Tests of Lepton Universality at LHCb

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Abstract

In this report, measurements of the ratios of branching fractions $R_K = \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)$ and $R(D^*) = \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$, as well as preliminary upper limits on the $B_{(s)}^0 \rightarrow \tau^+ \tau^-$ branching fractions are presented, using proton–proton collision data corresponding to an integrated luminosity of 3.0 fb^{-1} recorded by the LHCb experiment during 2011 and 2012. The value of R_K is measured to be $0.745^{+0.090}_{-0.074} (\text{stat}) \pm 0.036 (\text{syst})$, $R(D^*)$ equals $0.336 \pm 0.027 (\text{stat}) \pm 0.030 (\text{syst})$, and at 95% confidence level $\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 3.0 \times 10^{-3}$ and $\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 1.3 \times 10^{-3}$. The results for R_K and $R(D^*)$ are respectively -2.6 and $+2.1$ standard deviations away from the values expected from lepton universality of the Standard Model.

Keywords: Lepton flavour universality, B physics, Rare decays

1. Introduction

In the Standard Model (SM), the couplings between the gauge bosons and the three lepton families are flavour-independent. Global analyses of the recently observed tensions in $b \rightarrow s \ell \ell$ transitions using the effective field theory framework (see for example Ref. [1], among others), however, hint towards possible lepton flavour non-universal effects. Tests of lepton flavour universality violation (LUV), and in particular those involving the third generation leptons, are therefore both promising and powerful probes to search for physics beyond the SM.

This report presents the measurements of the ratios of branching fractions R_K [2] and $R(D^*)$ [3], as well as preliminary upper limits on the $B_{(s)}^0 \rightarrow \tau^+ \tau^-$ branching fractions [4]. All three analyses are performed using proton–proton collision data corresponding to an integrated luminosity of 3.0 fb^{-1} collected by the LHCb detector in 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV, respectively. The LHCb detector, described in detail in Refs. [5, 6], is a single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks.

2. LUV ratio test R_K

The $B^+ \rightarrow K^+ \ell^+ \ell^-$ decay, where ℓ represents either an electron or muon, is a flavour-changing neutral current process. In the SM, it can only proceed through suppressed loop diagrams, and the ratio of branching fractions between the electronic and muonic final states,

$$R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}, \quad (1)$$

is predicted to be unity within an uncertainty of 10^{-4} [7]. But certain extensions of the SM, like models involving a Z' boson or leptoquarks, need not couple equally to electrons and muons, thus leading to a value of R_K that is different from one.

LHCb has determined the value of R_K using the relative branching fractions of the decay channels $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^+ \rightarrow J/\psi (\rightarrow \ell^+ \ell^-) K^+$. This has the advantage that potential sources of systematic uncertainty cancel between the $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^+ \rightarrow J/\psi (\rightarrow \ell^+ \ell^-) K^+$ decays. The resulting ratio of branching fraction ratios is measured in the region

$$1 < q^2 < 6 \text{ GeV}^2/c^4, \quad (2)$$

where q^2 is the momentum transfer to the lepton system. This range is both experimentally and theoretically attractive as it excludes the $B^+ \rightarrow \psi(nS)K^+$ resonances, and precise theoretical predictions are possible.

The value of R_K is measured to be [2]

$$R_K = 0.745_{-0.074}^{+0.090} (\text{stat}) \pm 0.036 (\text{syst}), \quad (3)$$

which is 2.6 standard deviations below the expectation from lepton universality. It will be interesting to update this analysis adding the LHC Run 2 dataset.

3. LUV ratio test $R(D^*)$

The ratio of branching fractions

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)} \quad (4)$$

offers a test of lepton flavour universality involving the third family. In the SM, this ratio differs from unity due to phase-space effects caused by the different masses of the tau and muon. Owing to the cancellation of most of the uncertainties associated with the strong interaction in the B to D^* transition, the ratio can be predicted with high precision to be [8]

$$R(D^*) = 0.252 \pm 0.003. \quad (5)$$

The ratio $R(D^*)$ is determined from a combined measurement of the $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ and $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ decays, in which the tau candidates are reconstructed in the leptonic $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ mode and the D^* meson is reconstructed through the decay chain $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+$. They thus produce identical visible final-state topologies, which is advantageous to cancel potential sources of systematic uncertainty but challenging to separate both signals in the data.

The $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ signal is distinguished from the dominant $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ normalisation mode by exploiting the kinematic differences between both decays in the rest frame of the B meson. The most discriminating kinematic variables, computed in the B rest frame, are: the missing mass $m_{\text{miss}}^2 = (p_B^\mu - p_{D^*}^\mu - p_\mu^\mu)^2$, the muon energy E_μ^* , and the four momentum transfer $q^2 = (p_B^\mu - p_{D^*}^\mu)^2$ to the lepton system. Here p_B^μ , $p_{D^*}^\mu$, and p_μ^μ are the four-momenta of respectively the B meson, the D^{*+} meson and the muon. The determination of the rest-frame variables requires knowledge of the B candidate momentum vector in the laboratory frame, which is estimated from the reconstructed final-state particles: The B momentum direction is determined from the unit vector pointing from the primary interaction vertex to the

B decay vertex. The component of the B momentum along the beam axis is approximated using the relation $(p_B)_z = \frac{m_B}{m_{\text{reco}}}(p_{\text{reco}})_z$, where m_B is the known B mass, and m_{reco} and p_{reco} are the mass and momentum of the system of reconstructed particles, respectively.

The number of $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ and $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ candidates is determined from a three-dimensional template fit to the above listed kinematic variables. The templates extend over the kinematic region $-2 < m_{\text{miss}}^2 < 10 \text{ GeV}^2/c^4$ in 40 bins, $100 < E_\mu^* < 2500 \text{ MeV}$ in 30 bins, and $-0.4 < q^2 < 12.6 \text{ GeV}^2/c^4$ in 4 bins. The list of background sources include: combinatorial background, background from hadrons misidentified as muons, feed-down from $B \rightarrow D^{*+} \ell \nu$ decays, where D^{*+} represents a list of higher mass D resonances, and contributions from b -hadron decays to two charm hadrons. The shape of these background distributions as well as some of their yields are obtained by combining information from simulation with dedicated control regions in data. These control regions are constructed by inverting some of the selection requirements to enhance specific background contributions. Finally, the form factor parameters needed to describe the semileptonic decay channels, both signal and background, are included in the likelihood as nuisance parameters.

The fit finds $363\,000 \pm 1600$ $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ candidates in the signal sample and a ratio of yields

$$\frac{N(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{N(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)} = (4.54 \pm 0.46) \times 10^{-2}, \quad (6)$$

where the uncertainties are statistical only. For the high- q^2 bin, the result of the template fit is shown in Fig. 1.

Including efficiency corrections and systematic uncertainties, the value of $R(D^*)$ is measured to be [3]

$$R(D^*) = 0.336 \pm 0.027 (\text{stat}) \pm 0.030 (\text{syst}), \quad (7)$$

which is 2.1 standard deviations above the SM expectation, and in good agreement with results from the BaBar [9] and Belle [10, 11, 12] experiments. A combined analysis [13] of the $R(D)$ and $R(D^*)$ measurements differs from the SM expectation by 3.9 standard deviations.

4. Search for the rare decays $B_{(s)}^0 \rightarrow \tau^+ \tau^-$

The time-integrated $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ branching fractions have recently been measured by the LHCb and CMS experiments [14]. Comparing equivalent measurements of the $B_{(s)}^0 \rightarrow \tau^+ \tau^-$ branching fractions to the SM predictions [15], $\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) = (2.22 \pm 0.19) \times 10^{-8}$ and

Figure 1: Distributions of m_{miss}^2 (top) and E_μ^* (bottom) of the most sensitive q^2 bin of the signal data, overlaid with projections of the fit model with all normalisation and shape parameters at their best-fit values.

$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) = (7.73 \pm 0.49) \times 10^{-7}$, would therefore provide another test of lepton flavour universality involving the third family.

LHCb has performed a search for the rare decays $B_{(s)}^0 \rightarrow \tau^+ \tau^-$, where both τ leptons are reconstructed in the hadronic $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$ mode. The analysis exploits the intermediate resonances of the $\tau^- \rightarrow a_1^-(1260) \nu_\tau \rightarrow \rho^0(770) \pi^- \nu_\tau$ decay chain to define three subsamples according to the oppositely-charged two-pion invariant masses of each τ candidate, $m_{\pi_1^+ \pi_2^-}$ and $m_{\pi_3^+ \pi_2^-}$. The $(m_{\pi_1^+ \pi_2^-}, m_{\pi_3^+ \pi_2^-})$ plane is divided into nine sectors, as illustrated in Fig. 2. The signal region consists of candidates with both τ leptons in sector 5. The background region is defined as candidates having at least one τ lepton in sector 1, 3, 7 or 9. The control region corresponds to candidates with one τ lepton in sector 4, 5 or 8 and the other in sector 4 or 8. The signal selection is based on a two-stage neural network (NN) classifier using kinematic and topological variables. It is trained

Figure 2: Distribution of simulated $B_s^0 \rightarrow \tau^+ \tau^-$ candidates in the $m_{\pi_3^+ \pi_2^-} - m_{\pi_1^+ \pi_2^-}$ plane. The vertical and horizontal lines show region boundaries.

using simulated signal events and the background region from data. After the selection, the signal, background, and control regions contain 17, 11 and 55% of the simulated signal candidates, respectively. The corresponding fractions in data are 4.8, 44, and 41%. Most of the signal decays thus fall into the control region, but the signal region, which contains about 10 000 candidates in data after the full selection, is the most sensitive due to the low background contamination.

The signal yield is obtained from a binned maximum likelihood fit to a NN output, in which the signal model is taken from the $B_{(s)}^0 \rightarrow \tau^+ \tau^-$ simulation while the background model is taken from the data control region, subtracting the signal contribution. The fit model can be written as:

$$\text{NN}_{\text{data}}^{\text{SR}} = s \times \widehat{\text{NN}}_{\text{sim}}^{\text{SR}} + f_b \times \left(\text{NN}_{\text{data}}^{\text{CR}} - s \cdot \frac{\epsilon^{\text{CR}}}{\epsilon^{\text{SR}}} \widehat{\text{NN}}_{\text{sim}}^{\text{CR}} \right) \quad (8)$$

where $\text{NN}_{\text{sim/data}}^{\text{SR}}$ ($\text{NN}_{\text{sim/data}}^{\text{CR}}$) is the NN distribution in the signal (control) region from simulation/data, s is the signal yield, f_b is the scale factor for the background template, and ϵ^{SR} (ϵ^{CR}) is the signal efficiency in the signal (control) region. The $\widehat{}$ represents normalised distributions. The result of the fit to data [4] is shown in Fig. 3 and gives a signal yield $s = -46 \pm 51$, consistent with the background-only hypothesis.

The signal yield s obtained from the likelihood fit is normalised using the decay $B^0 \rightarrow D^+ D_s^-$ with $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s^- \rightarrow K^+ K^- \pi^-$ in order to convert it into a branching fraction

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) = \alpha^s \cdot s. \quad (9)$$

Figure 3: Distribution of the NN output in the signal region (points), overlaid data with the total fit result and the background component. The signal template can not be shown as it has a negative yield.

The normalisation factor α^s takes into account the ratio of selection efficiencies between both decay channels, as well as the observed number of $B^0 \rightarrow D^+ D_s^-$ candidates in data, and the different branching fractions for the intermediate resonances. For $B_s^0 \rightarrow \tau^+ \tau^-$, the normalisation factor has a value $\alpha^s = (3.16 \pm 0.43) \times 10^{-5}$, whereas for $B^0 \rightarrow \tau^+ \tau^-$, the value is $\alpha^d = (0.94 \pm 0.16) \times 10^{-5}$.

Since no signal excess is observed in the data, an upper limit on the $B_{(s)}^0 \rightarrow \tau^+ \tau^-$ branching fractions is calculated using the CLs method [16, 17]. Assuming the signal is fully dominated by B_s^0 decays, the limit is [4]

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 2.4 (3.0) \times 10^{-3} \text{ at } 90 (95)\% \text{ C.L.} . \quad (10)$$

Alternatively, assuming the signal is fully dominated by B^0 decays, the limit is [4]

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 1.0 (1.3) \times 10^{-3} \text{ at } 90 (95)\% \text{ C.L.} . \quad (11)$$

which is a factor four improvement over the previous limit from the BaBar experiment [18].

These limits are dependent on the $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$ decay model used in simulation, which is based on EVTGEN [19] and tuned to CLEO data. Other models, based on other CLEO [20] or BaBar [21] data are also available, but for the moment they are not implemented within the LHCb simulation framework. Further studies to understand the effects associated with the τ -decay modelling are ongoing.

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