the calorimeter or muon chamber hardware trigger in the event are selected. The software trigger requires a two- or three-body secondary vertex with significant displacement from any primary pp interaction vertex.

In the offline reconstruction and selection all final state candidates are required to have a K meson (K^+ or K^{*0}, reconstructed in the $K^+\pi^-$ final state within 100 MeV of its known mass [14]) and two oppositely charged electrons or muons. A combination of requirements on particle identification (PID) systems and multivariate classifiers, which combine information from all PID systems, is used to identify the final state particles. A series of vetoes are applied in order to reduce the contamination from specific peaking and semileptonic backgrounds. Finally, two groups of multivariate classifiers (MVA), are trained to separate signal from combinatorial and partially reconstructed backgrounds, respectively.

2.4 Analysis Validation

The double ratio method and efficiency calibration is crosschecked evaluating the compatibility with unity the ratios $r_{J/\psi}$ and $R_{\psi(2S)}$,

$$r^{K^{(*)}}_{J/\psi} = \frac{\mathcal{B}(B\to K^{(*)}J/\psi(\to\mu^+\mu^-))}{\mathcal{B}(B\to K^{(*)}J/\psi(\to e^+e^-))},\ R^{K^{(*)}}_{\psi(2S)} = \frac{\mathcal{B}(B\to K^{(*)}\psi(2S)(\to\mu^+\mu^-))}{\mathcal{B}(B\to K^{(*)}\psi(2S)(\to e^+e^-))} \times \left(r^{K^{(*)}}_{J/\psi}\right)^{-1}. \tag{3}$$

The single ratio allows to validate the scales of the efficiencies for electrons and muons against one another, while the double ratio exhibits the same cancellation of systematics as in R_X defined in (2). In both resonant channels LFU is fulfilled experimentally, thus the ratios are expected to be unitary[14]. The results obtained are compatible with unity.

2.5 Results

The ratios R_K (R_{K^*}) are extracted from a simultaneous unbinned maximum-likelihood fit to the reconstructed invariant $K^+(\pi^-)\,\ell^+\ell^-$ mass spectrum. The simultaneous analysis allows to constrain the partially reconstructed background $B^0 \to K^{*0}e^+e^-$ in the $m(K^+e^+e^-)$ spectrum, while the leakage from $B^{(+,0)} \to J/\psi(\to e^+e^-)K^{(+,*0)}$ decays is constrained from the resonant mass fit.

After all the selection criteria have been applied, the nonresonant muon candidate mass distributions are very clean, the fit only contains a signal and combinatorial background components. The obtained branching fractions for these channels are found to be compatible with previous measurements [1, 2].

The rare electron mass distributions of the B candidates present a more challenging situation (fig. 1). In addition to the signal and combinatorial background components of the fit, the leakage from the J/ψ q^2 region, partially reconstructed backgrounds and residual hadronic misidentified backgrounds components have also been considered to describe the data. This last background is modeled with a novel data-driven approach, using background enriched data samples obtained by inverting the electron identification requirements. The candidates are then weighted according to their misidentification probability, estimated on high statistics and high purity data control samples. The invariant mass shape of these backgrounds is modeled using an empirical function and their normalisation is constrained according to the prediction obtained from the reweighting procedure.

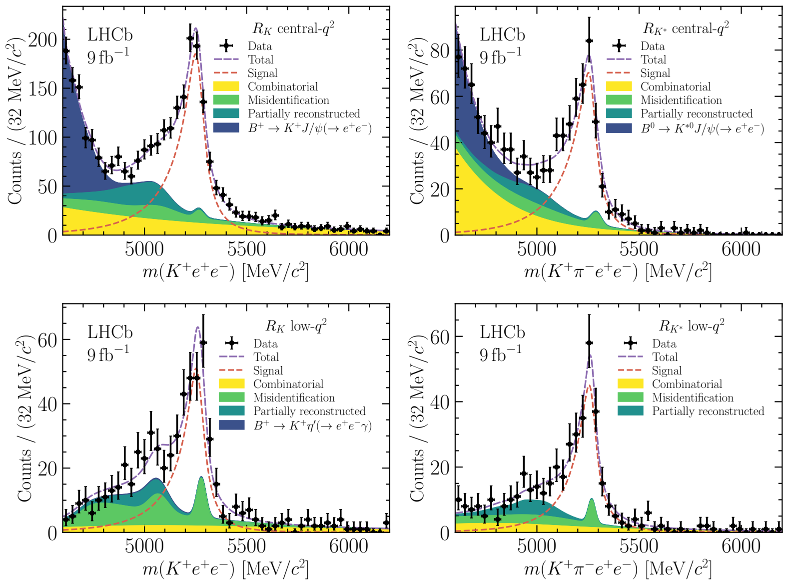

Figure 1: Invariant mass distributions of the (left) $B^+ \to K^+e^+e^-$ and (right) $B^0 \to K^{*0}e^+e^-$ candidates in the (upper) central-q^2 and (lower) low q^2 regions. The results of the fit described in the text are also presented in the plots.

The measured values of R_K and R_{K^*} are found to be:

$$\text{low-}q^2 \begin{cases} R_K & = 0.994\ ^{+0.090}_{-0.082}\ \text{(stat)}\ ^{+0.029}_{-0.027}\ \text{(syst)}, \\ R_K^* & = 0.927\ ^{+0.093}_{-0.087}\ \text{(stat)}\ ^{+0.036}_{-0.035}\ \text{(syst)}, \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K & = 0.949\ ^{+0.042}_{-0.041}\ \text{(stat)}\ ^{+0.022}_{-0.022}\ \text{(syst)}, \\ R_K^* & = 1.027\ ^{+0.072}_{-0.068}\ \text{(stat)}\ ^{+0.027}_{-0.026}\ \text{(syst)}, \end{cases}$$

which are the most precise and accurate LFU tests in $b \to s\ell^+\ell^-$ transitions, as well as the first R_K measurement in the low-q^2. The results are compatible with the Standard Model at 0.2σ. The ratios are dominated by statistical uncertainty, while the main source of systematic uncertainty is the hadronic misidentification modelling in the fit [9, 10].

3. Lepton Flavour Violation Searches

3.1 $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

Searches for LFV $b \to s\mu^\pm e^\mp$ decays have been performed in the LHCb experiment, such as $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$. The final states are reconstructed with the intermediate resonance decays $K^{*0} \to K^+\pi^-$ and $\phi \to K^+K^-$, and the analysis takes $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$ as normalisation modes. Similarly to the LFU analysis, the electron reconstruction makes use of the *Brem Recovery* algorithm and MVA and vetoes to specific backgrounds as a selection to reduce background. No significant excess is found and upper limits have been set at 90(95%) confidence level, which are the most stringent limits to date [11]:

$$\mathcal{B}(B^0 \to K^{*0}e^+\mu^-) < 6.8(7.9) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}e^-\mu^+) < 5.7(6.9) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}e^\pm\mu^\mp) < 10.1(11.7) \times 10^{-9}$$
$$\mathcal{B}(B_s^0 \to \phi\, e^\pm\mu^\mp) < 16.0(19.8) \times 10^{-9}$$

3.2 $B^0 \to K^{*0}\tau^\pm\mu^\mp$

A first search for the decay $B^0 \to K^{*0}\tau^\pm\mu^\mp$ was performed by LHCb. The K^{*0} meson is reconstructed in the $K^+\pi^-$ final state, while the τ^- with $\pi^-\pi^+\pi^-$ (π^0). To account for the neutrino missing energy the signal yield is measured via a fit in the corrected mass $m_{corr} = \sqrt{p_\perp{}^2 + m_{K^*\tau\mu} + p_\perp}$. The decay $B^0 \to D^-(\to K^+\pi^-\pi^-)D_s^+(\to K^+K^-\pi^+)$ is used as normalisation mode. No significant excess was found and the first upper limits were set at 90(95%) confidence level [12]:

$$\mathcal{B}(B \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$$
$$\mathcal{B}(B \to K^{*0}\tau^-\mu^+) < 8.2(9.8) \times 10^{-6}$$

4. Conclusion

Rare $b \to s\ell\ell^{(\prime)}$ decays are able to test the validity of the SM beyond the direct energy scale reached at colliders. In particular, LFU ratios and searches for LFV are extremely clean probes for potential NP effects. The LHCb collaboration has performed the most precise LFU test in $b \to s\ell^+\ell^-$ decays up to date, with a result compatible with the SM predictions, and upper limits have been provided in searches for LFV. The results presented in these proceedings are limited in precision due to statistics. The current Run3 data taking and the future upgrades of the LHCb experiment will allow to enhance the precision down to the theoretical one in LFU tests and improve the reach of LFV searches.

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