Rare decays and tests of lepton universality at LHCb

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Summary. — Recent studies on the semileptonic decays of heavy-quark hadrons at the LHCb experiment are presented. The excellent LHCb physics reach allows to study the meson and baryon decays, probe very rare transitions, and perform tests of lepton universality.

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1. – Introduction

Decays of hadrons containing heavy quarks (charm or beauty) allow to perform precision studies of the dynamics of the fundamental interactions. While in the Standard Model (SM) the decays with a quark-flavour change occur only through the weak interaction, in the scenarios beyond the SM (BSM) there might be new interactions at play. The large mass of the heavy-quark hadrons allows for hundreds of decay modes, with their relative rates (branching fractions) ranging from a few percent for the processes occurring at the tree-level, down to very rare processes occurring less than once per billion decays. There often is a pair of leptons produced in such decays. A pair of a charged lepton l^- and (anti-)neutrino $\bar{\nu}_\ell$ is produced at tree level in the SM through the W-boson exchange, in the processes where the heavy quark performs a charge-changing transition such as $b \to c$. A pair of oppositely-charged leptons of the same flavour can be produced in the transitions where the heavy quark transforms into a quark of the same electric charge (neutral-current transition). However, such flavour-changing neutral-current transitions cannot occur at the tree level in the SM. One way this can happen is through a cascade of several tree-level transitions, such as $b \to c \to s$, where the intermediate quark bounds into a vector meson that can decay in two leptons. The other way is through higher-order processes with a virtual loop: *penguin* or *box* diagrams. The loop processes are rare within the SM, with the typical rate of 10^{-6} and below, and are considered to offer a powerful laboratory for searches of beyond-the-SM interactions that might potentially be present in the loop. These rare processes can be distinguished from the tree-level cascades by selecting the appropriate regions of dilepton invariant-mass squared, q^2.

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This document discusses the recent progress on decays of heavy-flavour hadrons at the LHCb experiment, focusing mainly on the rare decays involving quark-level $b \to s\ell\ell$ and $c \to u\ell\ell$ transitions, and not-so-rare decays involving $b \to c\ell\nu$ transitions. The LHCb detector at the Large Hadron Collider is described in detail elsewhere [1, 2], it has collected about $9 fb^{-1}$ of proton-proton collision data at the center-of-mass energies of 7, 8 and 13 TeV during 2011-2018. Unless specified otherwise, all the results presented below use this complete LHCb dataset.

2. – Purely leptonic decays

The annihilation of a meson into a pair of leptons is one of the cleanest processes from both experimental and theoretical points of view. The decay $B_s^0 \to \mu^+\mu^-$ occurs through the loop-level $b \to s\mu^+\mu^-$ transition. Furthermore, such a decay of a spin-zero meson into two fermion receives a helicity suppression, with the decay rate being proportional to the lepton mass squared. This makes the rate of this decay very low. The hunt for experimental observation of this decay has spanned over decades, and this was only achieved at the LHC. The latest LHCb result [3, 4] finds $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}(\text{stat.})^{+0.15}_{-0.11}(\text{syst.})) \times 10^{-9}$, which is the most precise measurement to date and agrees with the SM prediction of $(3.66 \pm 0.14) \times 10^{-9}$ [5].

The process $B^0 \to \mu^+\mu^-$, governed by the loop-level $b \to d\mu^+\mu^-$ transition, is about two orders of magnitude more rare, as the element V_{td} of the quark-mixing CKM matrix is smaller than the V_{ts}. On the other hand, the production rate of B^0 mesons at LHCb is about factor four larger compared to that of the B_s^0 mesons. The significant challenge is however to control the rates of backgrounds from $B^0_{(s)} \to h^+h'^-$, where h^+ and h'^- are kaons or pions, misidentified as muons. Such processes have a rate much larger compared to that of the dimuon decay, which requires a sub-percent control of hadron-to-muon misidentification. The intrinsic experimental challenge is that kaons and pions can decay to muons within the volume of the LHCb detector. No significant $B^0 \to \mu^+\mu^-$ signal is found, and the upper limit set at 2.6×10^{-10} at 95% confidence level (CL).

The process $B_s^0 \to \mu^+\mu^-\gamma$ is an interesting sibling [3, 6]. The photon might be emitted from the initial-state quarks or final-state leptons, and it introduces a suppression in the rate proportional to the electromagnetic coupling constant α. However, the initial-state radiation turns a two-body decay into a three-body and effectively lifts the helicity suppression. The expected SM rate of this process is about 10^{-8}. While the direct search for this decay is challenging due to specifics of photon reconstruction, such an indirect search for it in a lower sideband of the $B_s^0 \to \mu^+\mu^-$ peak (with the photon not reconstructed in experiment) has found no significant signal at LHCb. It should however be noted that such indirect search is only sensitive to the events where the photon is soft, and these results are not trivial to extrapolate to the generic case.

One step further is the process $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$, which has the same underlying mechanism as $B_s^0 \to \mu^+\mu^-\gamma$, with the photon being virtual and transforming into a dimuon pair [7]. The rate of this process is further suppressed in the SM, but can be enhanced in the BSM models, with pair production of new resonances decaying to dimuons [9]. In the SM, one can reach this final state also through the resonant process such as $B_s^0 \to J/\psi\phi$ with both J/ψ and ϕ decaying in two muons. The clean signal of this decay is shown in Fig. 1 (left), and is used as a normalisation channel for the subsequent studies. The nonresonant four-muon decay can be probed once the resonances such as J/ψ, $\psi(2S)$ or ϕ are vetoed in each opposite-sign dimuon combination. As shown in Fig. 1 (right), no significant signal is observed, and the upper limits are set at $10^{-10}(10^{-9})$ level for the $B^0(B_s^0)$ mode.

In addition, the first search was performed for the decays $B_s^0 \to J/\psi\mu^+\mu^-$, with the J/ψ decaying to a dimuon. This decay has the same four-muon final state, but a different physics mechanism: it proceeds through the W-exchange between the quark lines, with the virtual-photon emission from the initial-state radiation. No significant signal was seen, with the upper limits set at the 10^{-9} level for both B^0 and B_s^0 decays. In the past, LHCb has also performed a search for the decay $B_{(s)}^0 \to J/\psi\gamma$ with an on-shell photon, with the upper limit set at the 10^{-6} level [8]. One can see that the experimental sensitivity is much stronger for the fully-charged final state.

Finally, a theoretical model predicting existence of a new neutral particle a with a mass about 1 GeV decaying to two muons [9], has been tested. No signal was found in the channel $B_{(s)}^0 \to aa$ with $a \to \mu^+\mu^-$.

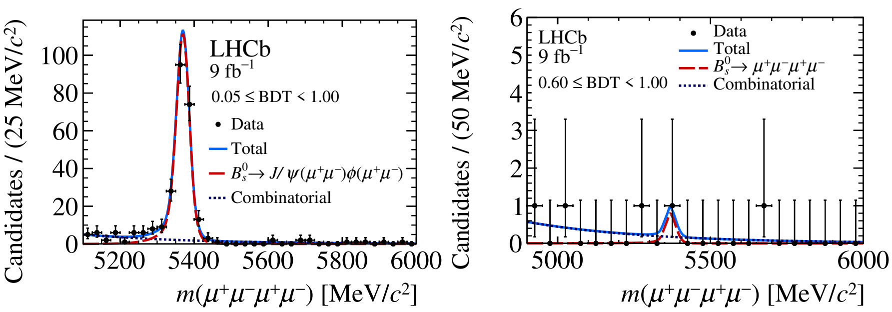

Fig. 1. – Distributions of the four-muon invariant mass. Left: with the dimuons originating from the J/ψ and ϕ resonances. Right: with the nonresonant dimuons. Taken from Ref. [7].

3. – Decays to the $\phi\mu^+\mu^-$ final state

The decay $B_s^0 \to \phi\mu\mu$ with $\phi \to K^+K^-$ offers a clean experimental probe of the $b \to s\mu^+\mu^-$ transitions. The narrow width of the ϕ resonance, as well as the fact that the partially-reconstructed backgrounds of a kind $B_s^0 \to \phi\pi^0\mu\mu$ are suppressed by the isospin conservation, makes the background in this channel low.

LHCb measured the differential branching fraction of this decay in Ref. [10], as shown in Fig. 2. The measured experimental values are consistently lower compared to the theoretical predictions. The most precise prediction is based on the combination of the lattice QCD and light-cone QCD sum rules approaches, as implemented in the `flavio` software package [11]; and it disagrees with the data at more than three standard deviations in the region $1.1 < q^2 < 6\,\mathrm{GeV}^2$. This picture needs clarification in the future with measurements from other experiments, and it should be checked if the theoretical uncertainties have not been underestimated. In addition, the angular analysis has been performed [12]. As the flavour of the initial meson was not tagged, it was not possible to distinguish the B_s^0 and $\overline{B_s^0}$ decays, thus only CP-averaged observables could be measured. The measured distributions of angular observables agree with the SM prediction (as per `flavio` package) at the level below two standard deviations.

The low background level allowed to also search for the decay $B^0 \to \phi\mu\mu$ in the lower sideband of the B_s^0 peak [13]. This decay proceeds through the W-exchange diagram with the initial-state radiation of the virtual photon transforming into a dimuon. In addition, it is suppressed as the ϕ meson must originate solely from the gluon lines. However, in the models with the large mixing between the ϕ and ω mesons, this decay can have an additional contribution: the $d\bar{d}$ pair in the final state can be achieved by a CKM-suppressed $b \to d\mu^+\mu^-$ transition, and mix into the ϕ meson. Theoretically, this contribution is expected at the rate of about 10^{-10}. No significant signal was seen, and the upper limit is set at the 3.2×10^{-9} at 90% CL. A larger amount of data is therefore needed to test the theoretical prediction.

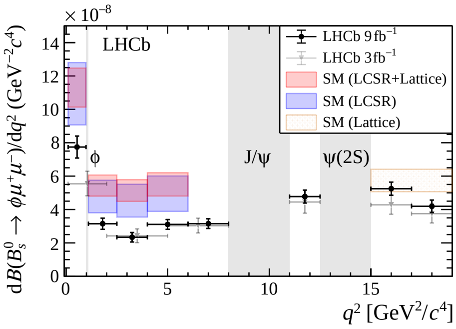

Fig. 2. – Differential branching fraction of the $B_s^0 \to \phi\mu^+\mu^-$ decay, measured by LHCb (black markers), compared to SM calculations with various methods (coloured boxes). From Ref. [10].

4. – Rare but charming

The rare $c \to u\mu^+\mu^-$ transition is a sibling of the $b \to s\mu^+\mu^-$. It is the only FCNC transition with the up-type quarks that can be studied with hadrons. Its phenomenology is quite different from the $b \to s\mu^+\mu^-$, as the nonresonant FCNC process is suppressed much more strongly. The decay rate is therefore dominated by the neutral resonances such as ρ, ω, ϕ in the dimuon spectrum. The resonant process interferes with the nonresonant one, and this interference effect is sensitive to the BSM contributions [14].

Experimentally, this effect is studied at LHCb with the $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ transitions [15]. The flavour of the initial meson is tagged by the $D^{*+} \to D^0\pi^+$ decay. This allows to perform the full angular analysis, as well as to determine the CP asymmetries. This is performed in bins of the q^2, with the bin ranges chosen to maximise the sensitivity to the interference effects. In the SM, all the studied observables are expected to be close to zero, which makes this measurement effectively a null-test of the SM. The global set of observables was found to be consistent with the SM expectation. However, curious trends with q^2 are seen in certain angular observables. With a larger dataset to be collected in the future, it will be possible to study this in better detail.

5. – Tests of lepton universality in $b \to s\ell^+\ell^-$ transitions

In SM interactions, the probabilities to produce charged leptons of different flavours, namely, electron, or muon, or tau lepton, only depend on the lepton masses [16]. This postulate is usually referred to as "lepton universality" (LU). While these leptons are equivalent with respect to the known interactions, except for the Higgs couplings, the LU might be violated in the potential BSM interactions. As the loop-level $b \to s\ell^+\ell^-$ transitions are sensitive to the possible BSM contributions, it is naturally interesting to probe the LU in these decays. This is performed by comparing the decay modes with two electrons and two muons in the final state; the modes with two tau leptons are experimentally challenging and have not been observed to date.

The final states with two muons and two electrons have considerably different reconstruction efficiencies at LHCb. While muons are easy to trigger, identify and reconstruct, electrons are more challenging. First, the electromagnetic calorimeter, that allows to trigger on electron signatures, has a high occupancy due to photons produced abundantly in π^0 decays at a hadron collider. This requires setting stringent energy thresholds and makes the trigger efficiency lower. Second, the low electron mass makes them prone to bremsstrahlung emission in interactions with the detector material. This worsens the momentum resolution and complicates the track reconstruction. To improve the experimental uncertainties arising from these differences between muons and electrons, a double-ratio approach is used at LHCb. This relies on a well-tested lepton universality of decays of the J/ψ meson to two leptons, which holds to a permille precision [17]. The LU ratios are then constructed as (on the example of $B^+ \to K^+\ell^+\ell^-$ decays): $R_{K^+} = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+J/\psi(\to\mu^+\mu^-))}\Big/\frac{\mathcal{B}(B^+\to K^+e^+e^-)}{\mathcal{B}(B^+\to K^+J/\psi(\to e^+e^-))}$.

The test of LU in the $B^+ \to K^+\ell^+\ell^-$ decays was performed in $1.1 < q^2 < 6\,\mathrm{GeV}^2$, and the value of $R_{K^+} = 0.846^{+0.042}_{-0.039}(\mathrm{stat.})^{+0.013}_{-0.012}(\mathrm{syst.})$ was found, which is about three standard deviations below the SM prediction of unity [18]. While the $B^+ \to K^+\ell^+\ell^-$ channel offers the best statistical sensitivity among all $b \to s\ell^+\ell^-$ transitions, it is worth exploring further decay modes. In particular, its isospin partner is studied at LHCb, $B^0 \to K^0_S\ell^+\ell^-$ [19]. It has a worse sensitivity: first, the K^0_S eigenstate amounts to only half of the produced K^0 mesons, while the other half (K^0_L) cannot be reconstructed efficiently at LHCb. Second, the K^0_S is long-lived and can decay outside the LHCb acceptance. Finally, it is reconstructed in its decay mode to $\pi^+\pi^-$, which has a branching fraction of only about 69%. The reconstruction of the K^0_S meson decays can be performed in two ways. If it decays early enough, the pions are produced inside the Vertex Locator of LHCb, and form *long tracks* with the information from both Vertex Locator and downstream tracking stations. If the K^0_S lives longer, it may still be reconstructed from the hits in the downstream tracking stations, with pions forming *downstream tracks*. While these two categories have different vertex and mass resolution on the K^0_S candidate, the resolution on the invariant mass of the B meson is very similar between the two, being mostly driven by the resolution on the lepton momenta. Therefore, the two categories are merged in the final analysis. The mass distributions of the observed $K^0_S\mu^+\mu^-$ and $K^0_Se^+e^-$ decays are shown in Fig. 3. The worse resolution in the electron case requires a wider fit range and modeling of the additional background components. In particular, the partially reconstructed backgrounds from the excited kaon states, as well as the bremsstrahlung-induced tail of the $B^0 \to K^0_SJ/\psi(e^+e^-)$ decays are included. The small contribution of misidentified $B^0 \to K^0_S\pi^+\pi^-$ decays is estimated from the subset of data with inverted electron identification requirements, and added to the fit.

As a result, the value of $R_{K^0_S} = 0.66^{+0.20}_{-0.14}(\mathrm{stat.})^{+0.02}_{-0.04}(\mathrm{syst.})$ is obtained, which is about 1.5 standard deviations below unity. In addition, a similar measurement is performed with the $B^+ \to K^{*+}\ell^+\ell^-$, with $K^{*+} \to K^0_S\pi^+$; where the result $R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\mathrm{stat.})^{+0.03}_{-0.04}(\mathrm{syst.})$ is about 1.4 standard deviations below unity. Although these measurements form a consistent picture with the R_{K^+}, their precision is worse, and more data needs to be collected to clarify the LU picture. It should be noted that the decays $B^0 \to K^0_Se^+e^-$ and $B^+ \to K^{*+}e^+e^-$ are observed for the first time with the significance exceeding five standard deviations.

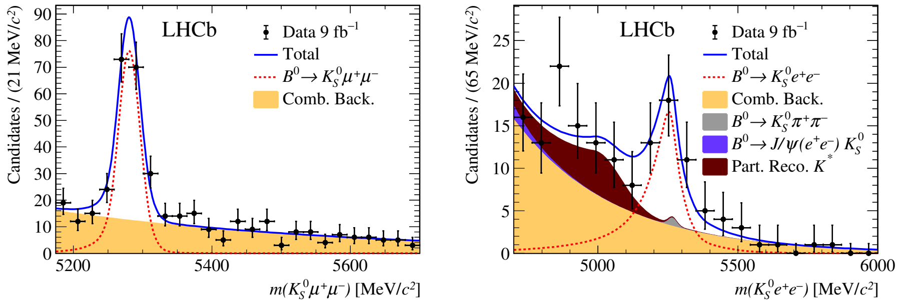

Fig. 3. – Distributions of the $K^0_S\mu^+\mu^-$ (left) and $K^0_S e^+e^-$ (right) invariant masses, with the fit components overlaid, in $1.1 < q^2 < 6\,\mathrm{GeV}^2$. Taken from Ref. [19].

6. – Tests of lepton universality in tree-level decays

The tree-level $b \to c\ell^-\bar{\nu}_\ell$ transitions offer another laboratory for testing the LU in heavy-flavour decays. Here, the possible BSM contributions could manifest themselves at the tree level. While in the ratios of decay channels with muons and electrons large BSM effects are not observed [20], the ratios of the channels with the tau leptons and light leptons are more curious. Although the SM rate of these decays is large, the experimental challenges are severe. In the channels $b \to c\ell^-\bar{\nu}_\ell$, the neutrino is not reconstructed. This leads to lack of a narrow invariant-mass peak, which means that a precision control and modeling of all possible backgrounds is required in order to obtain a reliable estimate of the signal yield. The situation is more difficult for the $b \to c\tau\bar{\nu}_\tau$ channels: the τ lepton decays can be reconstructed at LHCb in either leptonic decays to muon and two neutrinos, or hadronic decays to multiple pions and one neutrino.

The overview of the recent anomalies in the LU ratios between the $b \to c\tau\bar{\nu}_\tau$ and $b \to c\mu\bar{\nu}_\mu$ decays can be found in Refs. [16, 21]. All the measurements to date have been performed in decays of B mesons, and all have significant systematic uncertainties, related to the modeling of signal and background distributions in experiment.

The b baryons offer a complementary approach to testing the LU, as they show partly orthogonal experimental and theoretical challenges. Most interesting experimentally is the case of the Λ^0_b baryon (quark content udb) decays, as this baryon is produced abundantly at the LHC [22]. The spin 1/2 of the b baryons compared to spin 0 of the b mesons offers complementarity not only in calculation of hadronic form-factors, but also in sensitivity to specific BSM scenarios. In addition, on the experimental side, the isospin zero of the Λ^0_b baryon makes certain background modes suppressed. While the LU has been tested in the baryonic $b \to s\ell^+\ell^-$ transitions [23] and charm-baryon decays [24], there has been no experimental LU tests to date in the baryonic $b \to c\ell^-\bar{\nu}_\ell$ transitions.

Recently, the LHCb has published an observation of the $\Lambda^0_b \to \Lambda^+_c\tau^-\bar{\nu}_\tau$ decay with its dataset collected at the center-of-mass energies of 7 and 8 TeV [25]. The tau leptons are reconstructed in their hadronic decays to $\pi^+\pi^-\pi^-(\pi^0)\nu_\tau$; while the Λ^+_c baryon is reconstructed via its decay to $pK^-\pi^+$. The background from $\Lambda^0_b \to \Lambda^+_c\pi^+\pi^-\pi^-X$ decays is suppressed by requiring the significant displacement of the τ decay vertex from the Λ^+_c decay vertex in the projection on the beam axis. In order to control the background from double-charm decays such as $\Lambda^0_b \to \Lambda^+_c D^-_s$ with $D^-_s \to \pi^+\pi^-\pi^-$, the dynamics of the three-pion system is used. In particular, in the τ decays the majority of the decays to three pions happen via an intermediate chain of resonances $\tau^- \to a_1^- \nu_\tau; a_1^- \to \rho^0\pi^-$. In the D_s^- decays, other resonances play a role; this allows to develop a multivariate selection to suppress this type of background. Finally, the background due to random track combinations can originate from either $pK^-\pi^+$ combinations that do not originate from a real Λ_c^+; or the real Λ_c^+ candidates combined with a random pions. The first type can be parametrised using the sidebands of the Λ_c^+ mass peak, while the second – using the unphysical combinations of the Λ_c^+ with same-charge pion tracks. Having reconstructed the positions of the decay vertices of the τ, Λ_c^+ and Λ_b^0, it is possible to approximate the pseudo-decay-time of the tau lepton, and the invariant mass of the $\tau\nu$ system. A simultaneous template fit is then performed to these two observables, as well as to the output of the multivariate classifier trained against the D_s^- background. The fit components include the signal $\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau$, various types of double-charm background, as well as the combinatorial background. The component due to $\Lambda_b^0 \to \Lambda_c^{*+}\tau^-\bar{\nu}_\tau$ is constrained in the fit by its expected proportion to the signal yield.

The $\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau$ decay is observed for the first time with about 350 signal events. To measure its branching fraction, the $\Lambda_b^0 \to \Lambda_c^+\pi\pi\pi$ decay is used, which shares the same visible final state. Using the known value of the $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ [17], one obtains the value of the $R_{\Lambda_c^+} \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)$ equal to $0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{external})$. This has to be compared to the SM prediction of the 0.324 ± 0.004 [26]. One should note that in this case, the prediction is far from unity, due to the large mass of the tau lepton compared to the muon mass, which restricts severely the allowed phase-space in the $\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau$ decay. The uncertainty on this experimental result is clearly driven by the external inputs – knowledge of the branching fractions of the Λ_b^0 decays. This underlines the challenges in the baryonic physics, where a lot of gaps need to be filled by measuring precisely the rates of numerous decay channels.

7. – Summary

Studies of the weak decays of heavy-flavour hadrons into semileptonic and leptonic final states offer potential to search for the BSM effects indirectly – via its impact on the decay rates or angular observables. This is complementary to the direct searches performed at the energy frontier. While hints for BSM effects exist in the current LHCb data, none of the observables has crossed the 5σ criterion to claim the observation of BSM physics. It is important to not only collect more data in the future years, but also to explore the additional decay modes. In particular, baryonic decays offer complementary challenges compared to the meson decays, and should be explored more actively. As the b baryons cannot kinematically be produced in the experiments that use the $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ process, the LHC is a crucial playground for these developments. The other promising direction is to explore the decays with multiple leptons in the final state. However, larger datasets need to be collected in order to probe the tiny rate expected for these decays in the Standard Model.

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