Tests of Lepton Flavour Universality at LHCb

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Abstract. In the Standard Model of particle physics the three charged leptons are identical copies of each other, apart from mass differences, and the electroweak coupling of the gauge bosons to leptons is independent of the lepton flavour. This prediction is called lepton flavour universality (LFU) and is well tested. In tree level decays, any violation of LFU would be a clear sign of physics beyond the Standard Model. Experimental tests of LFU in semileptonic decays of b-hadrons or rare b decays are highly sensitive to New Physics particles which preferentially couple to the 2nd and 3rd generations of leptons. Recent results from LHCb on lepton flavour universality in $b \to c\ell\nu$ transitions and rare $b \to s\ell\ell$ decays are discussed. The results are based on $3\,\text{fb}^{-1}$ of proton-proton collisions collected at centre of mass energies $\sqrt{s} = 7\,\text{TeV}$ and $8\,\text{TeV}$.

1. Introduction

In the Standard Model of particle physics (SM), the electroweak gauge bosons Z and $W^{\pm}$ have identical couplings to all three lepton flavours. This means that branching fractions of decays involving different lepton families do not depend on lepton flavour but differ only by phase space and helicity-suppressed contributions. The prediction is called lepton flavour universality (LFU) and is well tested in e.g. decays of tau leptons, light mesons, as well as the gauge bosons. Any experimental evidence of Lepton Flavour Non-Universality would be a clear sign of physics beyond the SM (BSM).

Semileptonic decays of heavy hadrons are an excellent laboratory to test LFU as all three generations can be accessed. Many models extending the SM contain additional interactions that could violate LFU. These are for example BSM theories involving leptoquarks [1, 2] or Z' [3, 4] particles. Processes with third generation of quarks and leptons (B and tau) are well suited to search for LFU violation since many BSM theories with LFU violation predict stronger couplings to the third generation and experimental results have lower precision. One such example is an extended Higgs Sector, which could have a large effect on semitauonic decay rates through the coupling to new charged Higgs scalars [5].

These proceedings summarise recent measurements of these decays by the LHCb collaboration. Feynman diagrams for the SM processes are shown in figure 1. All measurements are based on $3\,\text{fb}^{-1}$ of proton-proton (pp) collisions collected at the LHC collider at centre of mass energies $\sqrt{s} = 7$ TeV and 8 TeV.

The remainder of this paper is organised as follows: section 2 discusses results from $b \to c\ell\nu$ decays with emphasis on the measurements of decays with a D or J/ψ meson in the final state, while section 3 presents results from $b \to s\ell^+\ell^-$ decays and section 4 concludes the paper.

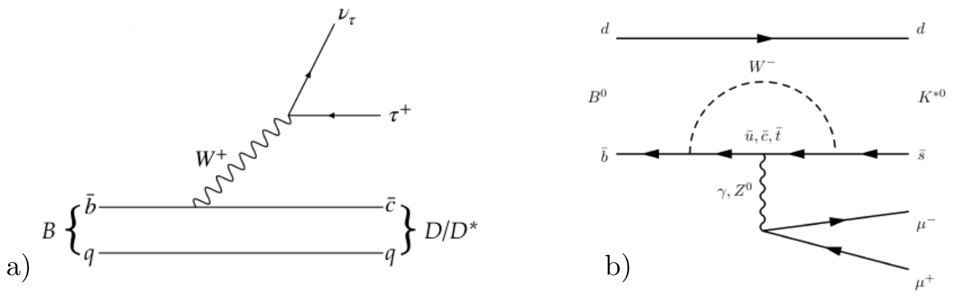

Figure 1. Feynman diagrams in the SM for a semileptonic $b \to c\ell\nu$ (a) and the rare electroweak penguin $b \to s\ell\ell$ (b) decays.

2. Lepton Flavour Universality in $b \to c\ell\nu$ decays

Charged current (semileptonic decays) tree-level $b \to c\ell\nu$ decays have a branching fraction of a few percent and are precisely predicted in the SM. The strongest evidence for a possible violation of LFU is currently seen in measurements of the branching fractions of semileptonic decays involving a tau lepton, in particular the measurement of the observables

$$R(D) = \frac{\mathcal{B}(B^0 \to D^+\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B^0 \to D^+\mu^-\overline{\nu}_\mu)} \text{ [6, 7]} \quad \text{and} \quad R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B^0 \to D^{*+}\mu^-\overline{\nu}_\mu)} \text{ [6, 7, 8]}. \qquad (1)$$

The observed enhancement can be explained in many extensions to the SM, which preferentially couple to third generation leptons.

2.1. Measurements of $R(D^*)$

A precise measurement of a B decay to tau leptons is experimentally challenging at a hadron collider due to the large background from partially reconstructed B-decays with similar topologies. Moreover, the signal decay kinematics can not be fully constrained because of the presence of neutrinos in the final state. Therefore the ratio of $R(D^*)$ is measured using different tau lepton decays to provide independent measurements. LHCb used the muonic $\tau \to \mu\nu_\tau\overline{\nu}_\mu$ as well as the hadronic $\tau \to \pi\pi\pi\nu_\tau$ decay channels.

The muonic decay of the tau has the advantage that both the signal and normalisation channel in $R(D^*)$ contain the same visible final state, with the difference of having one and three neutrinos in the final states, respectively.

The signal and normalisation channels are separated using a fit to three kinematic variables sensitive to the mass difference between the muon and the tau and the presence of additional neutrinos: E^*_μ the energy of the muon in the B^0 rest frame, $m^2_{miss} = (p(B^0) - p(D^*) - p(\mu))^2$, the squared missing mass, and $q^2 = (p(B^0) - p(D^*))^2$ the squared four-momentum transfer to the lepton system. The results of the fit are shown in figure 2. The yields extracted by the fit are used to make a measurement of

$$R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst}) \text{ [8]}.$$

The result was the first measurement of b-hadron decays to tau leptons at a hadron collider and deviates by $2.1\,\sigma$ from the SM (0.252 ± 0.003) prediction [9]. Systematic uncertainties are dominated by the size of the simulated and control samples.

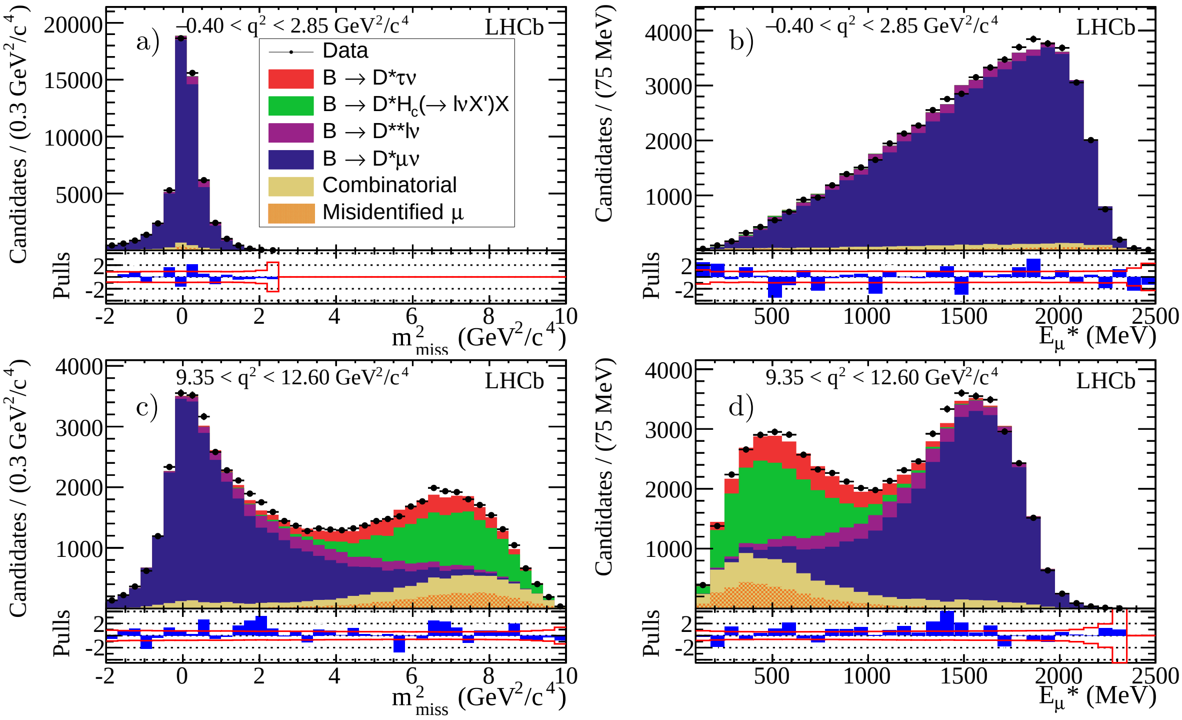

Figure 2. Distributions of m^2_{miss} (a and c) and E^*_μ (b and d) with the fit projections overlaid for the lowest (a and b) and the highest (c and d) q^2 bin (from [8]). The result is based on $3\,\text{fb}^{-1}$ of pp collisions at $\sqrt{s}$ = 7 TeV and 8 TeV.

A more recent measurement of $R(D^*)$ was performed using the hadronic decay of the $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ with the D^* meson reconstructed through the decay $D^* \to D^-(\to K^+\pi^-)\pi^-$.

In this analysis the ratio

$$K(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*3\pi)} \tag{2}$$

is measured. Both decays have the same visible final state which leads to a large cancellation of various experimental uncertainties. Subsequently, $R(D^*)$ is determined as

$$R(D^*) = K(D^*) \times \frac{\mathcal{B}(B \to D^*3\pi)}{\mathcal{B}(B \to D^*\mu\overline{\nu}_\mu)}, \tag{3}$$

with the branching ratios from external inputs [10]. The main background contribution is due to decays of B-hadrons to $D^*3\pi X$, where X represents unreconstructed particles. This decay is about 100 times more abundant. A good suppression is obtained by requiring the tau decay vertex being downstream of the B decay vertex with a $4\,\sigma$ significance as shown in figure 3. The remaining background comes mainly from double-charmed B decays (eg $B \to D^{*+}D^{*-}X$). A Boosted Decision Tree is used to discriminate the signal from doubly-charmed background. The signal yield is obtained from a three-dimensional extended maximum likelihood fit to the BDT output, the tau decay time, and q^2. The results of the fit are shown in figure 4. The yield of the normalisation mode is determined by fitting the invariant mass of the $D3\pi$ system.

The measured value of $K(D^*)$ is found to be

$$K(D^*) = 1.97 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})\ [11]$$

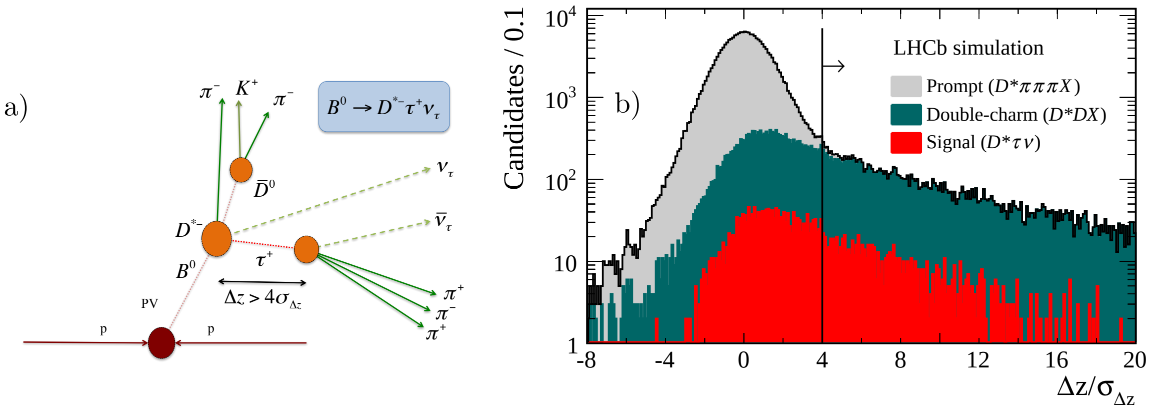

Figure 3. a) Topology of the signal decay. A requirement on the distance between the three-pion and the B^0 vertices along the beam direction to be greater than four times its uncertainty is applied. b) Distribution of the distance between the B^0 vertex and the three-pion vertex along the beam direction, divided by its uncertainty, obtained using simulation. The vertical line shows the $4\,\sigma$ requirement used in the analysis to reject the prompt background component (from [11]).

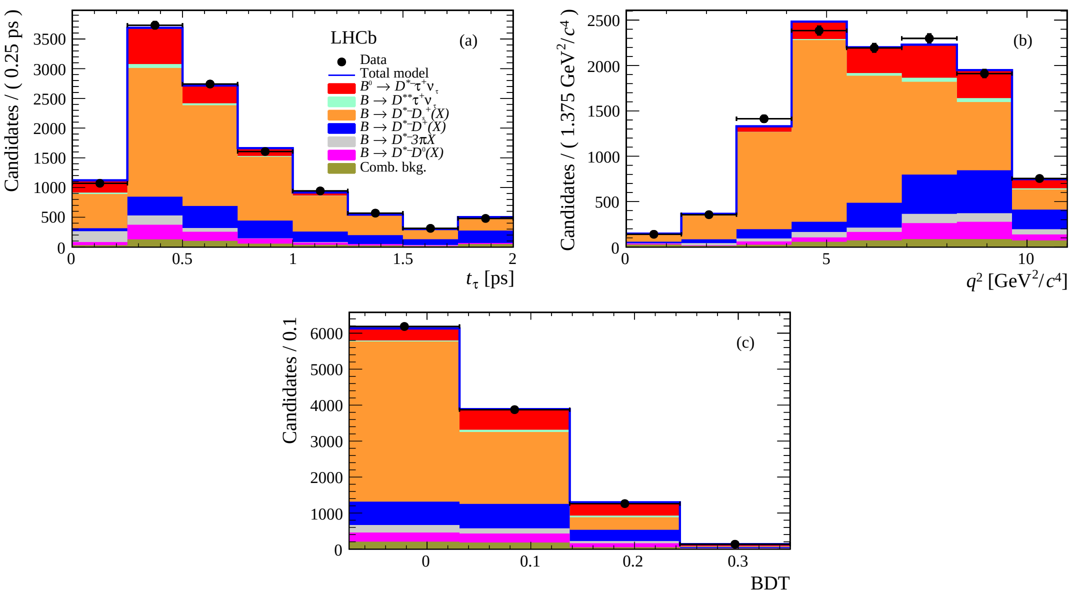

Figure 4. Projections of the three-dimensional fit on the three-pion decay time (a), q^2 (b) and BDT output (c) distributions. The fit components are described in the legend (from [11]).

and $R(D^*)$ is calculated to be

$$R(D^*) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})\ [11],$$

where the third uncertainty comes from uncertainties on the external input. This measurement is one of the most precise and compatible with the SM within $1\,\sigma$ [9].

Figure 5 shows the combination from the Heavy Flavour Averaging Group (HFLAV)

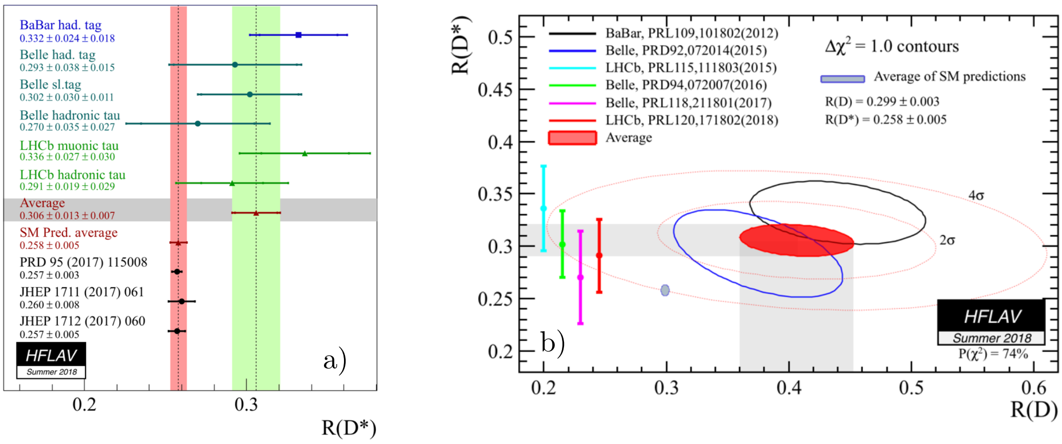

Figure 5. a) Comparison of $R(D^*)$ with the previous results from the B-factories and with SM expectations. b) Summary of the measurements of $R(D)$ and $R(D^*)$ (from [12]).

for $R(D^*)$ versus $R(D)$ along with the SM prediction and individual measurements by the experiments BaBar, Belle and LHCb [12]. All six $R(D^*)$ measurements lie above the SM predictions, the overall combination of the $R(D^*)$ and $R(D)$ measurements yield a $3.8\,\sigma$ tension with the SM.

2.2. Measurement of $R(J/\psi)$

The measurement of $R(J/\psi) = \mathcal{B}(B_c \to J/\psi\tau\overline{\nu}_\tau)/\mathcal{B}(B_c \to J/\psi\mu\overline{\nu}_\mu)$ probes similar physics as $R(D^*)$ but with a different spectator quark. The tau is reconstructed in the muonic and the J/ψ in the di-muon decay channel. The analysis strategy is very similar to the $R(D^*)$ analysis in the muonic channel with the B_c decay time as an additional discriminating variable. A binned maximum likelihood fit to m^2_{miss}, the B_c decay time and the quantity Z, where Z represents eight bins in (E^*_μ, q^2)[1], is performed to determine the signal and normalisation yield. The fit result to the three quantities is shown in figure6. The measured value of

$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst}) \ [13]$$

is compatible with the SM prediction (0.25-0.28) [14, 15, 16, 17] at the level of $2\,\sigma$. The unknown form factors used in the generation of the simulated samples gives rise to the largest systematic uncertainty.

3. Lepton Flavour Universality in $b \to s\ell^+\ell^-$ decays

A very clean test for New Physics (NP) can be performed by taking ratios of $b \to s\ell^+\ell^-$ decays to different lepton species. Since these decays are not allowed at tree level the branching fractions are highly sensitive to NP effects. Comparisons of decays with different leptons in the final state allow to probe NP models that involve LFU violation among different generations. Currently, $b \to s\ell^+\ell^-$ decays with electrons and muons in the final state are accessible to LHCb. If the momentum transfer of the dilepton system is sufficiently above the dilepton mass, uncertainties

[1] The values 0-3 of Z correspond to $q^2 < 7.15\,\text{GeV}^2/c^4$ and E^*_μ divided in bins with thresholds at [0.68, 1.15, 1.64] GeV. The values 4-7 correspond to bins with the same E^*_μ ranges, and $q^2 \geq 7.15\,\text{GeV}^2/c^4$.

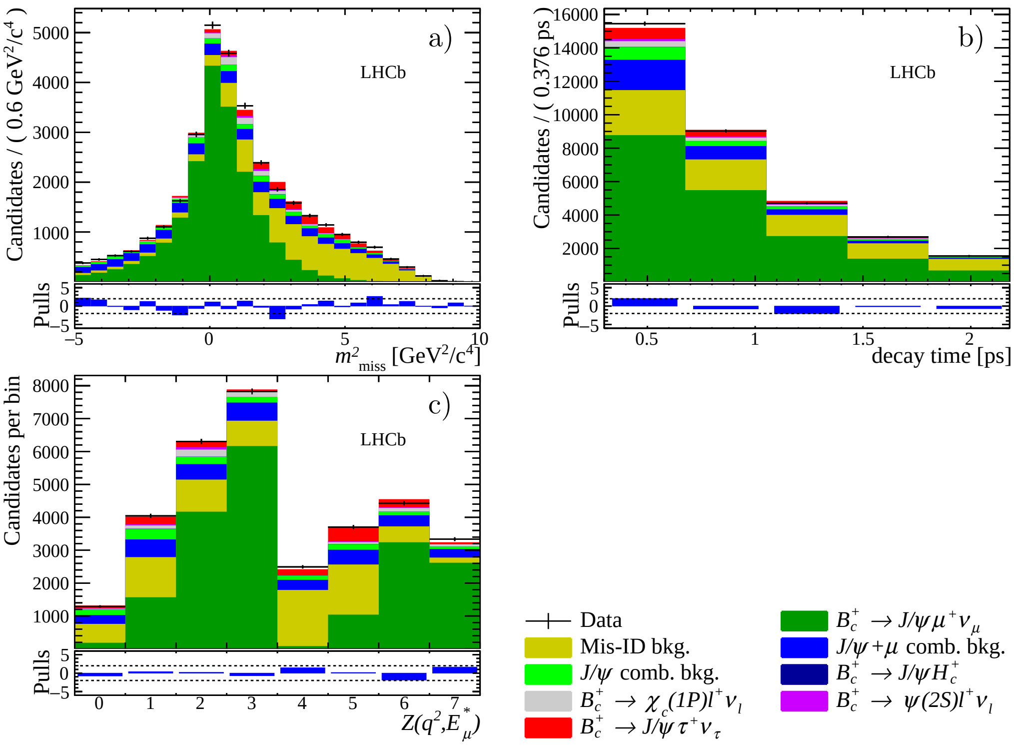

Figure 6. Measurement of $R(J/\psi)$: a) distributions of $m^2_{\rm miss}$, b) decay time, and c) Z of the signal data, overlaid with projections of the fit model with all normalisation and shape parameters at their best-fit values. Below each panel differences between the data and fit are shown, normalised by the Poisson uncertainty in the data; the dashed lines are at the values ± 2 (from [13]). The result is based on $3\,\text{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV.

in the hadronic form factors cancel to a very good approximation, leading to very precise SM predictions

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)} = 1 \pm \mathcal{O}(10^{-3}) \pm \mathcal{O}(10^{-2})\ [18], \tag{4}$$

where the first correction accounts for the difference of the lepton masses and the second for QED corrections. In recent years, the interest in LFU tests in $b \to s\ell^+\ell^-$ has increased, mainly driven by two measurements from the LHCb: the ratio $B^+ \to K^+\mu^+\mu^-$ to $B^+ \to K^+e^+e^-$[19] and more recently the ratio $B^0 \to K^*\mu^+\mu^-$ to $B^0 \to K^*e^+e^-$[20], presented below. The LFU testing ratio $R(K^{(*0)})$ is defined as

$$R(K^{(*)}) = \frac{\int \frac{d\Gamma(B\to K^{(*)}\mu^+\mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B\to K^{(*)}e^+e^-)}{dq^2} dq^2}. \tag{5}$$

Here, the differential decay rate is measured in a certain q^2 range, where q^2 corresponds to the invariant mass squared of the di-lepton pair. The q^2 ranges corresponding to the J/ψ and $\psi(2S)$ are excluded from the analysis. To cancel experimental uncertainties in the absolute efficiencies of the measurements, the ratio $R(K^{(*)})$ is measured as double ratio, normalising the non-resonant signal mode to the resonant J/ψ mode:

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{*}\mu^{+}\mu^{-})}{\mathcal{B}(B \to K^{*}J/\psi(\to \mu^{+}\mu^{-}))} \times \frac{\mathcal{B}(B \to K^{*}J/\psi(\to e^{+}e^{-}))}{\mathcal{B}(B \to K^{*}e^{+}e^{-})}. \tag{6}$$

The candidates for the normalisation channel $B \to K^{*}J/\psi(\to \ell^{+}\ell^{-})$ are selected using similar criteria to that of the non-resonant channel.

The main challenge of the measurement is the reconstruction of the electrons in the LHCb detector. While muons can be reconstructed with high efficiency and low misidentification probability, electrons are highly affected by bremsstrahlung. This results in a degraded B momentum and mass resolution. A bremsstrahlung recovery algorithm is used to improve the electron momentum reconstruction: clusters not associated with charged tracks are searched in the electromagnetic calorimeter in a region defined by the extrapolation of the electron track upstream of the magnet and added to the measured electron momentum. Moreover, the trigger thresholds on electrons are higher than those on muons due to the higher occupancy of the calorimeters which results in a lower efficiency. The distribution of q^2 as a function of the four-body invariant mass for the B^0 candidates is shown in figure 7 (a and b) for both muon and electron final states. In each plot, the contributions due to the charmonium resonances are visible as bands at the J/ψ and $\psi(2S)$ masses. In case of electrons the worse mass resolution due to bremsstrahlung is prominently visible: the reconstructed mass is smeared and generally shifted to lower values.

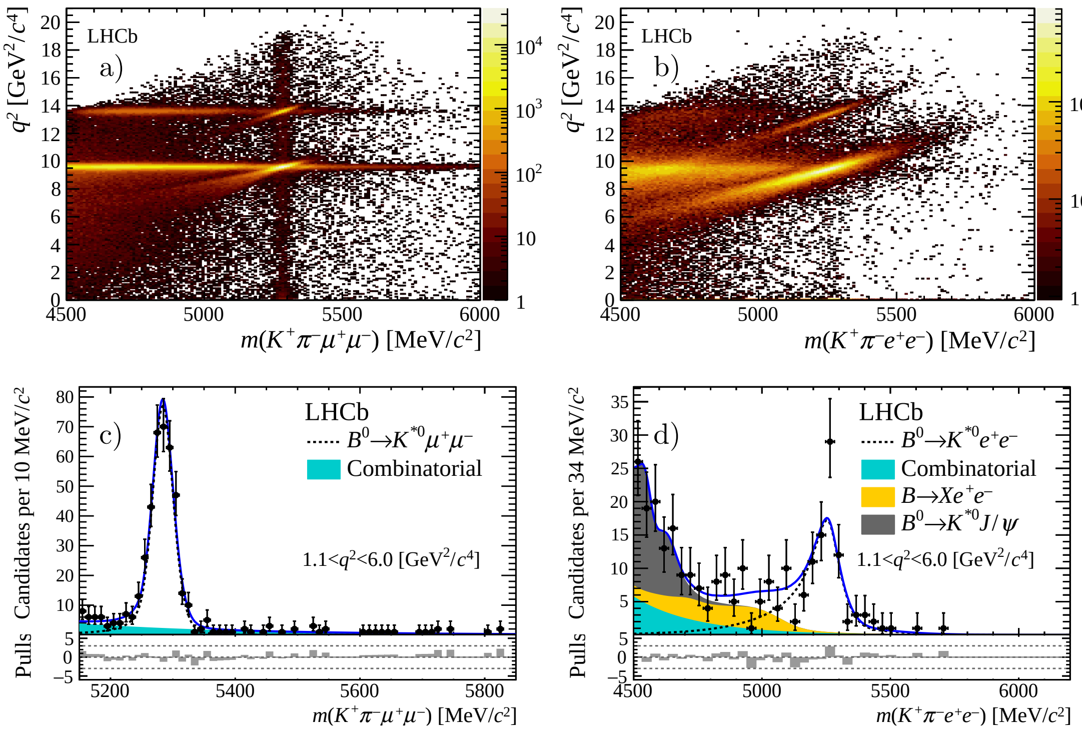

Figure 7. Number of candidates for $B^0 \to K^0\ell^+\ell^-$ final states with (a) muons and (b) electrons as a function of the dilepton invariant mass squared, q^2, and the four-body invariant mass of the B^0. Fit to the $m(K^+\pi - \mu^+\pi)$ invariant mass of $B^0 \to K^{*0}\mu^+\mu^-$ (c) and $B^0 \to K^{*0}\mathrm{e}^+\mathrm{e}^-$ (d) in the central-q^2 region. The dashed line is the signal PDF, the shaded shapes are the background PDFs and the solid line is the total PDF. The fit residuals normalised to the data uncertainty are shown at the bottom of each distribution (from [20]).

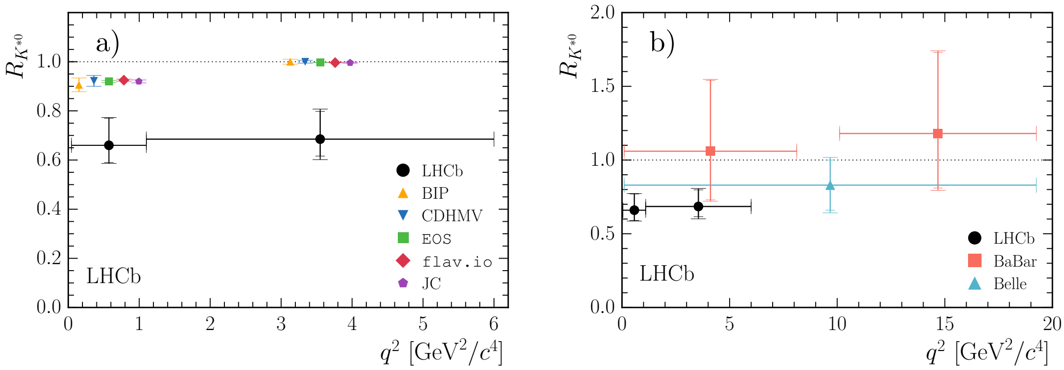

Figure 8. a) Comparison of the LHCb $R(K^*)$ measurements with the SM theoretical predictions. The predictions are displaced horizontally for presentation. b) Comparison of the LHCb $R(K^*)$ measurements with previous experimental results from the B factories [21, 22]. In the case of the B factories the specific vetoes for charmonium resonances are not represented. (from [20]). The result is based on $3\,\text{fb}^{-1}$ of pp collisions at $\sqrt{s}$ = 7 TeV and 8 TeV.

The measurement of $R(K^{*0})$ is performed in two q^2 bins that are sensitive to different physics contributions: the first one, $0.045 < q^2 < 1.1\,\text{GeV}^2/c^4$, is dominated by the photon pole while for the central bin, $1.1 < q^2 < 6\,\text{GeV}^2/c^4$, the contribution from the C_9 Wilson coefficient becomes more important.

Signal yields are extracted using an extended maximum likelihood fit to the reconstructed B mass, to the J/ψ and the non-resonant channel in the two q^2 regions; the fits in the central q^2 region are shown in figure 7 (c and d). While the muon sample has only a small background contribution from combinatorial background, several background contributions need to be considered for the electron channel. The ratio $R(K^*)$ is measured to be

$$0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) \quad \text{for} \;\; 0.045 < q^2 < 1.1\,\text{GeV}^2/c^4,$$

$$0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) \quad \text{for} \;\; 1.1 < q^2 < 6.0\,\text{GeV}^2/c^4,$$

where the precision of the measurements are limited by the size of the electron sample. The results are compatible with the SM expectations at the level of 2.1-2.3 σ (low bin) and 2.4-2.5 σ (central bin) [20]. Figure 8 shows the comparison with previous $R(K^*)$ measurements from the B-factories and with theoretical expectations.

The results show the same trend as a previous measurement on $R(K)$ as shown in figure 9 where the LHCb result is displayed together with results from Belle and Babar. In this analysis $R(K)$ as measured by LHCb is about 2.6 σ below the SM [19].

4. Summary and prospects

Three measurements that test LFU using semi-leptonic decays to tau leptons have been presented. They consist of the first measurement of $R(D^*)$ at a hadron collider in the leptonic decay channel of the tau, the most accurate single measurement of $R(D^*)$ using the hadronic decay channel of the tau and the first measurement of $R(J/\psi)$. The tension with the precise SM prediction is about 3.8 σ.

LFU was also tested in rare $b \to s\ell^+\ell^-$ decays by measuring the ratio $R(h)$ of branching fractions of $B \to h\mu^+\mu^-$ and $B \to he^+e^-$ with h either a K^+ or K^*. In both channels the data

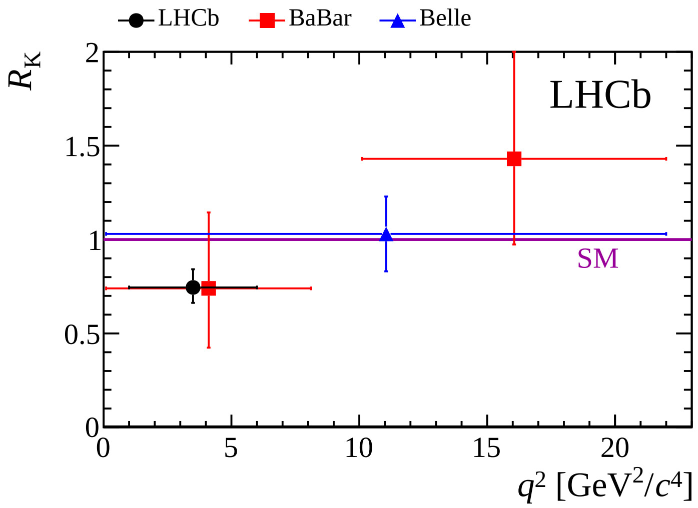

Figure 9. Summary of results on $R(K)$ determined by LHCb experiment together with the results from the BaBar[21] and Belle[22] experiments. The SM prediction is also shown as a continuous function of q^2. The theoretical uncertainty on $R(K)$ is expected to be $\mathcal{O}(10^3)$ (from [19]).

are below the SM prediction; $R(K^*)$ deviates from the SM by 2.1-2.3 σ (low bin) and 2.4-2.5 σ (central bin), while $R(K)$ is about 2.6 σ below the SM.

Many more additional channels are presently analysed, such as the $b \to c\ell\nu$ transitions $R(\Lambda^*)$, $R(D_s)$ or $R(D_s^*)$ or the $b \to s\ell^+\ell^-$ transitions $R(K\pi\pi)$, $R(pK)$, $R(\Phi)$, $R(\Lambda)$ and many more.

All these measurements are based on the Run 1 data collected in 2011 and 2012 with an integrated luminosity of 3 fb^{-1}. The LHCb experiment has collected about 9 fb^{-1} of data that is currently being analyzed. Updates to the analyses presented here are currently ongoing and will provide more accurate measurements. All the systematic uncertainties will decrease with larger simulation and control data samples. Also, the Belle 2 experiment has started to take data and will be able to provide an important cross check of the measurements from the LHCb collaboration.

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