PROCEEDINGS OF SCIENCE

Lepton Flavour Universality tests in $b \to c l \nu$ decays at LHCb

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The Standard Model predicts that the electroweak couplings to the three charged leptons are identical. However, in the last decade, experimental measurements have suggested that semileptonic processes involving taus could have a slightly enhanced decay rate compared to their muonic counterparts. If confirmed, this would be an unambiguous sign of New Physics, with various scenarios introducing additional interactions that couple preferentially to the third generation. Two recent lepton universality tests performed at LHCb are presented in these proceedings of the Eleventh Annual Conference on Large Hadron Collider Physics.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

PoS(LHCP2023)077

1. Introduction

Lepton Flavour Universality (LFU) is an accidental symmetry of the Standard Model (SM), and it predicts that the electroweak coupling to each generation of leptons is identical.

A common way to test LFU is to measure branching fraction ratios with $b \to c l \nu$ decays, i.e.

$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu \nu_\mu)} , \tag{1}$$

where H_b and H_c are beauty and charm hadrons, respectively. These measurements are powerful tests of LFU, since the ratio allows cancellation of some theoretical and experimental uncertainties.

Two recent tests of LFU performed at LHCb are presented here. The first is a simultaneous measurement of $\mathcal{R}(D^0)$ and $\mathcal{R}(D^*)$ with LHCb Run 1 data. The second is a measurement of $\mathcal{R}(D^*)$ with partial LHCb Run 2 data.

2. $\boldsymbol{\mathcal{R}(D^0)} - \boldsymbol{\mathcal{R}(D^*)}$ muonic

This measurement, reported in Ref. [1], reconstructs the τ in the muonic decay mode, meaning that the μ and τ decays in eq. (1) have the same visible final state. This allows $\mathcal{R}(D^0)$ and $\mathcal{R}(D^*)$ to be extracted directly. Previously, LHCb measured $\mathcal{R}(D^*)$ with this final state using the Run 1 dataset [2]. The new analysis extends the previous work by making a simultaneous measurement of $\mathcal{R}(D^0)$ and $\mathcal{R}(D^*)$ with the same dataset.

The LHCb Run 1 dataset corresponds to an integrated luminosity of 3 fb^{-1} collected at a centre of mass energy of 7 and 8 TeV. The dataset is first split into two samples, one of which has enhanced $D^{*+}\mu^-$ combinations, and the other has enhanced $D^0\mu^-$ as the D^{*+} state is vetoed.

The B rest frame is approximated by assuming its proper velocity is equal to the proper velocity of the visible component $(D^{(*)}\mu)$ along the z axis. The other B momentum components can be determined from knowledge of the B flight direction. With this estimate, the rest frame quantities of interest can be calculated. These are: the invariant mass of the lepton-neutrino system, $q^2 = (p_B - p_{D^{(*)}})^2$; the squared missing mass, $m^2_{miss} = (p_B - p_{D^{(*)}} - p_\mu)^2$; and the muon energy in the B rest frame, E^*_μ; where p_B, $p_{D^{(*)}}$ and p_μ are the four-momenta of the B, $D^{(*)}$ and the muon respectively.

Track isolation employs a boosted decision tree (BDT) to assess track compatibility with the B vertex, enabling the selection of background-enhanced control regions to improve background modeling. Three distinct control regions are used. The first includes an extra pion track to constrain $B \to (D^{**} \to D^*\pi)l\nu$ decays. Likewise, the second employs two additional pion tracks for modeling $B \to (D^{**} \to D^*\pi\pi), l\nu$ decays. The third involves at least one extra kaon track, modeling $B \to D^{(*)}DX$ backgrounds. These backgrounds are all modelled using simulations.

Other background processes considered in this study include decays of the form $B \to D^{(*)}hX$, where h is a charged hadron that is misidentified as a muon. Also, there are "combinatorial" backgrounds, which are random combinations of B and $D^{(*)}$ daughters leading to fake B and $D^{(*)}$ candidates. Both of these are modelled with data-driven methods.

To extract the parameters of interest, a three-dimensional maximum likelihood template fit is carried out in the variables: q^2, m^2_{miss} and E^*_l. The fit uses eight simultaneous data samples (the

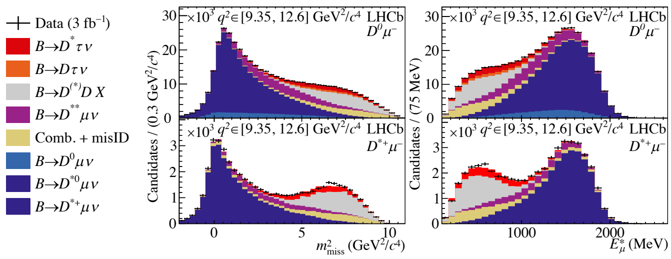

Figure 1: Fit projections for m^2_{miss} and E^*_μ in the highest q^2 bin for the $D^0\mu^-$ sample (top) and the $D^{*+}\mu^-$ sample (bottom).

signal and three control regions for the $D^0\mu^-$ and the $D^{*+}\mu^-$ datasets). The fit projections in the highest q^2 bin are shown in Figure 1.

The results of the measurement are:

$$\mathcal{R}(D^{*+}) = 0.281 \pm 0.018\,(\text{stat.}) \pm 0.024\,(\text{syst.})\,, \tag{2}$$

$$\mathcal{R}(D^{0}) = 0.441 \pm 0.060\,(\text{stat.}) \pm 0.066\,(\text{syst.})\,, \tag{3}$$

where the first uncertainty is statistical and the second is systematic. Overall the result has a 1.9σ agreement with the SM [3], and the correlation between $\mathcal{R}(D^{*+})$ and $\mathcal{R}(D^0)$ is -0.43.

3. $\mathcal{R}(D^*)$ hadronic

The second measurement is a determination of $\mathcal{R}(D^*)$, where the τ is reconstructed in the $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)$ final state [4]. This is an update to a previous LHCb measurement [5] which performed the same procedure on the Run 1 LHCb dataset. The previous measurement had an integrated luminosity of 3 fb^{-1}, and the new result uses data taken in 2015 and 2016, corresponding to 2 fb^{-1}. Despite the lower luminosity, the new analysis has approximately 40% more candidates than the previous measurement. This is due to a higher centre of mass energy in Run 2, as well as improvements in the LHCb trigger system.

In contrast to the measurement presented in Section 2, a separate normalisation channel is employed ($B^0 \to D^{*-}3\pi^\pm$), which was chosen as it has the same final state as the signal decay. The analysis measures the ratio $\mathcal{K}(D^*)$, defined as:

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}\,. \tag{4}$$

This can then be converted to a value of $\mathcal{R}(D^*)$ using:

$$\mathcal{R}(D^*) = \mathcal{K}(D^*)\,\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\,. \tag{5}$$

The value of the second ratio in the above equation is an external input, taken from the PDG [6].

The data used for this analysis contains a large background contribution from “prompt” $B \to D^*3\pi X$ decays. This is reduced using information from the 3π vertex. In the signal

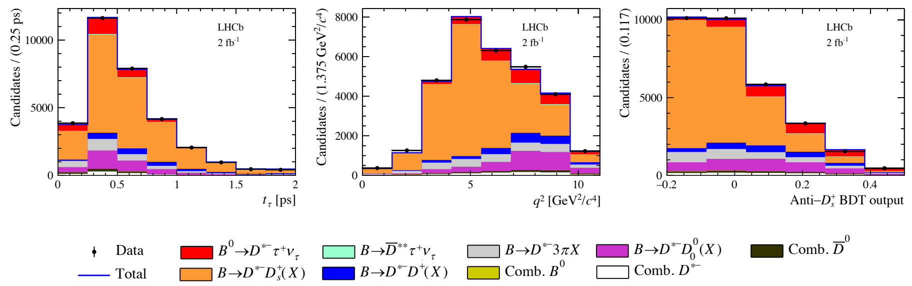

Figure 2: One-dimensional projections of the signal fit used to measure the yield of $B^0 \to D^{*-}\tau^+\nu_\tau$ events

mode, the 3π system is produced via the intermediate τ decay, whereas in the background, it comes directly from the B vertex.

Furthermore, there is a significant contribution from $B \to D^{*-}D_s^+ (\to 3\pi X)\, X$ events (double charm background). These events mimic the signal topology, as the D_s meson behaves similarly to the τ in the signal decay. To control this background, a dedicated BDT was trained using D_s kinematic variables and isolation variables, and is used as a variable in the signal fit. In addition, the modelling of this background is improved by performing two separate fits which correct the production and decay fractions of the various modes in the simulation.

A three dimensional maximum likelihood template fit is used in this work. In this case, the fit variables are q^2, the D_s BDT, and the τ lifetime. This signal fit measures the number of $B^0 \to D^{*-}\tau^+\nu_\tau$ events, the fit projections are shown in Figure 2. The yield of $B^0 \to D^{*-}3\pi$ is measured from a separate normalisation fit. From this, $\mathcal{K}(D^*)$ is calculated by taking the ratio of signal and normalisation events, correcting for the different efficiencies, and dividing by the $\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau$ branching fraction. The measured value is:

$$\mathcal{K}(D^*) = 1.700 \pm 0.101\,(\text{stat.})\,^{+0.105}_{-0.100}\,(\text{syst.})\,, \tag{6}$$

where the first uncertainty is statistical and the second is systematic. From this, $\mathcal{R}(D^*)$ is calculated as:

$$\mathcal{R}(D^*) = 0.247 \pm 0.015\,(\text{stat.}) \pm 0.015\,(\text{syst.}) \pm 0.012\,(\text{ext.})\,, \tag{7}$$

where the final uncertainty comes from the external branching fraction in Eq. (5). When this result is combined with the value obtained in the Run 1 analysis, $\mathcal{R}(D^*)$ is found to be:

$$\mathcal{R}(D^*) = 0.257 \pm 0.012\,(\text{stat.}) \pm 0.014\,(\text{syst.}) \pm 0.012\,(\text{ext.})\,. \tag{8}$$

The combined value is consistent with the SM prediction within 1σ [3].

4. Conclusions and prospects

Previously, the world average values for $\mathcal{R}(D^0)$ and $\mathcal{R}(D^*)$, including results from LHCb, BaBar and Belle had a combined 3.3σ deviation from the SM. The two new results presented here both have good agreement with the SM, so the tension between the experimental and predicted values is reduced to 3.2σ when they are included. Further measurements of $R(D^{(*)})$ and other LFU ratios present exciting prospects for potential New Physics (NP) in the lepton sector. The full Run 2 dataset at LHCb is yet to be exploited, and data taking for Run 3 has recently begun.

References

[1] LHCb collaboration, *Measurement of the ratios of branching fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$*, 2302.02886.

[2] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$*, Phys. Rev. Lett. **115** (2015) 111803 [1506.08614].

[3] Y. Amhis et al., *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021*, Phys. Rev. D **107** (2023) 052008 [2206.07501].

[4] LHCb collaboration, *Test of lepton flavour universality using $B^0 \to D^{*-}\tau^+\nu_\tau$ decays with hadronic τ channels*, 2305.01463.

[5] LHCb collaboration, *Measurement of the ratio of the $B^0 \to D^{*-}\tau^+\nu_\tau$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ branching fractions using three-prong τ-lepton decays*, Phys. Rev. Lett. **120** (2018) 171802 [1708.08856].

[6] Particle Data Group collaboration, *Review of Particle Physics*, PTEP **2022** (2022) 083C01.

[7] D. Hill, M. John, W. Ke and A. Poluektov, *Model-independent method for measuring the angular coefficients of $B^0 \to D^{*-}\tau^+\nu_\tau$ decays*, Journal of High Energy Physics **2019** (2019) .