PROCEEDINGS OF SCIENCE

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

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Rare b-hadron decays serve as powerful probes for investigating Lepton Flavour Universality (LFU) and Lepton flavour violation. These decays, mediated through $b \to s\ell\ell$ transitions, allow for stringent tests of LFU, a fundamental symmetry of the Standard Model (SM) that assumes the universal coupling of electroweak gauge bosons to leptons. However, presence of New Physics beyond the SM can manifest in sizeable deviations from LFU.

These proceedings present a summary of recent measurements focused on branching ratios of $B \to K^{(*)}\ell^{(\prime)+}\ell^{-}$ and $B^0_s \to \phi\ell^{\prime+}\ell^{-}$ decays, with $\ell = e, \mu$, performed at LHCb. The experimental techniques employed by LHCb are described, including the reconstruction and identification of the final-state particles, event selection criteria, and the estimation of systematic uncertainties. The discussed measurements constitute the most precise tests of LFU in $b \to s\ell\ell$ transitions to date and are compatible with the SM predictions.

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1. Introduction

Rare b-hadron decays mediated through $b \to s\ell\ell$ transitions play a crucial role in investigating Lepton Flavour Universality (LFU) and its potential violation, providing an excellent avenue to test the Standard Model (SM). These transitions are Flavor Changing Neutral Currents, and therefore particularly suppressed within the SM, making them highly sensitive to virtual contributions of New Physics beyond the SM.

The past decade has witnessed intriguing discrepancies, often referred to as "flavor anomalies", in measurements of branching fractions and angular distributions of rare B-decays performed by the LHCb collaboration. These deviations from the SM predictions have sparked significant interest in the physics community. Notably, the branching fractions of $B \to K^{(*)}\mu^+\mu^-$ and $B^0_s \to \phi\mu^+\mu^-$ consistently exhibit values below the SM predictions [1–3]. Additionally, the angular analyses of $B \to K^*\mu^+\mu^-$ and $B^0_s \to \phi\mu^+\mu^-$ reveal tensions with the SM expectations [4–6]. Globally, the significance of the $b \to s\mu\mu$ anomalies is estimated to be at the $4\,\sigma$ level [7].

However, the predictions for these observables are affected by hadronic uncertainties. These uncertainties arise from the presence of $c\bar{c}$ loops and, for the branching fractions in particular, form factors which require non-perturbative methods to be computed within the SM. These complexities pose considerable theoretical challenges and contribute to the ongoing discussion about the significance of the tensions observed by LHCb in $b \to s\mu\mu$ transitions.

In contrast to the uncertainties surrounding the predictions for individual decay rates, the LFU ratios

$$R_X(q^2_{\text{min}}, q^2_{\text{max}}) = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(B\to X_s\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(B\to X_s e^+e^-)}{dq^2}\, dq^2}, \tag{1}$$

with q^2 being the squared invariant mass of the di-lepton system, are predicted with high precision at the percent level [8], when the lepton masses can be neglected. These ratios provide a robust framework for testing LFU, offering an opportunity to rigorously probe the universality of the $b \to s\ell\ell$ transitions.

These proceedings focus on the recent simultaneous measurement of the LFU ratios R_K and R_{K^*} [9, 10] and the search for the lepton flavor violating decays $B^0 \to K^{*0}e^\pm\mu^\mp$ and $B^0_s \to \phi e^\pm\mu^\mp$ [11] using the full Run 1 and Run 2 dataset collected by LHCb, corresponding to an integrated luminosity of $9\,\text{fb}^{-1}$.

2. Lepton Flavour Universality Tests R_K and R_{K^*}

2.1 Analysis Strategy

The measurement of the R_X ratios at LHCb adopts a double-ratio approach, which offers several advantages. By expressing the rare $b \to s\ell\ell$ branching fractions as ratios relative to suitable normalisation modes, R_X is given by

$$R_X = \frac{\mathcal{B}(B \to X_s\mu^+\mu^-)}{\mathcal{B}(B \to X_s J/\psi\,(\mu^+\mu^-))} \times \frac{\mathcal{B}(B \to X_s J/\psi\,(e^+e^-))}{\mathcal{B}(B \to X_s e^+e^-)} = \frac{\mathcal{N}^{\mu^+\mu^-}\,\epsilon^{\mu^+\mu^-}_{J/\psi}}{\mathcal{N}^{\mu^+\mu^-}_{J/\psi}\,\epsilon^{\mu^+\mu^-}} \times \frac{\mathcal{N}^{e^+e^-}_{J/\psi}\,\epsilon^{e^+e^-}}{\mathcal{N}^{e^+e^-}\,\epsilon^{e^+e^-}_{J/\psi}}, \tag{2}$$

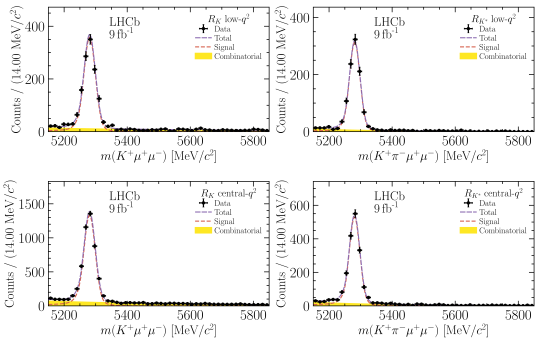

Figure 1: Invariant mass spectra for the $B^+ \to K^+\mu^+\mu^-$ (left) and $B^0 \to K^{*0}\mu^+\mu^-$ (right) decays in the low- (top) and central-q^2 (bottom) regions, compiled from Ref. [10]

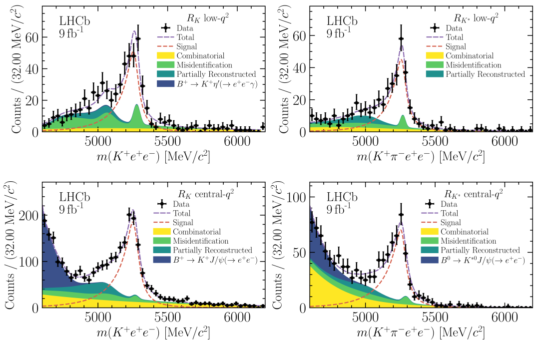

Figure 2: Invariant mass spectra for the $B^+ \to K^+e^+e^-$ (left) and $B^0 \to K^{*0}e^+e^-$ (right) decays in the low- (top) and central-q^2 (bottom) regions, compiled from Ref. [10]

where most systematic uncertainties connected to the selection and reconstruction efficiencies cancel at leading order, enhancing the precision of the measurement. The reconstruction and selection efficiencies are evaluated using simulated signal samples calibrated with background-subtracted control modes obtained from data. This approach ensures reliable estimates of the efficiencies and enables the determination of the R_X ratios with high precision and is made possible due to the established LFU in tree-level $J/\psi \to \ell^+\ell^-$ decays [12].

To disentangle potential New Physics effects, the analysis is divided into two distinct q^2 regions: a low-q^2 region ranging from 0.1 to 1.1 GeV$^2/c^4$ and a central-q^2 region ranging from 1.1 to 6.0 GeV$^2/c^4$. This choice is motivated by the ability to probe different manifestations of New Physics in different regions of q^2. Moreover, the K and K^{*0} final states provide sensitivity to distinguish between vector and axial-vector contributions to the SM.

2.2 Event Reconstruction and Selection

The event reconstruction and selection process for the R_X ratios presents several experimental challenges, particularly connected to detecting electrons at LHCb. Addressing these challenges is crucial to ensure accurate measurements. The key issues encountered in the analysis are outlined below:

Triggering the Events Electrons are triggered by the electromagnetic calorimeter, which is more challenging compared to triggering on muons in the muon chambers, due to the higher occupancy that results from the abundantly produced π^0s in the proton-proton collisions. In order to compensate for signal decays which may not pass the calorimeter trigger, the rest of the event is leveraged as an additional trigger. To ensure consistency between the electron and muon samples, this strategy is adopted for both lepton datasets, with the rest-of-event trigger serving as the primary trigger.

Mass Resolution of Electron Final States Electrons frequently emit bremsstrahlung photons while traversing the detector material, resulting in a reduction of the measured momentum. To address this, a recovery algorithm is utilised to identify bremsstrahlung photons in the calorimeter that are consistent with being emitted by the signal electrons. Despite the inclusion of this recovery algorithm, the momentum resolution of the electrons is deteriorated compared to muons, leading to a degraded resolution of the reconstructed B mass which is illustrated in Figs. 1 and 2.

Background Suppression and Modeling Careful handling of backgrounds is crucial, particularly due to the compromised mass resolution in the electronic final states. Several techniques are employed to mitigate different types of backgrounds. Combinatorial backgrounds are suppressed using a multivariate classifier that combines variables pertaining to reconstruction-quality of the candidate, and the underlying kinematics. Partially reconstructed backgrounds are addressed by a combination of a multivariate classifier that utilises vertexing and track isolation, along with a requirement on a corrected mass that correlates the flight direction of the B meson with that of the final state particles. Peaking backgrounds are mitigated through dedicated vetoes based on particle identification and kinematics.

To address residual backgrounds resulting from hadron-to-electron mis-identification, a novel data driven approach is employed to estimate the size and shape of the pollution. This inclusive approach in particular allows to quantify contamination from single mis-identification, which cannot be estimated using simulated decays, as they are not dominated by one single source. A background enriched data sample is created by inverting the electron particle identification requirements, and the candidates in this sample are then weighted according to their mis-identification probability, estimated on high statistics and high purity data-control samples. The resulting model for the residual misidentification is incorporated into the fit to determine the R_X ratios.

2.3 Validation

The reconstruction and selection efficiencies are validated using the resonant $B \to K^{(*)} J/\psi\ (\ell^+\ell^-)$ decays via the ratio of branching fractions

$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^{(*)} J/\psi\ (\mu^+\mu^-))}{\mathcal{B}(B \to K^{(*)} J/\psi\ (e^+e^-))}, \tag{3}$$

which allows to validate the scales of the efficiencies for electrons and muons against one another. The ratio is found to be unity, and independent on kinematic or geometric variables, thus validating the efficiency scales. The double ratio approach is validated using the ratio

$$R_{\Psi(2S)} = \frac{\mathcal{B}(B \to K^{(*)} \Psi(2S)\ (\mu^+\mu^-))}{\mathcal{B}(B \to K^{(*)} J/\psi\ (\mu^+\mu^-))} \times \frac{\mathcal{B}(B \to K^{(*)} J/\psi\ (e^+e^-))}{\mathcal{B}(B \to K^{(*)} \Psi(2S)\ (e^+e^-))}. \tag{4}$$

Similar to R_X defined in Eq. (2), this ratio exhibits cancellation of systematic effects related to the efficiencies determined on simulated signal decays. It is found to be compatible with unity and demonstrates stability even without calibrating the efficiencies, reinforcing the robustness of the double-ratio approach.

The treatment of the residual backgrounds from hadron-to-electron mis-identification is validated by repeating the determination of R_X without modelling the mis-identification component in the fit. The particle identification criteria on the electrons are incrementally tightened, as illustrated in Fig. 3, where the default requirement is highlighted by the red square. The values obtained for R_K and R_{K^*} converge to a value compatible with the default when the mis-identification component is included, confirming the validity of the treatment of the residual mis-identified backgrounds and the stability of the obtained results.

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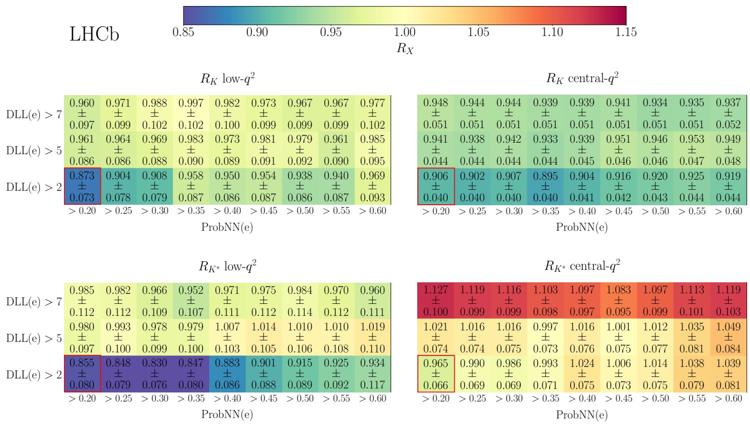

Figure 3: Results for R_K (top) and R_{K^*} (bottom) in the low- (left) and central-q^2 (right) regions when varying the particle identification requirements for the electrons and not including the residual mis-identification backgrounds in the determination of R_X. Extracted from Ref. [10].

2.4 Results

The ratios R_K and R_{K^*} are determined in a simultaneous extended maximum likelihood fit to the invariant mass distributions of the $K^+(\pi^-)\ell^+\ell^-$ system, as depicted in Figs. 1 and 2. This approach allows to constrain partially reconstructed $B^0 \to K^{*0}e^+e^-$ decays in the $K^+e^+e^-$ spectrum, as well as radiative tails from the $B \to K^{(*)}J/\psi\,(e^+e^-)$ decays. The measured values for R_K and R_{K^*} are found to be

$$\begin{aligned}
R_K \text{ low-}q^2 &= 0.994^{+0.090}_{-0.082}\,(\text{stat})^{+0.029}_{-0.027}\,(\text{syst}),\\
R_K \text{ central-}q^2 &= 0.949^{+0.042}_{-0.041}\,(\text{stat})^{+0.022}_{-0.022}\,(\text{syst}),\\
R_{K^*} \text{ low-}q^2 &= 0.927^{+0.093}_{-0.087}\,(\text{stat})^{+0.036}_{-0.035}\,(\text{syst}),\\
R_{K^*} \text{ central-}q^2 &= 1.027^{+0.072}_{-0.068}\,(\text{stat})^{+0.027}_{-0.026}\,(\text{syst}).
\end{aligned}$$

The measurement is statistically dominated, with the leading systematic uncertainty stemming from the modelling of the residual hadron-to-electron mis-identification in the fit. These measurements constitute the most precise test of LFU in $b \to s\ell\ell$ transitions to date and are consistent with the SM.

The difference with respect to the previously published result for R_K [13], is primarily attributed to systematic differences in the analysis procedures. This analysis employs stricter particle identification requirements, significantly reducing background contamination that account for a shift of +0.064. Additionally, the inclusion of the residual hadron-to-electron mis-identification component in the fit leads to a shift of +0.038, which combines linearly with the previous shift. Considering the overlap of the analysed samples, the allowed statistical variation is assessed to be ±0.033 and can therefore not account for the observed differences.

3. Lepton Flavour Violation Searches

Most New Physics scenarios that try to explain the flavour anomalies with lepton flavour non universal contributions imply the existence of decays that are of flavour violating structure. LHCb also searches for transitions of the form $b \to s\ell'\ell$, such as $B^0 \to K^{*0}e^{\pm}\mu^{\mp}$ and $B_s^0 \to \phi e^{\pm}\mu^{\mp}$. The existence of any of these forbidden decays in the SM would be a smoking gun for New Physics.

Recent results on these searches are published in Ref. [11], where no significant signal for any of the signatures is found and hence a limit of

$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 9.9 \times 10^{-9} (90\,\%\ \mathrm{CL}),$$
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp}) < 16 \times 10^{-9} (90\,\%\ \mathrm{CL})$$

is set at 90 % confidence level. These limits are the most stringent limits for these decays to date and place strong constraints on New Physics scenarios involving lepton flavour violation.

4. Conclusion

These proceedings provide a comprehensive summary of the latest tests of LFU using $b \to s\ell\ell$ transitions conducted by LHCb. The ratios R_K and R_{K^*} [9, 10], performed in two regions of q^2, are found to be in excellent agreement with the SM, surpassing the precision of previous measurements. In addition to testing LFU, LHCb also explores transitions of the form $b \to s\ell'\ell$, that would indicate lepton flavour violation. Thus far, no evidence for such decays has been observed, leading to stringent limits on their existence [11].

While tensions with the SM in the tests of LFU are not confirmed, tensions in the decay rates and angular distributions remain an intriguing topic of discussion. Further work from both theory and experiment are required to clarify the observed tensions.

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