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Lepton flavour universality tests in electroweak penguin decays at LHCb

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Rare b-hadron decays mediated by $b \to s\ell^+\ell^-$ transitions provide a sensitive test of lepton flavour universality, a property of the Standard Model of particle physics which states that the coupling of the electroweak gauge bosons to all lepton flavours is equal. Extensions of the Standard Model do not necessarily preserve this symmetry and may give sizeable contributions to these processes. Precise measurements of lepton flavour universality ratios are, therefore, an extremely sensitive probe for new physics beyond the Standard Model. Recent results from LHCb on lepton flavour universality tests in rare $b \to s\ell^+\ell^-$ decays are discussed.

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1. Introduction

In the Standard Model of particle physics (SM), the interactions of the three lepton flavours with the gauge bosons exhibit the same coupling strength. This symmetry is called lepton flavour universality (LFU) and is established in for example $Z^0 \to \ell^+\ell^-$ decays at the per mille level [1]. Potential physics beyond the SM (BSM) may violate this universality and tests of LFU can therefore act as a powerful null-test of the SM and a smoking gun for BSM physics.

The $b \to s\ell^+\ell^-$ transitions, where ℓ is either an electron or a muon[1], belong to the so-called flavour-changing neutral currents in the SM that occur via the weak interaction. These rare processes occur at lowest order at *one-loop-level* through *pengiun* and *box* diagrams. Potential new physics in which LFU is violated may contribute significantly to the SM amplitudes, and as a result, $b \to s\ell^+\ell^-$ transitions are considered an excellent laboratory for BSM searches.

Tests of LFU in $b \to s\ell^+\ell^-$ transitions have been performed by measuring ratios of branching fractions

$$R_X = \frac{\int\limits_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(H_b \to X_s \mu^+\mu^-)}{dq^2} dq^2}{\int\limits_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(H_b \to X_s e^+e^-)}{dq^2} dq^2},$$

where H_b represents a b-hadron and X_s indicates a hadronic system with at least one s-quark. The charge-conjugate modes are implied for all decays throughout these proceedings. These ratios are measured in regions of the squared invariant mass of the di-lepton system, q^2, where different BSM mechanisms may contribute. Due to LFU in the SM, these ratios are predicted to be unity, modulo small effects related to the different masses of the leptons. The uncertainties on the SM predictions of the R_X ratios are controlled at the percent level [2], thanks to the cancellation of the hadronic uncertainties.

These proceedings focus on LFU tests performed with data collected by the LHCb detector [3] in pp collisions provided by the Large Hadron Collider during 2011-2018. The data correspond to an integrated luminosity of about 9 fb^{-1} and are collected at centre-of-mass energies from 7 to 13 TeV, unless specified differently.

2. Analysis strategy

The signal candidate reconstruction at LHCb is different for the electronic and muonic final states. While the minimally ionising muons are comparably easy to trigger, reconstruct, and identify, thanks to their distinct signature with hits in the muon stations, electrons present more experimental challenges. As a result of the comparably high occupancy of the calorimeter, due to abundantly produced photons from π^0 decays, the trigger selection, which requires significant transverse energy deposits, is tighter than for the muons. To compensate for the lower trigger efficiencies, typically also events triggered by the hadronic decay products or the rest of the event are used. Additionally, due to their smaller mass, electrons frequently emit hard bremsstrahlung photons when interacting with the

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[1] The $b \to s\tau^+\tau^-$ transitions are experimentally challenging to reconstruct and have not been observed yet.

detector material. Even though a recovery algorithm for emitted bremsstrahlung is employed, the limitations of this algorithm, combined with the poorer calorimeter resolution when compared to that of the tracking systems, results in a reduced resolution of the reconstructed electron momentum. From this follows a reduced resolution on the reconstructed b-hadron mass and a lower signal to background ratio, which makes modelling background contributions more challenging. The corresponding reconstruction and selection efficiencies are evaluated on simulated signal samples that are calibrated using abundant background subtracted control modes from data.

In order to reduce experimental systematic uncertainties connected to the different final states, the R_X ratios are measured using *double ratios* of branching fractions, where the rare $b \to s\ell^+\ell^-$ branching fraction is measured relative to a normalisation mode. At LHCb, resonant $H_b \to X_s J/\psi(\to \ell^+\ell^-)$ decays are used as normalisation channels, as they share the same final state as the rare $b \to s\ell^+\ell^-$ decays. Since common factors such as integrated luminosities and production cross-sections cancel, R_X is given by

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

with the yield $\mathcal{N}$ and corresponding selection and reconstruction efficiency ϵ, where the superscript $\ell^+\ell^-$ and the index J/ψ indicate the lepton flavour and the q^2 region, respectively. This method relies on the LFU in the tree-level $J/\psi \to \ell^+\ell^-$ decays which is well tested and established at per mille level [1].

The yields for the normalisation modes are extracted from unbinned extended maximum likelihood fits to the invariant mass distribution of the final state particles. The ratio R_X is determined similarly using simultaneous fits expressing the yields for the rare processes through R_X and the corresponding efficiencies and normalisation yields. Systematic uncertainties are in most analyses included via multivariate normal constraints to the parameters of interest.

The analysis is validated using the normalisation modes with the most stringent validation being the measurement of the *single ratio* of branching fractions

$$r_{J/\psi} = \frac{\mathcal{B}\left(H_b \to X_s J/\psi(\to \mu^+\mu^-)\right)}{\mathcal{B}\left(H_b \to X_s J/\psi(\to e^+e^-)\right)} = \frac{\mathcal{N}_{J/\psi}^{\mu^+\mu^-}\,\epsilon_{J/\psi}^{e^+e^-}}{\mathcal{N}_{J/\psi}^{e^+e^-}\,\epsilon_{J/\psi}^{\mu^+\mu^-}}.$$

It is validated that $r_{J/\psi}$ is consistent with unity and independent of any relevant variables, as expected given that LFU holds in the J/ψ decays [1]. Since $r_{J/\psi}$ is measured as a single ratio of branching fractions, systematic uncertainties related to electron and muon reconstruction at LHCb do not cancel in the ratio. Another validation method is the measurement of the ratio of branching fractions for $H_b \to X_s\psi(2S)(\to \ell^+\ell^-)$ decays,

$$R_{\psi(2S)} = \frac{\mathcal{B}\left(H_b \to X_s\psi(2S)(\to \mu^+\mu^-)\right)}{\mathcal{B}\left(H_b \to X_s J/\psi(\to \mu^+\mu^-)\right)} \times \frac{\mathcal{B}\left(H_b \to X_s J/\psi(\to e^+e^-)\right)}{\mathcal{B}\left(H_b \to X_s\psi(2S)(\to e^+e^-)\right)}.$$

This ratio is also expected to be unity and serves as a validation in a different kinematic region of the phase-space. The optimisation of the selection, determination of the reconstruction and selection efficiencies, as well as the validation are performed while keeping R_X *blind* in order to avoid experimenter's bias.

3. Measurements

The LHCb collaboration has measured five LFU ratios in different q^2 regions to date which are summarised in Tab. 1. The most precise LFU test, R_K [4], is performed using $B^+ \to K^+\ell^+\ell^-$ decays in a q^2 region from 1.1 to 6.0 GeV$/c^2$ and exhibits the largest tension with the SM prediction. The $R_{K^{*0}}$ measurement [5] is performed in two adjacent q^2 regions and obtains a precision of 17 % albeit using only a subset of the currently available data. The capability of LHCb to precisely test LFU in b-baryons is demonstrated by the R_{pK} measurement [6].

Table 1: Measurements LFU tests in $b \to s\ell^+\ell^-$ transitions performed by the LHCb collaboration. The probed decays, corresponding q^2 regions, results, compatibility with SM predictions, and integrated luminosity equivalent of the datasets are given.

R_X	Decay	q^2 region $[\,\mathrm{GeV}^2/c^4]$	Result ($\pm$ stat. $\pm$ syst.)	Agreement with SM	Dataset $\int\mathcal{L}$
R_K [4]	$B^+ \to K^+\ell^+\ell^-$	$[1.1, 6.0]$	$0.846^{+0.042\,+0.013}_{-0.039\,-0.012}$	$3.1\,\sigma$	$9\,\mathrm{fb}^{-1}$
$R_{K^{*0}}$ [5]	$B^0 \to K^{*0}\ell^+\ell^-$	$[0.045, 1.1]$	$0.66^{+0.11}_{-0.07} \pm 0.03$	2.1-2.3 σ	$3\,\mathrm{fb}^{-1}$
$R_{K^{*0}}$ [5]	$B^0 \to K^{*0}\ell^+\ell^-$	$[1.1, 6.0]$	$0.69^{+0.11}_{-0.07} \pm 0.05$	2.4-2.5 σ	$3\,\mathrm{fb}^{-1}$
R_{pK} [6]	$\Lambda_b \to pK^-\ell^+\ell^-$	$[0.1, 6.0]$	$0.86^{+0.14}_{-0.11} \pm 0.05$	$< 1\,\sigma$	$4.7\,\mathrm{fb}^{-1}$
$R_{K^{*+}}$ [7]	$B^+ \to K^{*+}\ell^+\ell^-$	$[0.045, 6.0]$	$0.70^{+0.18\,+0.03}_{-0.13\,-0.04}$	$1.6\,\sigma$	$9\,\mathrm{fb}^{-1}$
$R_{K^0_S}$ [7]	$B^0 \to K^0_S\ell^+\ell^-$	$[1.1, 6.0]$	$0.66^{+0.20\,+0.02}_{-0.14\,-0.04}$	$1.5\,\sigma$	$9\,\mathrm{fb}^{-1}$

Recently, LHCb has published the measurement of $R_{K^0_S}$ and $R_{K^{*+}}$ [7]. The tests are performed in $B^0 \to K^0_S\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays, the isospin partners of $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays, respectively. Since the K^{*+} is reconstructed using $K^{*+} \to K^0_S\pi^+$ decays, in both cases neutral Kaons are present. The reconstruction of the K^0_S final states involves $K^0_S \to \pi^+\pi^-$ decays, which results in a smaller reconstruction efficiency compared to their isospin partners, due to the long lifetime of the K^0_S. As a consequence of the long lifetime, the K^0_S candidates are reconstructed in one of two possible ways. If the K^0_S mesons decay inside the acceptance of the Vertex Locator (VELO) they form so-called *long tracks*, whereas in the case of a decay outside of the VELO they form *downstream tracks*. For the *downstream tracks*, only the tracking stations downstream of the VELO, the Tracker Turicensis and the tracking stations, can be used for track reconstruction. The resolution of key variables of the K^0_S, such as the impact parameter or invariant mass, varies depending on the track type. However, it is found that the resolution of the reconstructed B-meson mass is mainly driven by the lepton momentum and is, therefore, similar between the two track categories. Consequently, the two track categories are combined for the extraction of the R_X ratio and the resulting reconstructed B-meson mass spectrum is illustrated in Fig. 1.

Whereas in the di-muon final states the only background contribution in the fit range is formed by random combinations of tracks, the di-electron spectra present more challenges in the modelling due to reduced mass resolution and consequently larger fit range. Resonant $H_b \to X_s J/\psi(\to e^+e^-)$ decays *leak* into the fit region due to radiative tails of the q^2 distribution. Furthermore, partially reconstructed B decays involving excited kaon states and an electron pair result in prominent

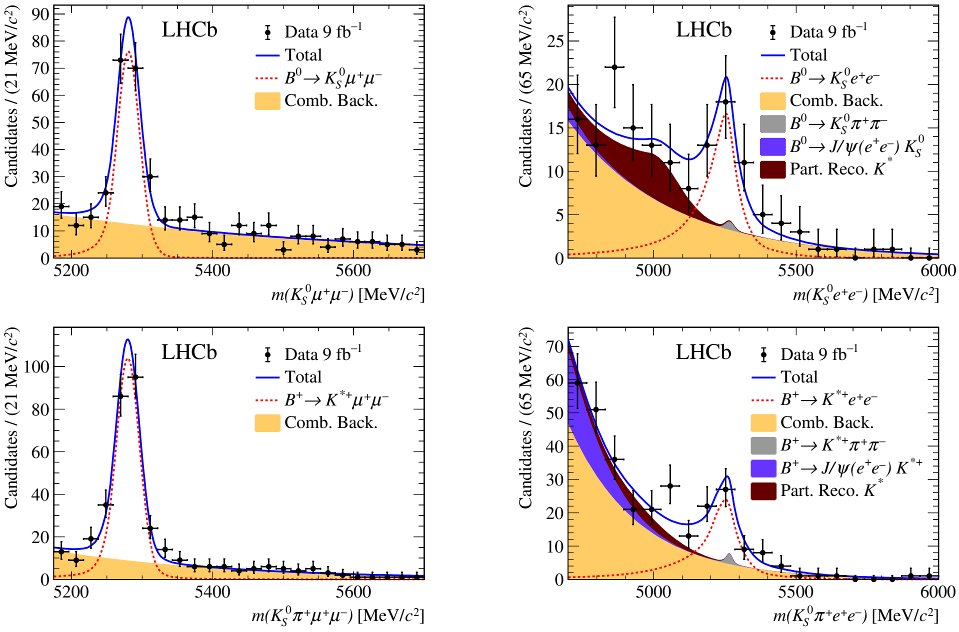

Figure 1: Invariant mass of the $K_S^0\ell^+\ell^-$ (top) and $K^{*+}\ell^+\ell^-$ (bottom) candidates, with muons on the left and electrons on the right. The mass fit is indicated in blue. The figures are extracted from Ref. [7].

structures in the lower mass side-band. Lastly, mis-identified $H_b \to X_s\pi^+\pi^-$ decays, whose levels of pollution are estimated using data driven methods, contribute to the spectrum, as shown in Fig. 1.

Besides testing LFU, LHCb is able to report the *first observation* of $B^0 \to K_S^0 e^+e^-$ and $B^+ \to K^{*+}e^+e^-$ decays with a significance of 5.3 and 6.0 σ, respectively.

4. Conclusion

While in general the LFU tests are found to be compatible with the SM, tensions that need to be clarified are observed in for example the R_K measurement [4]. Since the LFU tests are dominated by statistical uncertainties, additional data from Run 3 of the Large Hadron Collider is expected to help to clear up the experimental situation. In addition, other q^2 regions and decay modes, such as a *high* q^2 region with $q^2 > 15\,\text{GeV}^2/c^4$, will help to resolve the observed tensions as they provide complementary experimental information. LHCb has the unique opportunity to precisely test LFU not only in B^+ and B^0 decays but also in b-baryons, as demonstrated by R_{pK} [6], and B_s^0 mesons that are otherwise inaccessible by B-factories such as Belle II.

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