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Lepton flavour universality tests using semileptonic b-hadron decays at LHCb

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Summary. — The standard model assumes that the three charged leptons, namely electrons e, muons μ, and taus τ, have an identical electroweak coupling, and the distinction arises from their different masses. Several independent experiments, including BaBar, Belle, and LHCb, have found deviations from SM predictions. Some of these anomalies arises in the $b \to c\ell\nu$ transition, referred to as *charged anomalies*. Recent measurements have been reported with the purpose of addressing these anomalies, a brief overview of these results is provided. It is worth noting that the overall tension between theoretical predictions based on the Standard Model and the world average including these new measurements remains at the 3σ level.

1. – Introduction

In the framework of the Standard Model of particle physics, lepton flavor universality (LFU) is the principle under which the three families of quarks and (charged) leptons are distinct only by their mass, and all the other quantum numbers are the same. In recent years, there have been several indications of potential violation of the LFU assumption through experimental observations. These deviations can manifest through two distinct processes: *flavor-changing neutral currents* (FCNC) involving the transition of a quark from $b \to s\ell\ell$, and *flavor-changing charged currents* (FCCC), which can occur at the tree level, involving the transition $b \to c\ell\nu_\ell$, where ℓ is a charged lepton.

Numerous experimental investigations are currently in progress to elucidate the observed anomalies regarding LFU, by performing more precise measurements. In this paper, the focus is placed on the FCCC tests at LHCb, which are performed with observables involving semileptonic decays of X_b hadrons. The branching fractions of two decays([1]) $X_b \to X_c\ell^+\nu_\ell$ where ℓ is either τ or μ, is measured in order to reduce both

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([1]) With $(X_b, X_c^{(*)}) \in \{(B, D^{(*)}), (\Lambda_b, \Lambda_c)\}$.

theoretical and experimental uncertainties. This ratio is determined as follows:

$$R(X_c^{(*)}) = \frac{\mathcal{B}(X_b \to X_c^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(X_b \to X_c^{(*)}\mu^+\nu_\mu)}. \tag{1}$$

In LHCb, two independent and complementary analyses of $R(X_c^{(*)})$ are conducted. Both methods and recent results will be briefly discussed in next sections. A common challenge arises due to the presence of neutrino(s) in the final state, rendering the identification of a signal region challenging.

2. – $R(D^*)$ with hadronic τ decays

In this analysis, the τ is reconstructed from its hadronic decay $\tau^+ \to 3\ \pi^\pm\ (\pi^0)$. The features of the detector including the good vertex resolution is exploited to reject substantial portion of background events. Additionally, high-purity samples can be extracted, and the specific decay dynamics of $\tau^+ \to 3\pi^\pm\bar{\nu}_\tau$ is utilized. In contrast, the muonic channel (sect. **4**) benefits from a larger statistical sample.

In the following, the $R(D^*)$ measurement using hadronic τ decays at LHCb [1], based on data acquired during partial run 2 —corresponding to 2015 and 2016 datasets— at the center-of-mass energy $\sqrt{s} = 13$ TeV, is provided.

The methodology employed for the extraction of $R(D^*)$ involves the introduction of a normalisation mode $B^0 \to D^{*-}3\pi^\pm$ as an intermediate step, which shares the same visible state as the signal mode:

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} = \mathcal{K}(D^*)\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}, \tag{2}$$

where

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}, \tag{3}$$

in which $\mathcal{K}(D^*)$ is measured, then $R(D^*)$ is determined by the utilization of external inputs.

The primary sources of backgrounds originate from the inclusive B decay to three pions $B \to D^*3\pi^\pm X$, a set of criteria is imposed to minimize this background, including a separation requirement between the τ vertex and the B vertex, along with the application of a BDT classifier. Additional backgrounds arise from the double charm B decays ($B^0 \to D^*DX$), which exhibit a similar decay topology to the signal. A separate BDT classifier is employed to distinguish the D_s and τ decays, which is also used as template in the signal fit.

The signal yield is determined from a three-dimensional maximum likelihood binned fit to q^2 (8 bins), τ^+ lifetime t_τ (8 bins) and the anti-D_s BDT (6 bins) which are shown in fig 1. The PDF is a sum of 16 templates: 13 templates are obtained from simulation and 3 templates are derived from data.

The fit gives 2469 ± 154 of signal candidates $B^0 \to D^{*-}3\tau\nu_\tau$. The normalisation yield is extracted from an unbinned fit to $m(D^{*-}3\pi^\pm)$ and leads to 30540 ± 182 candidates.

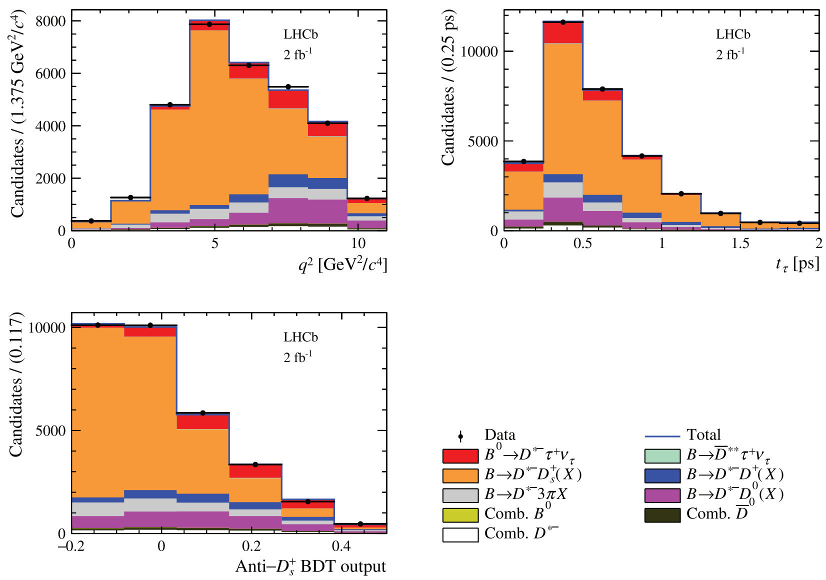

Fig. 1. – Signal fit projections on q^2, τ lifetime, and the anti-D_s BDT.

The absolute branching fraction is measured to be

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.23 \pm 0.07 \pm 0.08 \pm 0.05) \times 10^{-2},$$

and the ratio

$$R(D^*)_{2015-2016} = 0.247 \pm 0.015 \pm 0.015 \pm 0.012. \tag{4}$$

The uncertainties are, respectively, statistical, systematics and the last one is coming from the external input. The following result is obtained by combining this measurement with the previous result [2]:

$$R(D^*)_{2011-2016} = 0.257 \pm 0.012 \pm 0.014 \pm 0.012. \tag{5}$$

The result is compatible with the Standard Model calculations [3],

$$R(D^*)_{SM} = 0.254 \pm 0.005, \tag{6}$$

and with the $R(D^*)$ world average.

3. – $R(\Lambda_c)$ with hadronic τ decays

This analysis is the first LFU test in a baryonic $b \to c\ell\nu_\ell$ transition with hadronic $\tau^+ \to 3\pi^\pm(\pi^0)$ decay. The measurements [4] uses data collected during Run 1 at LHCb.

The analysis follows a methodology similar to the one employed in the hadronic $R(D^*)$ analysis. In this approach, a normalization mode, $\Lambda_b \to \Lambda_c 3\pi^\pm$, is introduced, and external inputs are incorporated to derive the value of $R(\Lambda_c)$.

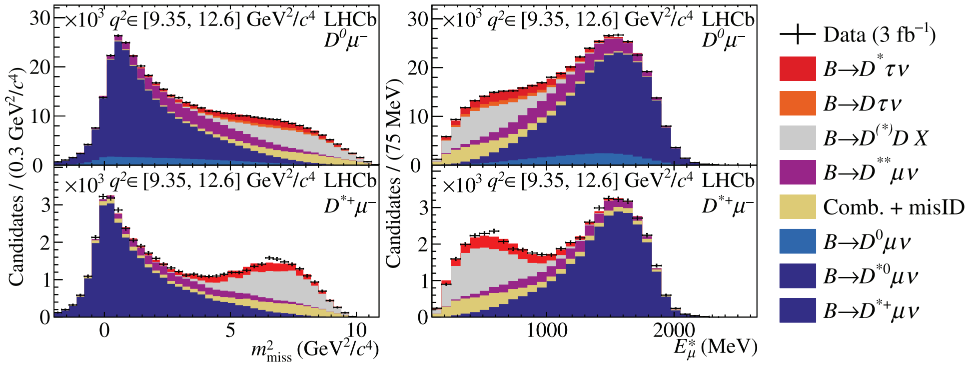

Fig. 2. – Distributions of $m^2_{\rm miss}$ (left) and E^*_μ (right) in the highest q^2 bin of the $D^0\mu^-$ (top) and $D^{*+}\mu^-$ (bottom) signal data, over projections of the fit model.

The result is given by

$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau^+ \nu_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c 3\pi^\pm)} = 2.46 \pm 0.27 \pm 0.40. \tag{7}$$

With the external branching fraction inputs, the following result is obtained:

$$R(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059. \tag{8}$$

The uncertainties are respectively statistical, systematics and uncertainties from external branching fractions. The result is compatible with the Standard Model expectation.

4. – $R(D) - R(D^*)$ muonic τ decay

The observables $R(D)$ and $R(D^*)$ are simultaneously measured, using data collected during Run 1 at LHCb [5]. The tau τ is reconstructed from its muonic decay $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$. The final-state particles are identical in both numerator and denominator of the ratio $R(D^{(*)})$, which allows direct measurements (without external input). In addition, the decay rate of τ through the *muon* channel is higher that of the hadronic one, resulting in more statistics.

The primary sources of background originate from partially reconstructed B decay processes, specifically $B \to D^*\mu\nu$, $B \to D^{**}\mu\nu$, $B \to D^*DX$ with $D \to \mu\nu X$, and so on. The identification of signal candidates, namely $D^0\mu^-$ and $D^+\mu^-$, relies on the reconstruction of D^0 from $K^-\pi^+$ and D^* from $D^0\pi^+$. To prevent double counting, the reconstructed $D^{*+} \to D^0\pi^+$ is excluded from the $D^0\mu^+$ sample. Additionally, a trigger on D^0 is employed to maintain acceptance for soft muons. Furthermore, a custom muon ID classifier, characterized by a more uniform kinematic acceptance, is utilized to reduce the misidentification background. The signal yields are extracted from 3D template fit to $q^2 = (p_B - p_{D^*})^2$, $m^2_{\rm miss} = (p_B - p_{D^*} - p_\mu)^2$ and E^*_μ energy of μ. The fit projections with the highest q^2 bin are shown in fig 2. The following results are obtained:

$$R(D) = 0.441 \pm 0.060 \pm 0.066, \tag{9}$$
$$R(D^*) = 0.281 \pm 0.018 \pm 0.023, \tag{10}$$

where the first uncertainty is statistical and the second systematics. The agreement with the Standard Model prediction is within 1.9σ.

5. – Conclusion

In this brief summary, the recent results on the LFU tests using ratios from semileptonic B and Λ_b decays have been reported. The tension between the average $R(D) - R(D^*)$ measurements and the Standard Model prediction remains at the 3σ level [3].

The $R(D^*)$ with hadronic τ decay analysis using the full Run 2 dataset is currently in progress. The statistical uncertainties are expected to decrease to the order of 3%. As a consequence, the increase in sample size will also lead to a reduction in several systematic uncertainties. The future analysis will take into account the recent results from BESIII Collaboration [6, 7] on inclusive $D_{(s)}^{(0,+)} \to 3\pi^{\pm}X$, which could reduce the systematic uncertainties in the legacy measurement to come. Furthermore, the new LHCb data taking has started, and many more analyses are about to come: $R(D^0)$, $R(D^+)$, $R(D_s)$, $R(D^*)_{e/\tau}$, $R(D^*)_{e/\mu}$, $R(J/\Psi)$ and *angular analysis* to determine spin structure of potential beyond Standard Model effects.

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