PROCEEDINGS OF SCIENCE

$b \to c$ status and prospects with focus on ratio observables

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Ratio observables ($R(H_c)$) are a benchmark to study Lepton Flavour Universality (LFU) in $b \to c$ transitions. The status and prospects of these measurements are presented, along with related studies on these transitions.

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1. Introduction

The Standard Model (SM) of particle physics organises leptons and quarks in three families or generations, distinguished only by their masses. The SM assumes that the couplings between leptons and the electroweak gauge bosons (Z^0, $W^\pm$) are independent of the generation. This property is known as Lepton Flavour Universality (LFU). Many new physics (NP) scenarios foresee LFU-violating processes, involving mostly the third generation [1].

2. Status of ratio observables

In order to test LFU, one interesting observable is the ratio of branching fractions of decays involving leptons from different generations $R(H_c)$, defined as

$$R(H_c) = \frac{BR(H_b \to H_c \tau^- \bar{\nu}_\tau)}{BR(H_b \to H_c \mu^- \bar{\nu}_\mu)}, \qquad \text{where} \quad H_c = D^*, D^+, J/\psi, \ldots \quad \text{and} \quad H_b = B^\pm, B^0, B_c^+. \tag{1}$$

In the SM, $R(H_c)$ deviates from unity, due to the different lepton masses. The experimental measurements of $R(D)$ and $R(D^*)$ show some tensions from the expected values, $\sim 1.4\sigma$ and $\sim 2.5\sigma$ respectively [2]. The combined $R(D)$ and $R(D^*)$ measurements show an overall tension of about 3.08σ, as shown in Fig. 1 [2].

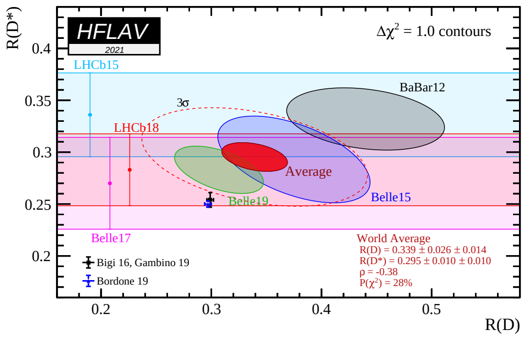

Figure 1: Average of the ratios and comparison with SM predictions [2]. Measurements of $R(D)$ and $R(D^*)$ performed by BaBar [3–6], Belle [7, 8] and LHCb [9–11]. The SM predictions are the black [12, 13] and blue [14] crosses, the simultaneous measurements are represented as ellipses while $R(D^*)$ only are vertical lines.

At the LHCb experiment [15], $b \to c\tau\nu$ processes have two main features. First of all, due to the design of the detector, it is not possible to estimate the neutrino momentum using the missing transverse energy. Secondly, the kinematical constraints used in B factories cannot be exploited in the reconstruction. In $R(H_c)$ analyses at LHCb, two different decay channels are considered to study the tau lepton: the muonic $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ and the hadronic $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ decay modes.

The majority of the measurements presented here, when not specified, are based on the LHCb Run I data sample, recorded with a centre-of-mass energy of 7 and 8 TeV, corresponding to an integrated luminosity of 3.0 fb^{-1}.

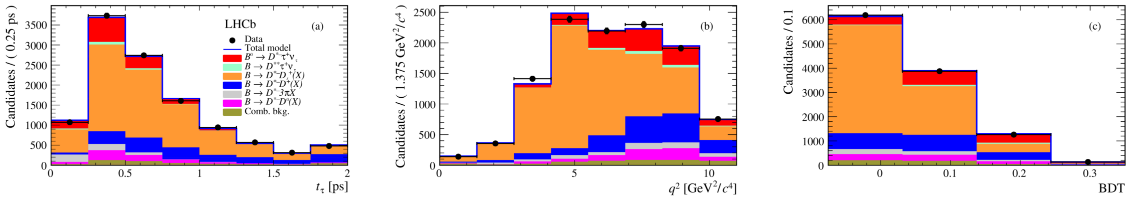

Figure 2: Fit projections [10, 11]. From left to right, distributions of the τ decay time t_τ, the tranfer momentum q^2 and the BDT output. The different components are represented with different colours (in orange $B^0 \to D^{*-}D_s^+(X)$).

2.1 Muonic $R(H_c)$ measurements

For muonic $R(H_c)$ measurements a kinematical approximation of the momentum is used [9, 16]. The first $R(D^*)$ measurement by LHCb was performed using the decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$, where the D^{*+} is reconstructed through the decay $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ [9]. The final result is $R(D^*) = 0.366 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$ [9].

A generalisation in the B_c^+ sector of this measurement is done by exploiting the decay $B_c^+ \to J/\psi\ell^+\nu_\ell$. The final result is $R(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$ [16]. The main systematic uncertainties are due to the size of the B_c^+ sample and the poor knowledge of the form factors involved in these semileptonic decays.

2.2 Hadronic $R(D^*)$ measurements

The first measurement of $R(D^*)$ using the 3-prong final state, $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$, in a hadronic collider has been published by LHCb [11]. The measured quantity is $K(D^{*-}) = BR(B^0 \to D^{*-}\tau^+\nu_\tau)/BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$. Thus, the same visible final state for the normalisation and the signal channel is exploited, so that systematic uncertainties cancel in the ratio.

In this way, $R(D^*)$ is obtained as $R(D^*) = K(D^{*-})\times\big(BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)/BR(B^0 \to D^{*-}\mu^+\nu_\mu)\big)$, where the branching fractions of $B^0 \to D^{*-}3\pi$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ are averages from external measurements.

The yield of the normalisation channel is obtained from an unbinned maximum likelihood fit to $M(D^{*-}\pi^+\pi^-\pi^+)$. The signal yield is extracted by performing a 3-dimensional fit to data, where the variables are the q^2, the τ decay time t_τ and the output of a multivariate classifier (BDT) (Fig. 2). The measured value is $R(D^*) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$ [10, 11].

3. Other $b \to c$ measurements

In order to have a better knowledge of the composition of the sample used in the $R(H_c)$ analyses, different studies have been performed.

Firstly, it is important to know the form factors (FF) shapes of the signal channels with high precision. The latest measurements of the FF shape of $b \to c$ transitions have been performed for the $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ [17] and the $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays, the latter at $\sqrt{s} = 13$ TeV (1.7 fb^{-1}) [18].

In addition to study the FF shapes of the signal decays, it is of great importance to study the background composition. The $B^0 \to D^{*-}D_s^+$ decay is an important contribution to the background in hadronic $B^0 \to D^{*-}\tau^+\nu_\tau$ analyses, because of the missing neutrals (γ or π^0) from the D_s^{*-}. An angular analysis of $B^0 \to D^{*-}D_s^+$ has been performed at 13 TeV (6 fb^{-1}) [19].

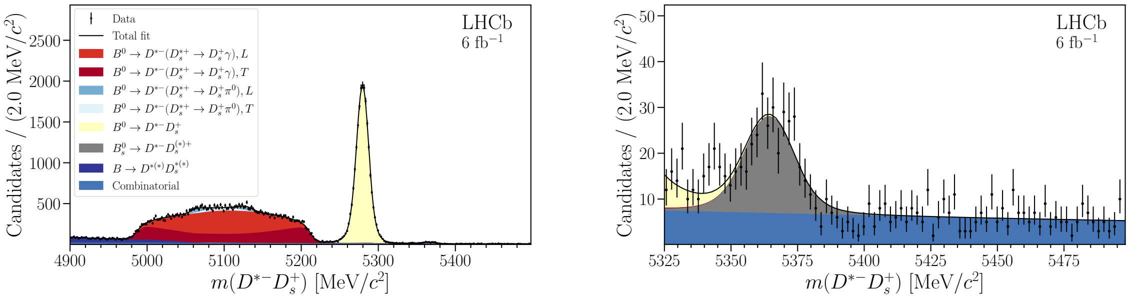

Figure 3: Distribution of $m(D^{*-}D_s^+)$ for selected candidates in data, with the fit overlaid. Right side: region for candidates with $m(D^{*-}D_s^+) > 5325$ MeV$/c^2$, where the $B_s^0 \to D^{*-}D_s^+$ contribution is visible [19].

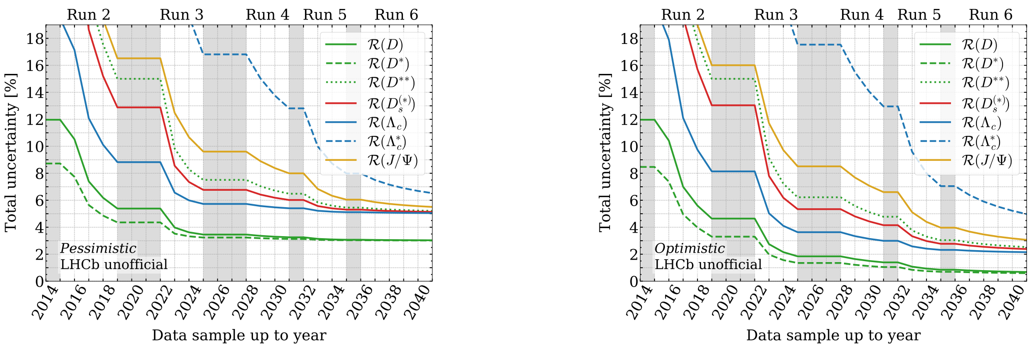

Figure 4: Expected precision on the measurement of $R(H_c)$ ratios at LHCb as a function of the year for two different scenarios. Left (right): expected irreducible systematic uncertainty of 3% (0.5%) on $R(D^{(*)})$ and 5% (2%) on the other ratios from [20].

The longitudinal polarisation fraction (f_L) and the branching ratios of the single components relative to $B^0 \to D^{*-}D_s^+$ are obtained by performing a fit to the invariant mass of the partially reconstructed $D^{*-}D_s^+$ system. Among these, the first observation of the Cabibbo-suppressed $B_s^0 \to D^{*-}D_s^+$ decay is presented, visible in the right side of Fig. 3, with a relative branching ratio of 0.049 ± 0.006 (stat) $\pm$ 0.003 (syst) $\pm$ 0.002 (ext). The helicity amplitudes and phases of $B^0 \to D^{*-}D_s^+$ are then obtained from a maximum-likelihood fit to the three-dimensional angular distribution of the fully reconstructed $D^{*-}D_s^+$ sample.

4. Conclusions and future prospects

The experimental results on the combination of $R(D)$ and $R(D^*)$ show a discrepancy with respect to the SM of ~ 3.1 standard deviations. As shown in Fig. 4, the uncertainties in ratio measurements are expected to improve for different reasons. Firstly, statistical uncertainties and data driven systematics will be reduced by the use of the complete LHCb data sample (9 fb^{-1}). Moreover, FF parameters measurements give fundamental inputs to future measurements of ratio observables. Finally, measuring the composition of specific $b \to c$ transitions, such as $B_s^0 \to D^{*-}D_s^+$ [19], is fundamental in reducing background model systematics.

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