IL NUOVO CIMENTO **42 C** (2019) 154
DOI 10.1393/ncc/i2019-19154-2

Colloquia: IFAE 2018

Measurements of lepton universality at LHCb

F. Betti(1)(2)

(1) *INFN, Sezione di Bologna - Bologna, Italy*
(2) *Dipartimento di Fisica e Astronomia, Università di Bologna - Bologna, Italy*

received 31 January 2019

Summary. — Lepton universality violation would represent a signal of physics beyond the Standard Model. Anomalies have been observed in the measurement of the branching ratios of semileptonic decays of beauty mesons in third-generation leptons. This contribution reports on the measurements of the observable $\mathcal{R}(D^{*-}) = \mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$ and $\mathcal{R}(J/\psi) = \mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)$ performed at LHCb with data collected during the Run 1 of the LHC.

1. – Introduction

In the Standard Model (SM) of particle physics the electroweak couplings of the gauge bosons to the leptons have the same value for all the lepton families. This property is known as lepton universality (LU), and if LU violation is observed, it will represent a clear signal of New Physics (NP).

The branching fractions ratio, calculated with high precision in the SM [1],

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}, \tag{1}$$

represents a sensitive probe for LU violation.

BaBar and Belle measured $\mathcal{R}(D^*)$, reporting respectively discrepancy of 3.4σ and consistency at 1σ level with the theoretical expectations [2, 3].

The analogous ratio in the B_c sector,

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}, \tag{2}$$

has been calculated with less precision due to large uncertainties on the form factors [4], and it has never been measured so far.

This document presents the measurements of $\mathcal{R}(D^{*-})$ and $\mathcal{R}(J/\psi)$ performed at LHCb with data collected during 2011 and 2012 at a centre-of-mass energy of 7 and 8 TeV, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$.

2. – Measurement of $\mathcal{R}(D^{*-})$

The first measurement of $\mathcal{R}(D^{*-})$ at a hadron collider was performed by LHCb [5], using the muonic τ decay channel $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$(1). The normalization mode $B^0 \to D^{*-}\mu^+\nu_\mu$ is also the main background source for the signal $B^0 \to D^{*-}\tau^+\nu_\tau$. In order to achieve a good separation between the two modes, three key kinematic observables are computed in the B^0 rest frame: the muon energy E^*_μ, the squared missing mass $m^2_{miss} = (p_{B^0} - p_{D^*} - p_\mu)^2$ and the squared four-momentum transfer $q^2 = (p_{B^0} - p_{D^*})^2$, where p_{B^0}, p_{D^*} and p_μ are the four-momenta of the B^0, the D^{*-} and the muon. Because of the presence of neutrinos in the decay, the exact determination of the B^0 momentum in the laboratory frame is not possible, only the momentum direction is determined from the B^0 decay vertex and the associated primary vertex (PV). The three kinematic observables are therefore computed by approximating the Lorentz boost of the B^0 with the boost of the visible $D^{*-}\mu^+$ system, resulting in a resolution of about 15–20% on the rest-frame variables, sufficient to preserve the discrimination between the two modes. A binned multidimensional maximum-likelihood fit is performed to data on the distribution of the three observables, with templates for signal, normalization and background channels extracted from simulation and data-driven control samples. The result

$$\mathcal{R}(D^{*-}) = 0.336 \pm 0.027\ (\text{stat}) \pm 0.030\ (\text{syst})$$

is in good agreement with previous measurements and 2.1 standard deviations higher than the SM expectation.

A second measurement of $\mathcal{R}(D^{*-})$ was performed in LHCb [6, 7] on an independent sample, with the τ lepton reconstructed through the $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$ decay. It is experimentally more convenient to measure the ratio:

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

where the normalization channel $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ has been chosen in order to have most of the systematic uncertainties cancelled out in the efficiency ratio. The second term of eq. (3) is obtained using externally measured branching fractions.

The most dominant background, consisting of inclusive decays of b-hadrons to $D^*3\pi X$, is suppressed by requiring the τ vertex to be downstream, along the beam direction, with respect to the B^0 vertex with a 4σ significance. In order to discriminate from the signal the remaining background, mainly due to double-charmed B decays, a set of variables is used: variables computed with two partial reconstruction techniques, one in signal hypothesis and the other in background hypothesis; variables related to the 3π system dynamics; isolation variables. All these variables are used as input to train a Boosted Decision Tree (BDT). Through the partial reconstruction in the signal, hypothesis q^2

---

(1) Charge conjugated decay modes are implied throughout the document.

and the τ decay time are computed with a sufficiently good resolution to maintain the separation between signal and background.

The signal yield is extracted by performing a multidimensional maximum-likelihood template fit on data in the high-BDT region, on three-dimensional shapes of q^2, τ decay time and BDT, derived from simulated and data-driven control samples. The normalization yield is obtained by fitting the $D^*3\pi$ invariant-mass distribution in the B^0 peak region, after reverting the τ vertex requirement.

The result of this analysis is

$$\mathcal{R}(D^{*-}) = 0.286 \pm 0.019\ (\text{stat}) \pm 0.025\ (\text{syst}) \pm 0.021\ (\text{ext}),$$

where the last uncertainty originates from the uncertainties on the external branching fractions [8-11]. This result is higher than the SM calculation, consistent with it within one standard deviation, and compatible with all the previous measurements. The combination of all available measurements of $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$ shows a discrepancy from the SM prediction by 4.1σ [11].

3. – Measurement of $\mathcal{R}(J/\psi)$

$\mathcal{R}(J/\psi)$ has been measured in LHCb [12] reconstructing the τ from its muonic decay and the J/ψ in the $J/\psi \to \mu^+\mu^-$ mode. The adopted strategy is similar to the one used for the muonic $\mathcal{R}(D^{*-})$ measurement, adding to the list of discriminating variables the B_c^+ decay time, since its distribution is significantly different between signal and background of semileptonic decays of lighter b-hadron decays. The measured value is

$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17\ (\text{stat}) \pm 0.18\ (\text{syst}),$$

which is 2σ higher than the SM calculations.

4. – Conclusions

LHCb performed three measurements of observables sensitive to LU violation in semitauonic decays with the data collected during the Run 1 of the LHC. Updates of these measurements with the data collected during the Run 2 are currently ongoing, and at the same time similar observables, like $\mathcal{R}(D)$, $\mathcal{R}(D_s)$, $\mathcal{R}(\Lambda_c)$ and $\mathcal{R}(\Lambda_c^*)$, are under study, in order to test the consistency of the anomalies in other decay modes.

REFERENCES

[1] Fajfer S., Kamenik J. F. and I. Nišandžić, *Phys. Rev. D*, **85** (2012) 094025.
[2] The BaBar Collaboration (Lees J. P. *et al.*), *Phys. Rev. D*, **88** (2013) 072012.
[3] Belle Collaboration (Huschle M. *et al.*), *Phys. Rev. D*, **92** (2015) 072014.
[4] Ivanov M. A., Korner J. G. and P. Santorelli, *Phys. Rev. D*, **73** (2006) 054024.
[5] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. Lett.*, **115** (2015) 111803.
[6] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. Lett.*, **120** (2018) 171802.
[7] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. D*, **97** (2018) 072013.
[8] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. D*, **87** (2013) 092001.
[9] The BaBar Collaboration (Lees J. P. *et al.*), *Phys. Rev. D*, **94** (2016) 091101.
[10] Belle Collaboration (Majumder G. *et al.*), *Phys. Rev. D*, **70** (2004) 111103.
[11] HFLAV Collaboration (Amhis Y. *et al.*), *Eur. Phys. J. C*, **77** (2017) 895.
[12] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. Lett.*, **120** (2018) 121801.