Tests of lepton universality with semi-tauonic b-quark decays

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Abstract. Several measurements have shown deviations from lepton universality in tree-level semi-leptonic decays of *b* hadrons. In these proceedings three LHCb measurements of lepton universality in such decays are presented along with a brief overview for the future possibilities of these and similar observables.

1. Introduction

In the Standard Model (SM) the three lepton generations all have the same coupling strength to the electroweak gauge bosons. Such lepton universality can be tested in semi-leptonic decays with observables $R(X)$, typically defined by

$$R(X) = \frac{\mathcal{B}(H_b \to X\tau^+\nu_\tau)}{\mathcal{B}(H_b \to X\mu^+\nu_\mu)},$$

where H_b denotes some decaying *b* hadron and X is a hadron in the final state. In the case of lepton universality the only deviation of $R(X)$ from unity would be due to the different masses of the leptons leading to different available phase spaces in the decay and varying the impacts of the hadronic form-factors.

Several independent measurements have shown deviations from the SM predictions in the observables $R(D^*)$ ($B \to D^*l^+\nu_l$) and $R(D)$ ($B \to Dl^+\nu_l$) [1–8]. The current experimental average and theoretical prediction are shown in Fig. 1. The combination of the individual measurements can be seen to lie approximately 3.7σ away from the theory expectation. If this is taken to be a sign of physics beyond the SM then such new physics (NP) is competing with SM tree-level diagrams.

LHCb has made two measurements of $R(D^*)$ using $3\,\text{fb}^{-1}$ of *pp* collision data with centre-of-mass energies of 7 and 8 TeV collected in 2011 and 2012 during Run 1 of the LHC. A measurement has also been made of a complementary observable $R(J/\psi)$ with the same dataset. These measurements are described in the following sections.

2. Reconstructing semi-tauonic *B* decays at LHCb

τ leptons are short lived so they can only be reconstructed via their decays. At LHCb this is done either with the $\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu$ leptonic mode, or the $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\nu_\tau$ hadronic decay. The branching fractions of both are significant, $\sim 17.4\%$ and $\sim 13.9\%$, respectively [10]. Due to
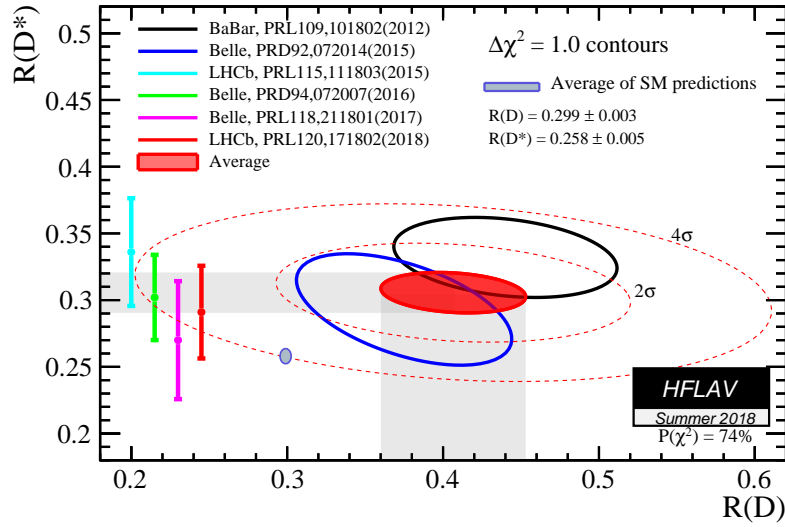
Figure 1. (Colours online) The current status of $R(D)$ and $R(D^*)$ measurements [9]. The average of all the experimental results is shown by the solid red circle with the 2 and 4σ uncertainty regions shown by the marked dash lines.

the undetected neutrinos in the final state the kinematics of the decaying b hadron cannot be precisely determined and some estimations must be made.

For the final states of the B decay where the τ^+ has decayed leptonically a simple estimation is made of the B momentum in the z direction, along the beam line. The visible B momentum, $p_z^{vis}(B)$, is simply scaled by the ratio of the true and visible B invariant masses

$$p_z^{true}(B) = \frac{m_B^{true}}{m_B^{vis}} \times p_z^{vis}(B),$$

to give the estimated true B momentum in the z direction. As both the pp interation point and B decay-vertex can be well measured thanks to LHCb's excellent vertex resolution, the B flight path is known and so the B momentum vector can be constructed from $p_z^{true}(B)$ and the angle between the B flight vector and the z direction. Using this approximation quantities can be constructed: the square of the invariant mass of the three neutrinos, m_{miss}^2; the square of the invariant mass of the lepton system, q^2; and the muon energy in the approximated B rest-frame, E_μ^*. Such variables can be used to discriminate the $B^0 \to D^{*-}\tau^+\nu_\tau$ signal from the backgrounds and from the $B^0 \to D^{*-}\mu^+\nu_\mu$ normalisation mode.

For the hadronic decays of the τ^+ both the B^0 and τ^+ flight vectors are known from the vertex formed by the $\bar{D}^0\pi^-$ of the D^{*-} candidate for the former and the three pion vertex of the latter. This means that the kinematics of τ^+ and B^0 candidates can be determined up to a two-fold ambiguity. In each case the minimum possible value of each is chosen. Again this approximation allows the kinematics of the decay to be estimated so that the signal can be separated from the backgrounds and normalisation modes.

3. Muonic $R(D^*)$

A measurement of $R(D^*)$ has been made using $3\,\text{fb}^{-1}$ of data collected by LHCb in Run 1 of the LHC using the $\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu$ decay [6]. The observable of interest was extracted by
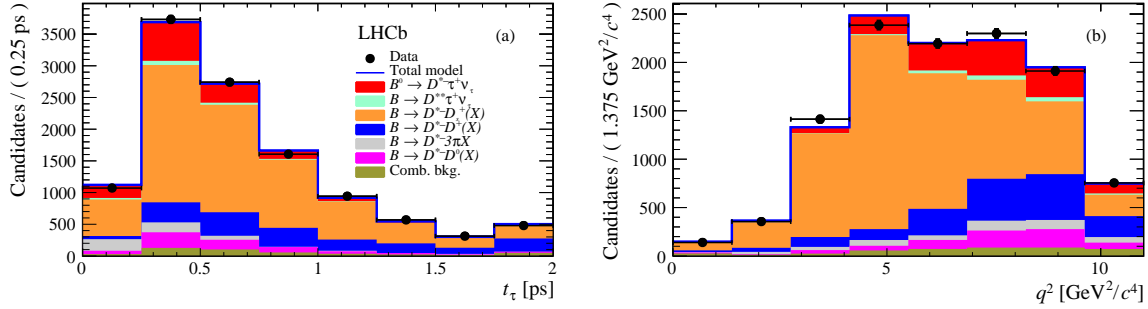
Figure 2. (Colours online) The distributions of the proper decay-time of the τ^+ candidate, t_τ, and q^2 variables from the hadronic $R(D^*)$ analysis [8]. Overlaid are the projections of the fit.

a three-dimensional binned template fit to the three kinematic variables q^2, m^2_{miss} and E^*_μ. Backgrounds arise from particles being mis-identified as a muon, random combinations of D^{*-} and μ^+ (referred to as combinatorial), $B \to D^{*-}X_c$ where X_c represents a charm hadron that decays semi-leptonically and $B \to D^{*-}\mu^+\nu_\mu X$, which is dominated by the $B \to D^{**}\mu^+\nu_\mu$ decays that are not well measured. The templates from the first two components can be taken from data using dedicated samples. For the signal, normalisation and other background components simulation was used.

The fitted value of $R(D^*)$ is

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030,$$

where the first uncertainty is statistical and the second systematic. Although the result appears to be limited by the systematic uncertainty the dominant contribution is the limited statistics of the simulation samples. This should be readily reducible such that one should expect the precision of $R(D^*)$ to continue improving in the future.

4. Hadronic $R(D^*)$

A further measurement of $R(D^*)$ has been made utilising the hadronic decay mode of the τ [7, 8]. In this case the signal and normalisation final states are not the same. Instead, the $B^0 \to D^{*-}\tau^+\nu_\tau$ branching fraction is normalised to the decay $B^0 \to D^{*-}\pi^+\pi^+\pi^-$ and an external measurement of the latter branching fraction is used to extract $R(D^*)$.

The sources of backgrounds for the hadronic mode are different to those from the muonic measurement. These include $B \to D^{*-}\pi^+\pi^+\pi^-X$ with the pions originating at the B vertex and $B \to D^{*-}X_c$ with the second charm hadron decaying to at least three pions. The former can be reduced by considering the displacement of the three π vertex from the B vertex. The latter is reduced by means of a Boosted Decision Tree (BDT) discriminant. The signal is extracted by means of a three-dimensional template fit to the variables q^2, the proper decay-time of the τ^+ candidate, t_τ, and the BDT discriminant. The fit projections are shown in Fig. 2.

The extracted value of $R(D^*)$ is

$$R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013,$$

where the first and second uncertainties are statistical and systematic. The third uncertainty arises from the $B^0 \to D^{*-}\pi^+\pi^+\pi^-$ branching fraction. This result is consistent with both the SM prediction and the experimental average. Again the dominant systematic uncertainty is due to the limited size of the simulation samples.

5. Muonic $R(J/\psi)$

Beyond $R(D)$ and $R(D^*)$ there are other ratios that merit investigation in order to understand the structure of the NP contributions. Different observables may be sensitive to different NP contributions. They will certainly also have different theoretical and experimental uncertainties and so provide an excellent check of existing measurements. To that end LHCb has measured the observable $R(J/\psi)$ defined as

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

with $\tau^+ \to \mu^+ \bar{\nu}_\tau \nu_\mu$ and $J/\psi \to \mu^+ \mu^-$ [11]. B_c^+ decays are unique to the LHC experiments as they cannot be studied at the B factories.

The analysis method is very similar to the other two measurements; the $R(J/\psi)$ observable is extracted by means of a three-dimensional binned template fit to the kinematic variables. In addition the B_c^+ proper decay-time was fitted in order to control backgrounds from mis-identified muons. Most of these will come from $B \to J/\psi X$ decays where the X is a hadron that has been mis-identified. As the B_c^+ is shorter lived than the B^0 and B^+ the proper decay-time offers some discriminating power.

The result of the fit is

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18,$$

where the first uncertainty is statistical, the second systematic. This result is about $2\,\sigma$ from the SM expectations of 0.25–0.28 [12–15] and represents the first evidence of the decay $B_c^+ \to J/\psi \tau^+ \nu_\tau$. As previously the dominating systematic uncertainty is due to the limited size of the simulation samples. There is also a significant source of uncertainty from the $B_c^+ \to J/\psi$ form-factors. There are lattice calculations underway so this source of uncertainty should be reduced in the future and the SM predictions will also become more precise.

6. Future prospects at LHCb

All of the analyses presented here were done using the $3\,\mathrm{fb}^{-1}$ of data collected during Run 1 of the LHC. It is expected that by the end of Run 2 in 2018 LHCb will have collected a further $6\,\mathrm{fb}^{-1}$. The yield of b hadrons per fb^{-1} is greater in Run 2 than Run 1 due to the increased production cross-section at the higher collision energy (7 and 8 TeV in Run 1, 13 TeV in Run 2) and some improvements in the trigger. Therefore one can reasonably expect that the decrease in the statistical uncertainties of the measured quantities will be greater than a naive scaling for integrated luminosities.

Beyond Run 2 the first upgrade to the LHCb detector [16] will be installed in the long shutdown two (LS2), commencing at the end of 2018. The upgraded detector will start collecting data in 2021 and it is envisaged that $50\,\mathrm{fb}^{-1}$ of integrated luminosity will be in hand by the end of LHC Run 4 (2030). Subsequently another upgrade of the detector is proposed [17] to fully take advantage of the HL-LHC and collect $300\,\mathrm{fb}^{-1}$ in total.

In order to improve the precision on the presented results it will be necessary to produce larger samples of simulation as this is already the dominating source of systematic uncertainty. Assuming this technical difficulty can be overcome then there is little to prevent the full exploitation of the expected large-yield data samples. Furthermore one can hope that in collaboration with the theory community LHCb will be able to make several new measurements in this area in order to further disentangle these anomalies.

7. Conclusions

Three tests of lepton universality in semi-leptonic b decays carried out by the LHCb collaboration have been described. The two measurements of $R(D^*)$ are consistent with the experimental average which shows a deviation from the SM prediction of approximately $3\,\sigma$ [9]. The measurement of $R(J/\psi)$ also suggests a tension with the SM although with lower significance. These were all made with the LHCb Run 1 dataset.

At the time of writing the LHC is coming to the end of its second data-taking period by which time LHCb will have in total $9\,\text{fb}^{-1}$ of data in hand. There is therefore much work to be done to analyse this large volume of data and shed further light on the lepton universality anomalies.

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