Lepton Flavour Universality tests with B decays at LHCb

Johannes Albrecht
Fakultät Physik, TU Dortmund, Germany

This article discusses tests of lepton flavour universality that are carried out with the LHCb experiment. The experimental situation of $b \to s \ell^+ \ell^-$ and $b \to c \ell \nu$ decays is summarised.

1 Introduction

In the Standard Model of particle physics (SM), the electroweak gauge bosons $Z^0$ and $W^\pm$ have identical couplings to all three lepton flavours. This prediction is called lepton flavour universality (LFU) and is well tested in tree level decays, e.g. of tau leptons, light mesons or the gauge bosons themselves.\(^1\)

Recent measurements of loop level beauty decays of the type $b \to s \ell^+ \ell^-$ and semileptonic beauty decays of the type $b \to c \ell \nu$ have shown tensions with the SM prediction of LFU. The most precise measurements of these quantities, performed by the LHCb collaboration, are summarised in these proceedings. All measurements are based on 3 fb\(^{-1}\) of data collected at $\sqrt{s} = 7$ TeV and 8 TeV.

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

A very clean test for new physics can be performed by taking ratios of $b \to s \ell^+ \ell^-$ decays to different lepton species. At the current experiments, $b \to s \ell^+ \ell^-$ decays with electrons and muons in the final state are accessible. If the momentum transfer of the dilepton system is sufficiently above the dilepton mass, uncertainties in the hadronic form factors cancel to a very good approximation, leaving a SM prediction with uncertainties below 1%.\(^2\)

In the recent years, the interest in lepton flavour universality tests has increased, mainly driven by two measurements from the LHCb collaboration: the ratio of $B^+ \to K^+ \mu^+ \mu^-$ to $B^+ \to K^+ e^+ e^-$, called $R_{K^+}$,\(^3\) and the ratio of $B^0 \to K^{*0} \mu^+ \mu^-$ to $B^0 \to K^{*0} e^+ e^-$, called $R_{K^{*+}}$.\(^4\) The LHCb collaboration uses basically the same strategy for both analyses, that is discussed here for general $b \to s \ell^+ \ell^-$ decays with the corresponding hadron named $H$. The LFU testing ratio $R_H$ is then defined as

$$R_H = \frac{\int dq^2 \frac{d\Gamma(B \to H \mu^+ \mu^-)}{dq^2}}{\int dq^2 \frac{d\Gamma(B \to H e^+ e^-)}{dq^2}},$$

where the differential decay rate is measured in certain $q^2$ ranges. The $q^2$ ranges corresponding to the $J/\psi$ and $\psi(2S)$ is always excluded from the LFU analysis and is used as control channel. To cancel experimental uncertainties in the absolute efficiencies of the measurements, the ratio $R_H$ is not measured directly, but as double ratio, normalising the non-resonant signal mode to...
the corresponding high-statistics $J/\psi$ mode. The ratio $R_H$ is then measured as

$$R_H = \frac{\mathcal{B}(B \to H \mu^+ \mu^-)}{\mathcal{B}(B \to H J/\psi(\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B \to H e^+ e^-)}{\mathcal{B}(B \to H J/\psi(\rightarrow e^+ e^-))}.$$ 

A few comments are in order to explain this experimental strategy: firstly, this method tests for LFU violations in the FCNC decays, it relies on the conservation of LFU in the corresponding resonant decay modes. To test this assumption, the ratio of the resonant channels

$$r(J/\psi) = \frac{B \to K^{(*)} J/\psi(\rightarrow \mu^+ \mu^-)}{B \to K^{(*)} J/\psi(\rightarrow e^+ e^-)},$$

is confirmed to agree with LFU conservation. It has to be stressed that this test is a more stringent test than necessary, because it tests the absolute ratio of muon to electron reconstruction, identification and selection efficiencies while in the analyses of $R_H$, only relative efficiencies between non-resonant and resonant channels are required. If the ratio $r(J/\psi)$ is tested in bins of the daughter particle momenta, it can directly test the range of $q^2$ covered in the analysis.

The most precise test of $r(J/\psi)$ has been performed in LHCb’s analysis of $R_{K^*}$, it was found to be in agreement with unity with a precision of 4.5%. Compared to the statistical uncertainties of the LFU tests of the order of 10%, this uncertainty is subdominant. For further tests with enlarged datasets, the precision in the determination of efficiencies as cross-checked in $r(J/\psi)$ needs to be studied in more detail.

The experimentally best accessible mode of all $b \to s \ell^+ \ell^-$ decays is $B^+ \to K^+ \ell^+ \ell^-$. The LHCb collaboration published a measurement using 3 fb$^{-1}$ of data. The uncertainty of the measurement is dominated by the statistical uncertainty of the electron channel, with a signal yield of 172$^{+20}_{-19}$ events, i.e. the statistical uncertainty is of the order of 12%. Dominant systematic uncertainties are the modelling of the mass shape and the determination of the trigger efficiencies, both accounting for about 3%. The value of $R_K$ is found to be

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst}),$$

which is in tension with the SM prediction$^5$ of 1.0 with a significance of 2.6 standard deviations ($\sigma$). The BaBar and Belle experiments have also published$^6,7$ tests of LFU, but their analysed dataset is much smaller than the LHCb dataset and hence the measurement has significantly larger uncertainties. The status of all measurements is summarised in Fig. 1 (left).

The next accessible $b \to s \ell^+ \ell^-$ channel is $B^0 \to K^{(*)} \ell^+ \ell^-$, which has been published by the LHCb collaboration with 3 fb$^{-1}$ with a signal yield of 89 and 111 events in the low and central bin of $q^2$, respectively. Similarly to $R_K$, the measurement is implemented as double ratio with the resonant decay mode. Both $q^2$ bins are found below the SM prediction,

$$R_{K^*} = \begin{cases} 
0.66 \pm 0.11 \pm 0.07(\text{stat}) \pm 0.03(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4, \\
0.69 \pm 0.11 \pm 0.07(\text{stat}) \pm 0.05(\text{syst}) & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4.
\end{cases}$$

The measurement of $R_{K^*}$ is shown in Fig. 1 (right). The significances of the deviation of the SM expectation are 2.1 and 2.4 $\sigma$ for the low and middle $q^2$ bin, respectively. The statistical uncertainty is of the order of 15%, dominant systematic uncertainties are due to data/MC corrections (up to 5%) and background modelling (up to 5%).

The LHCb experiment has already collected a factor three more beauty mesons with respect to the 3 fb$^{-1}$ that are used for the measurements described above. Therefore, the tensions seen in the $R_K$ and $R_{K^*}$ measurements should get clarified in the foreseeable future. Then, the Belle 2 experiment will start to take data and will be able to further test LFU.

Additionally to the channels discussed above, LFU can be tested in $B_s^0 \to \phi \ell^+ \ell^-$ decays, where a first observation of the channel $B_s^0 \to \phi e^+ e^-$ should be possible already with 3 fb$^{-1}$.
of LHCb data. Also $B^+ \rightarrow K^-\pi^+\pi^-\ell^+\ell^-$ and $A_b \rightarrow \Lambda\ell^+\ell^-$ decays are analysed to test for violation of lepton universality. Combining the already collected large datasets and the analysis of more channels, the question if LFU is conserved in the SM should be conclusively answered in the near future. A quantitative analysis of the future sensitivities to discover LFU is discussed in Ref.\textsuperscript{8}

3 Lepton Flavour Universality in $b \rightarrow c\ell\nu$ decays

Lepton flavour universality can also be tested in semileptonic decays of the type $b \rightarrow c\ell\nu$. The observable $R_D^*$ is defined as $R_D^* = \frac{B(\bar{B} \rightarrow D^+\tau^-\nu_\tau)}{B(\bar{B} \rightarrow D^+\mu^-\nu_\mu)}$. The SM prediction is calculated to be $R_D^* = 0.252 \pm 0.009\textsuperscript{9}$, the difference to unity originates in the non-negligible tau-lepton mass. LHCb has also measured $R_D^* = 0.336 \pm 0.027 \pm 0.030$, using the leptonic $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$ decay mode. The compatibility with the SM prediction is $2.1 \sigma$. More recently, LHCb has also measured $R_D^*$ in the hadronic $\tau^- \rightarrow \pi^+\pi^-\pi^0\nu_\tau$, in which the neutral pion is not reconstructed. $R_D^*$ was measured\textsuperscript{11} to a value of $0.291 \pm 0.019 \pm 0.026 \pm 0.013$, compatible with the SM prediction at $1.0 \sigma$. The experimental situation of the measurements of $R_D$ and also the here not discussed $R_D$ is shown in Fig. 2. The combination of both ratios is in tension with the SM with a significance of $4.1 \sigma$.\textsuperscript{12}

![Figure 1](image1.png)

**Figure 1** – (left) Summary of the measurements of $R_K$ of the LHCb, BaBar\textsuperscript{3} and Belle\textsuperscript{7} experiments. The SM prediction is indicated as a line at 1.0. (right) LHCb measurement\textsuperscript{4} of $R_{K^*}$, together with several SM predictions.

![Figure 2](image2.png)

**Figure 2** – Summary of the measurements of $R_D$ and $R_{D^*}$.\textsuperscript{12}

LFU can also be tested in $B_c^+$ decays. LHCb has performed a measurement of the ratio $R_{B_c^+} = \frac{B(B_c^+ \rightarrow J/\psi\tau^+\nu_\tau)}{B(B_c^+ \rightarrow J/\psi\mu^+\nu_\mu)}$, where the $\tau^+$ is reconstructed in the leptonic

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decay mode.\textsuperscript{13} The value found is $R_{B^+_d} = 0.71 \pm 0.17 \pm 0.18$ which is $2.0\sigma$ above the SM prediction. It should be noted that the tensions seen in $R_{B^+_d}$ are in the same direction as the tensions seen in $R_{D^{(*)}}$.

4 Summary

The recent experimental results testing lepton flavour universality show intriguing tensions. In $b \to s \ell^+ \ell^-$ decays, a tension of $4.0\sigma$ is observed, it is even increased if the muonic measurements discussed in Ref.\textsuperscript{14} are included. In $b \to c \ell \nu$ decays, a tension with a combined significance of also about $4\sigma$ is seen. Significant theoretical efforts are ongoing to explain both types of anomalies in unified models, a detailed discussion can be found in Refs.\textsuperscript{15,16} On the experimental side, the dataset already collected by the LHCb collaboration is about a factor three larger than the dataset analysed here, so interesting updates on the presented measurements can be expected in the near future. 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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