TESTS OF LEPTON FLAVOUR UNIVERSALITY IN $b \to c\ell\nu$ DECAYS AT THE LHCb EXPERIMENT*

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(Received April 14, 2020)

Several measurements, aimed at testing the lepton flavour universality hypothesis, have been performed by the B-physics experiments which exploit both neutral current ($b \to s\ell\ell$) and charged current ($b \to c\ell\nu$) decays. The combination of the measurements carried out in the charged current sector shows possible hints of deviations with respect to the Standard Model predictions. This document reports the analyses, performed by the LHCb experiment, of semi-tauonic decays with both leptonic and the hadronic decays of the τ lepton.

DOI:10.5506/APhysPolB.51.1479

1. Introduction

Lepton flavour universality (LFU) is an accidental symmetry of the Standard Model (SM) that predicts the equality of the coupling of the gauge bosons to the three lepton families. As a result, within the SM, any difference in the rates of the decays involving different species of the lepton, should originate only from phase-space factors and helicity-suppressed contributions. The observation of any discrepancy with respect to the LFU predictions can be a clear sign of New Physics (NP) beyond the SM.

Intriguing discrepancies between the SM prediction and measurements of B-meson decays, mediated both by the neutral current ($b \to s\ell\ell$) and the charged current ($b \to c\ell\nu$) interactions, have been reported [1].

* Presented at XXVI Cracow Epiphany Conference on LHC Physics: Standard Model and Beyond, Kraków, Poland, January 7–10, 2020.

Charged current decays offer a very powerful test bench for the LFU hypothesis, both from an experimental point of view, thanks to their high transition rate ($\mathcal{O}(10\%)$) [2], and from a theoretical point of view, thanks to their precise prediction.

To test the LFU hypothesis, the variables usually measured are ratios branching fractions

$$\mathcal{R}(H_c) = \frac{\mathcal{B}\left(B \to H_c \tau \nu_\tau\right)}{\mathcal{B}\left(B \to H_c \mu \nu_\mu\right)}\,, \tag{1.1}$$

where H_c stands for the charmed meson involved in the decay.

Thanks to cancellations of the hadronic uncertainties, the theoretical uncertainties on the prediction of these ratios is well under control ($\mathcal{O}(\%)$) [1].

LFU analyses performed at the LHCb experiment exploit either the fully leptonic decay of the τ lepton, $\tau \to \mu\bar{\nu}_\mu\nu_\tau$[1], or the three-prongs hadronic decay, $\tau \to 3\pi^\pm(\pi^0)\nu_\tau$.

When combining the measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ performed by the Belle, BaBar and LHCb collaborations, a tension at the level of 3σ [1] with respect to the SM prediction is observed.

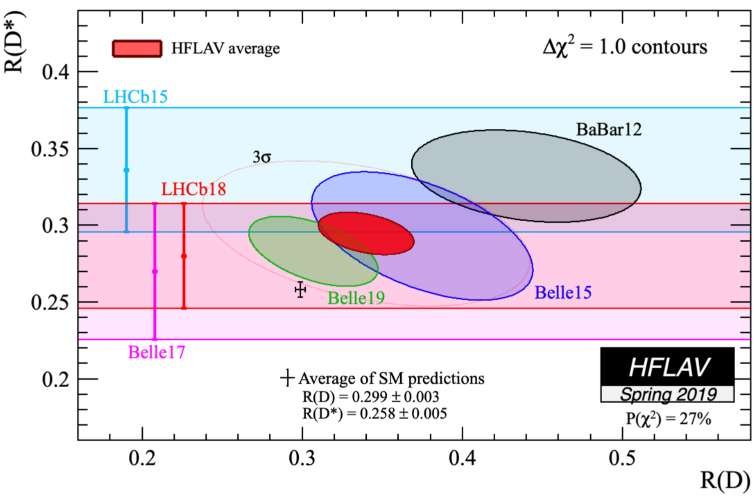

Fig. 1. Measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ and their average compared with the average of the SM predictions [1].

In the following sections, the LHCb measurements of $\mathcal{R}(D^*)$ and $\mathcal{R}(J/\psi)$, performed on a dataset of 3 fb^{-1} integrated luminosity collected during the 2011 and 2012 data taking periods, at the center-of-mass energies of 7 and 8 TeV respectively, will be summarized.

[1] The inclusion of charge-conjugate processes is implied throughout this document.

2. Measurement of $\mathcal{R}(D^*)$ with $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$

This measurement exploits the $D^{0*} \to D^+\pi^-$ decay and the leptonic decay of the *tau* lepton ($\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$) [3]. $\mathcal{R}(D^*)$ is extracted from a binned maximum-likelihood fit to variables that separate the signal ($B \to D^*\tau\nu$), normalization ($B \to D^*\mu\nu$) and background contributions. These variables include the squared missing mass (m^2_{miss}), the invariant squared mass of the leptonic system (q^2) and the energy of the lepton in the B-meson rest frame (E^*_μ).

The momentum of the B meson cannot be inferred in pp collisions, therefore, it is reconstructed using an approximated method that exploits the flight direction, measured from the position of the production and the decay vertex. Thanks to the excellent resolution of the VELO detector, the resolution that can be achieved with this method on the fit variables ($\sim 20\%$) is sufficient to obtain a good separation between the signal and normalization contributions [3].

The physical backgrounds are rejected using a Boosted Decision Tree (BDT) that assigns to each track in the event a probability of originating from the B vertex. By inverting this selection, different control regions, enriched with specific decays, are defined and used to calibrate the background contributions.

The measured value is $\mathcal{R}(D^*) = 0.336 \pm 0.027(\mathrm{stat.}) \pm 0.030(\mathrm{syst.})$ [3], which exhibits a tension with respect to the SM prediction at the level of 2.1σ.

3. Measurement of $\mathcal{R}(D^*)$ with $\tau^- \to 3\pi(\pi^0)$

In this analysis, the D^{*+} candidate is reconstructed through the $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ decay chain, while the τ lepton is reconstructed through the $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ decay [4]. Due to the hadronic final state, the data sample is contaminated mostly by physical backgrounds coming from hadronic B meson decays.

The most dominant background before the selection requirements consists of inclusive decays of b-hadrons to $D^*3\pi X$ with the three pions coming directly from the B decay vertex. Since the τ decay vertex is reconstructed with a good resolution and distinguished from the B decay vertex, this $D^*3\pi X$ background is very efficiently suppressed by requiring the τ vertex to be downstream of the B vertex along the beam axis, and separated from it with a 4σ significance.

The highest background source after the selection requirements is given by $B \to D^*D_sX$ decays. A BDT is trained to separate this contribution from the signal decay.

The number of signal candidates is measured relative to the number of events recorded from a fully hadronic B meson decay with the same final state, $B^0 \to D^{*+}3\pi^{\pm}$, which forms the normalization channel of the measurement. The number of normalization events is measured from a fit to the $D^*3\pi$ invariant mass distribution, in a data sample in which the τ vertex requirement is inverted. The parameter of interest reported by the analysis is given by

$$\mathcal{K}\left(D^*\right) = \frac{\mathcal{B}\left(B^0 \to D^{*-}\tau^+\nu_\tau\right)}{\mathcal{B}\left(B^0 \to D^{*-}3\pi^{\pm}\right)}\,. \tag{3.1}$$

This quantity is then converted into $\mathcal{R}(D^*)$ using the external measurements of branching fractions [2]

$$\mathcal{R}\left(D^*\right) = \mathcal{K}\left(D^*\right)\frac{\mathcal{B}\left(B^0 \to D^{*-}3\pi^{\pm}\right)}{\mathcal{B}\left(B^0 \to D^{*-}\mu^+\nu_\mu\right)}\,. \tag{3.2}$$

The analysis is performed by means of a binned maximum-likelihood fit to the lifetime of the τ, q^2 and the BDT output. Various different control regions are defined to calibrate the composition of the Monte Carlo background models used in the fit.

The measured value is $\mathcal{R}(D^*) = 0.283 \pm 0.019(\text{stat.}) \pm 0.025(\text{syst.}) \pm 0.013(\text{ext.})$ [4], where the first uncertainty is statistical only, the second is systematic, and the third one is due to the external inputs. This value exhibits a tension with the SM predictions at the 1σ level.

4. Measurement of $\mathcal{R}(J/\psi)$ with $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$

The $B_c \to J/\psi\ell\nu$ decay has been exploited by the LHCb experiment to perform the measurement of $\mathcal{R}(J/\psi)$ [5], using $J/\psi \to \mu^+\mu^-$ decays. This measurement also resulted in the first evidence of the $B_c \to J/\psi\tau\nu_\tau$ decay with a significance of 3σ.

The B_c lifetime is much smaller than the lifetimes of the B^0 and $B^{\pm}$ mesons. This enables rejection of backgrounds involving semileptonic B^0 and $B^{\pm}$ decays, by cutting on the flight distance of the B_c candidate.

The signal ($B_c \to J/\psi\tau\nu_\tau$) and normalization ($B_c \to J/\psi\mu\nu_\mu$) modes have the same ($\mu\mu\mu$) final state. They are separated using a fit to q^2, m^2_{miss}, E^*_μ and the B_c lifetime, reconstructed in the same approximated rest frame reported in Section 2.

The main systematic uncertainty comes from the poor knowledge of the $B_c \to J/\psi\mu\nu$ form factors, for which no precise Lattice QCD calculation was performed at the time of the measurement. The measured value is $\mathcal{R}(J/\psi) = 0.71 \pm 0.017(\text{stat.}) \pm 0.018(\text{syst.})$ [5], representing a discrepancy at the level of 2σ with respect to the SM prediction.

5. Future prospects

New analyses are under way to test the LFU hypothesis using $b \to c\ell\nu$ decays, exploiting both muonic and hadronic τ decay channels [6].

Of special interest are baryonic decays which are exclusive to hadron colliders. A very interesting measurement can be the one of $\mathcal{R}(\Lambda_c)$, using $\Lambda_b \to \Lambda_c\ell\nu$ decays.

From an experimental point of view, this measurement would benefit from a high Λ_b production cross section and a high $\Lambda_b \to \Lambda_c\ell\nu$ decay branching fraction of around 6% [2]. Furthermore, there will be lower feed-down contributions from Λ_c^{**} due to isospin conservation. This conservation law imposes that Λ_c^{**} decays to at least two pions, leading to a simpler signature to reject this contribution.

From a theoretical point of view, it will probe a different NP Lorentz structure with respect to the one probed by the analyses with B mesons. Lastly, it has been shown that an approximated relation links $\mathcal{R}(\Lambda_c)$ with the already measured $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ parameters [7]

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}(\Lambda_c)_{\rm SM}} \approx 0.262\frac{\mathcal{R}(D)}{\mathcal{R}(D)_{\rm SM}} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}(D^*)_{\rm SM}}\,. \tag{5.1}$$

This relation is model-independent and could offer, in fact, a very useful cross check for the present reported discrepancies.

In the coming years of data taking, the integrated luminosity will greatly increase, with an expected integrated luminosity after the proposed Upgrade II phase of around 300 fb^{-1}. The big amount of data will enable the analyses to reduce the statistical uncertainty and many systematic uncertainties, especially the ones related to the calibration of the shape and the normalization of the background contributions, which are mostly data-driven.

In order to control the systematic uncertainty introduced by the limited statistics of the Monte Carlo samples, which is already one of the main sources of uncertainty in the current analyses, the measurements will have to exploit fast simulations. Many options are already being implemented in the LHCb analysis framework [8].

At the time of writing this document, only ratios of branching fractions have been used to test the LFU hypothesis in $b \to c\ell\nu$ decays, even though these decays offer a very rich angular structure that can be further studied experimentally. This is especially interesting because it has been shown [9–11] in the theoretical literature that measurements of the angular structure of the decays can offer higher sensitivity to NP Wilson Coefficients. The high statistics datasets will enable the study of the angular distributions of these decays, even if the resolution on the angular observables is not ideal [6] due to the presence of neutrinos in the final state.

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