Tests of lepton flavour universality at LHCb

A. Buonaura on behalf of the LHCb collaboration
Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich
E-mail: `annarita.buonaura@cern.ch`

Abstract. In the Standard Model the three charged leptons are identical copies of each other, apart from mass differences, and the electroweak coupling of the gauge bosons to leptons is expected to be independent of the flavour. This prediction is called lepton flavour universality (LFU) and is well tested in tree-level decays; any violation of LFU would be a clear sign of physics beyond the Standard Model. Experimental tests of LFU in semileptonic decays of b hadrons and in rare b decays are highly sensitive to models of New Physics in which new, heavy particles couple preferentially to the 2nd and 3rd generations of leptons. Recent results from LHCb on LFU in semileptonic $b \to c\ell\nu$ transitions and rare $b \to s\ell\ell$ decays are discussed.

1. Introduction

The Standard Model (SM) is the most validated theory describing the fundamental constituents of Nature. It contains three generations of quarks and leptons which can only be distinguished by their different masses. It is assumed that the three generations of leptons have identical couplings to the electroweak Gauge bosons ($Z^0, W^{\pm}$). This is what is referred to as *Lepton Flavour Universality (LFU)*. Tests of LFU are a probe of the validity of the SM itself, since the LFU symmetry can be violated in many New Physics (NP) scenarios which also foresee a stronger coupling of the NP particles with the third generation of quarks and leptons [1–6].

The Large Hadron Collider beauty (LHCb) experiment [7] is an excellent place to search for indirect evidences of NP studying the decays of bottom hadrons. It is a single-arm forward spectrometer covering the pseudorapidity range $2.0 < \eta < 5.0$, designed for the study of particles containing charm and bottom quarks. The $b(\bar{b})$ quarks are produced with a large forward boost, hence the corresponding hadrons travel for ≈ 1 cm before decaying. LHCbs excellent vertex resolution allows to distinguish between the proton interaction vertex and the beauty hadron vertex.

Two interesting sets of measurements that can be carried out to probe violation of LFU are reviewed in this contribution. The first involves Flavour Changing Charged Current (FCCC) $b \to c\ell^-\bar{\nu}_\ell$, where $\ell = \mu, \tau$, commonly referred to as *semileptonic decays*. These are tree level processes with a branching fraction of the order of a few percent and they are sensitive to NP up to the scale of 1 TeV [8]. The second class of measurements involves Flavour Changing Neutral Current (FCNC) $b \to s\ell^+\ell^-$ transitions, with $\ell = e, \mu$. FCNC processes are not allowed at tree level in the SM, but can occur only at loop level with branching fractions ranging from $10^{-6} \div 10^{-7}$ [9] (hence the name *rare decays*) and are highly sensitive to virtual particles and interactions which mediate the transition from the b to the s quark. Rare decays are sensitive to new physics up to a scale of 100 TeV [8, 10].

All measurements presented here are based on the whole LHC Run I data sample recorded by the LHCb experiment, with center-of-mass energies of 7 and 8 TeV and an integrated luminosity of 3.0 fb^{-1}.

2. Lepton Flavour Universality violation searches in semileptonic b decays

The observable of interest for these types of processes is the ratio:

$$R(X) = \frac{BR(B \to X\tau\bar{\nu}_\tau)}{BR(B \to X\mu\bar{\nu}_\mu)}, \qquad \text{with: } X = D, D^*, J/\psi. \tag{1}$$

The ratio is expected to differ from unity only due the non negligible mass difference between muons and taus. However recent measurements performed by BaBar [11, 12], Belle [13, 14] and LHCb [15–17] show an excess with respect to the most recently calculated SM predictions for $R(D)$ and $R(D^*)$ with a significance of 2.3σ and 3.0σ respectively. The combined $R(D)$ and $R(D^*)$ measurements [18] show an overall tension with the SM prediction of 3.8σ [19–22] (see Fig. 1).

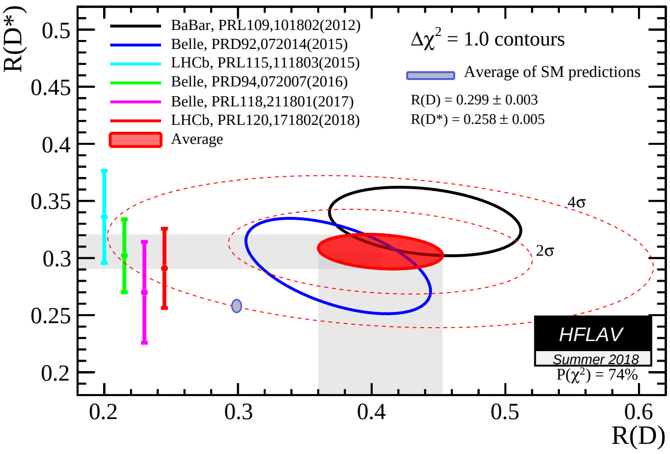

Figure 1. Measurements of the ratios $R(D)$ and $R(D^*)$ for B-factories (Belle, BaBar) and the LHCb experiment. The ellipses are simultaneous measurements of $R(D)$ and $R(D^*)$ while the vertical measurements are only $R(D^*)$. The discrepancy between the combination of all measurements and the SM predictions is around 3.8σ.

2.1. $R(D^*)$ muonic

The first measurement of $R(D^*)$ performed at LHCb [15], exploits $B \to D^*\tau$ decays where the τ is reconstructed in the $\mu^-\bar{\nu}_\mu\nu_\tau$ decay channel ($BR(\tau \to \mu^-\bar{\nu}_\mu\nu_\tau) = 17.39 \pm 0.04\%$ [9]), while the D^{*+} is reconstructed to the $D^0(\to K^-\pi^-)\pi^+$ final state. The signal and the normalisation channels share the exact same visible final state, hence a common procedure can be applied to select candidates belonging to both channels.

The separation of the two channels, as well as from all the other background processes, is achieved exploiting the distinct kinematic distributions of the decay modes. These result from the difference in mass between the τ and μ leptons and the presence of extra neutrinos in the signal final state. The most discriminating variables are the muon energy, E^*_μ, the squared missing mass, $m^2_{miss} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$ and the squared four-momentum transfer to the lepton system, q^2, evaluated in an approximated $\bar{B}^0$ rest frame. On these variables a three-dimensional binned template fit was performed, using template distributions derived from control samples and from simulation validated against data. The main background sources considered are: partially reconstructed decays (i.e. decays to higher D^* and D^{**} resonances, and decays to pairs of charm hadrons), combinatorial background (i.e. candidates from combinations of unrelated muons and D^* hadrons produced from different decays) and misidentification background (candidates where the muon is a misidentified hadron). The results of the fit are shown in Fig. 2 for a specific q^2 bin.

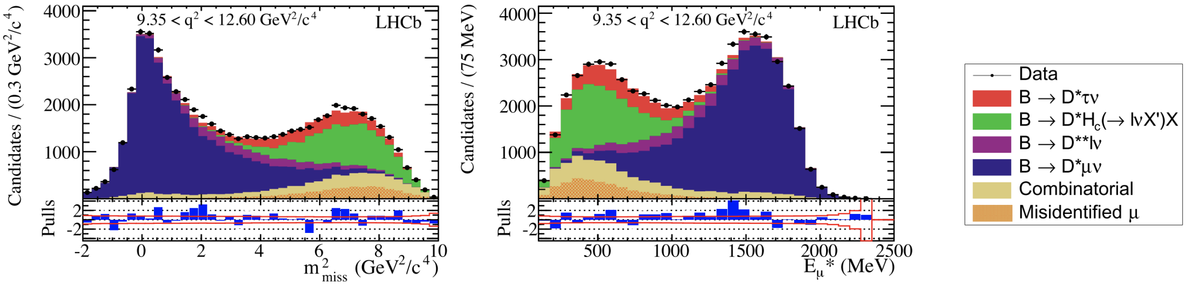

Figure 2. Distributions of m^2_{miss} (left) and E^*_μ (right) in the q^2 bin between 9.35 and 12.60 GeV^2/c^4 [15]. The data points are in black. The different colours represent the different fit components. The lower panels show the difference between the data and the fit, normalised by the Poisson uncertainty in the data. The red bands give the 1σ template uncertainties.

The value of $R(D^*)$ is found to be $0.336 \pm 0.027 \pm 0.030$, where the first uncertainty is statistical and the second one is systematic. This result, representing the first measurement of b-hadron decays to τ at a hadron collider, exceeds the SM prediction by 1.9 standard deviations.

2.2. $R(D^*)$ hadronic

A subsequent measurement of $R(D^*)$ from LHCb uses hadronic τ decays ($\tau \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$) [16, 17]. As for $R(D^*)$ muonic, the D^{*-} meson is reconstructed through the $D^{*-} \to \bar{D}^0(\to K^+\pi^-)\pi^-$ decay. In order to reduce experimental systematic uncertainties, the normalisation channel is chosen to be $B^0 \to D^{*-}\pi^+\pi^-\pi^+$. Defining $K(D^*)$ as the ratio of branching fractions of the signal and normalisation channel, the value of $R(D^*)$ is obtained as:

$$R(D^*) \equiv K(D^*) \times \frac{BR(B^0 \to D^{*-}3\pi)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}, \tag{2}$$

where $BR(B^0 \to D^{*-}3\pi)$ is the weighted average of the measurements in reference [23–25] and $BR(B^0 \to D^{*-}\mu^+\nu_\mu)$ is taken from reference [26].

The use of the 3-prong decay of the τ allows to reconstruct the τ decay vertex, and this is an important tool to discriminate signal from background events. As a matter of fact, prompt decays of a b-hadron in the system $D^*3\pi$ plus any other unreconstructed particle, X, can be discriminated with respect to signal events (where the 3π system is originated by the τ decay) requiring the position of the 3π vertex to lie further away from the proton-proton interaction vertex than that of the B^0.

The other major source of background is represented by double charm $B \to D^{*-}D_s^+(X)$ decays (B stands for B^0, B^+ or B_s^0) and is suppressed by means of a multivariate algorithm (BDT) [27] exploiting the differences in the decay dynamics of the three-pion system generated by the decay of the D_s^+ with respect to the one from the τ decay.

The yield of the normalisation mode is extracted from a fit around the known B^0 mass of the invariant mass distribution of the $D^*3\pi$ system for candidates in the normalisation sample. The signal yield is obtained from a three-dimensional binned fit to the data where the fit variables are q^2, the lifetime of the τ (t_τ) and the output of the BDT (Fig. 3).

The measured value of $R(D^*)$ is found to be 0.291±0.019(stat)±0.026(syst)±0.013(ext), where the last uncertainty is due to the external input branching fractions. This result is compatible within 1σ with the SM prediction.

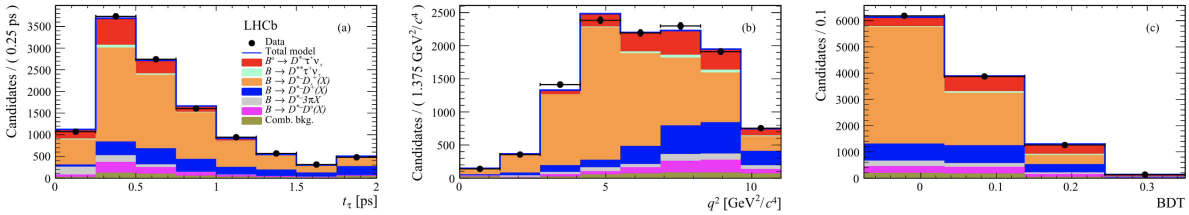

Figure 3. Fitted distributions of the lifetime of the τ (left), of q^2 (centre) and of the BDT output (left). The different fit components are represented with different colors.

2.3. $R(J/\psi)$

To investigate the sources of theoretical and experimental uncertainties plus the potential origin of the LFU violation, it is of great importance to investigate semitauonic decays of other species of B hadrons, such as the B_c meson. The abundance of B_c hadrons produced in LHCb has made possible to perform the measurement of $R(J/\psi)$ [28].

The signal and normalisation modes share again the same visible final state, hence they are selected with a common procedure and are later discriminated through a tridimensional fit as done for the previously described R observables. This time the fit variables used are: m^2_{miss}, the B_c^+ decay time (τ) and a categorical quantity z representing 8 bins in (E^*, q^2). The measured value of $R(J/\psi)$ is $0.71 \pm 0.017 \pm 0.018$, again exceeding as $R(D)$ and $R(D^*)$ by 2σ the SM prediction $R(J/\psi)_{SM} \in [0.25, 0.28]$ [29–32].

3. Lepton Flavour Universality violation searches in rare b-decays

In $b \to s\ell^+\ell^-$ processes, one interesting observable to search for LFU violation is:

$$R(H_s) = \frac{BR(B \to H_s\mu^+\mu^-)}{BR(B \to H_s e^+e^-)} \qquad \text{where: } B = B^+, B^0 \text{ and: } H_s = K^+, K^{*0} \tag{3}$$

The SM predictions for these ratios of branching fractions is 1 with an uncertainty of the order of 1% [33].

The bremsstrahlung emission and the trigger efficiency are different for electrons and muons, hence the experimental uncertainties of the decays in eq. 3 do not cancel effectively. This motivated the computation of $R(H_s)$ as a double ratio to the corresponding more abundant resonant mode $B \to H_s J/\psi$ where the J/ψ decays to either a muon or an electron pair. Thanks to the topological similarity between the non-resonant and resonant modes, the systematic uncertainties related to the differences in the reconstruction of electron and muon tracks largely cancel. Hence, the definition given in Eq. 3 modifies:

$$R(H_s) = \frac{BR(B \to H_s\mu^+\mu^-)}{BR(B \to H_s J/\psi(\to \mu^+\mu^-))} / \frac{BR(H_s \to H_s e^+e^-)}{BR(B \to H_s J/\psi(\to e^+e^-))} \tag{4}$$

3.1. R(K)*

The measurement of this observable exploits the decay $B^0 \to K^{*0}\ell^+\ell^-$ [34]. The K^{*0} is reconstructed through its decay into a kaon and a pion ($K^{*0} \to K\pi$), by selecting those candidates lying in a 100 MeV/c^2 window around the $K^*(892)$ mass. The K^{*0} meson and the $\ell^+\ell^-$ pair are required to originate from a common vertex in order to form a B^0 candidate.

Two separate bins of q^2 have been considered for the measurement: $q^2 \in [0.045, 1.1]$ GeV^2 (low q^2 region) and $q^2 \in [1.1, 6]$ GeV^2 (central q^2 region) being sensitive to different NP. The signal yields are obtained using unbinned maximum-likelihood fits to the reconstructed B^0 mass of the selected candidates in each q^2 interval, for each lepton type and for both rare and resonant modes (Fig. 4).

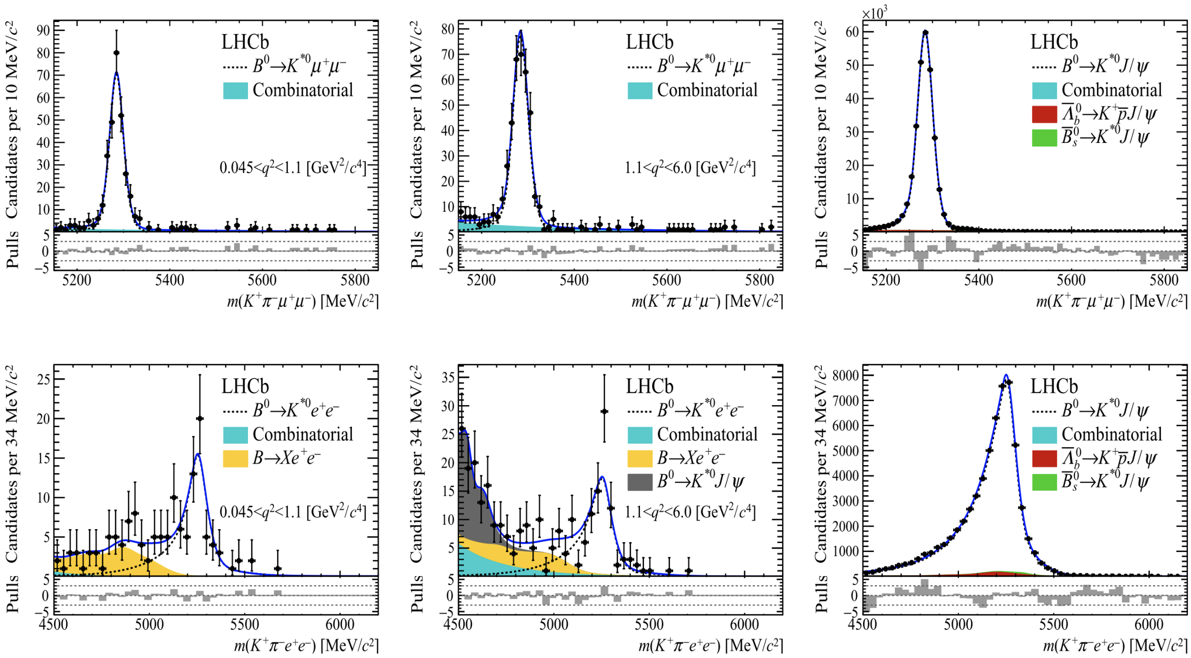

Figure 4. (Top) Reconstructed B^0 invariant mass in the muonic channel for $B^0 \to K^{*0}\mu^+\mu^-$ in the (left) low-q^2 region and in the (centre) central one and reconstructed B^0 invariant mass for $B^0 \to K^{*0}J/\psi$ (right). (Bottom): Same for the electronic channel.

The measured values of $R(K^*)$ are:

$$R(K^*) = 0.66^{+0.11}_{-0.07} \pm 0.03 \qquad \text{low-}q^2 \text{ bin} \tag{5}$$

$$R(K^*) = 0.69^{+0.11}_{-0.07} \pm 0.05 \qquad \text{central-}q^2 \text{ bin} \tag{6}$$

which deviate by 2.2 and 2.4σ from the SM prediction respectively.

3.2. R(K)

The decays used to measure $R(K)$ are of the type $B^+ \to K^+\ell^+\ell^-$ [35]. For this measurement only the central-q^2 bin ($q^2 \in [1.0, 6.0]$ GeV^2/c^4) is used. The analysis procedure is very similar to the one described for $R(K^*)$. The measured value of $R(K)$ is found to be $0.745^{+0.090}_{-0.074} \pm 0.036$ and it shows a discrepancy of 2.6σ with respect to the SM prediction.

3.3. Global fits to $b \to s\ell^+\ell^-$ transitions

The effective NP hamiltonian used to describe the $b \to s\ell^+\ell^-$ transitions, depends on the so-called Wilson coefficients C_l^i [36–38]. Using the measured values of $R(K)$ and $R(K^*)$ together with other observables from $b \to s\ell^+\ell^-$ transitions, it is possible to perform a global analysis to constrain the Wilson coefficients. Fig. 5 [10] shows the best fit value obtained for C_9^μ and C_{10}^μ considering LFU observables ($R(K)$, $R(K^*)$ and differences in angular observables performed at Belle). The tension with respect to the SM hypothesis is of approximately 4σ and it further increases when measurements from all the $b \to s\mu^+\mu^-$ observables are taken into account.

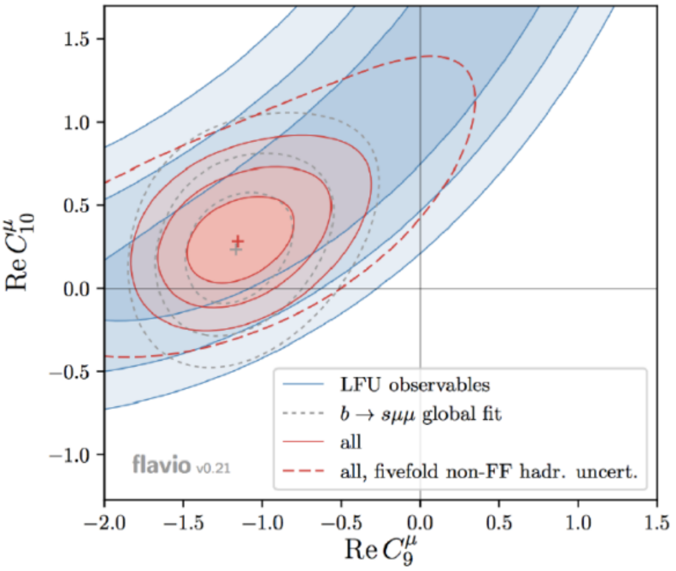

Figure 5. C_9^μ and C_{10}^μ Wilson coefficient allowed regions. The remaining parameters are assumed to be SM-like [10]

4. Conclusions

Tests of lepton universality are excellent ways to look for New Physics in a complementary way to the direct searches performed at the ATLAS and CMS experiments. So far, using B-meson decays, intriguing deviations with respect to the SM predictions have been observed. For $R(D)$ and $R(D^*)$, measurements performed by LHCb, BaBar, and Belle show an overall tension with the SM prediction of 3.8 standard deviations. Discrepancies with respect to the values predicted by the SM have also been found in measurements involving $b \to s\ell^+\ell^-$ transitions: $R(K)$, $R(K^*)$.

All presented results are based on Run I data. Efforts to update these measurement using the full Run II samples are currently ongoing. To better shed light on the nature of the observed anomalies, other measurements in different channels are also being carried out.

References

[1] Buttazzo D, Greljo A, Isidori G and Marzocca D 2017 *JHEP* **11** 044 (*Preprint* `1706.07808`)
[2] Wei M and Chong-Xing Y 2017 *Phys. Rev.* **D95** 035040 (*Preprint* `1702.01255`)
[3] Bauer M and Neubert M 2016 *Phys. Rev. Lett.* **116** 141802 (*Preprint* `1511.01900`)
[4] Greljo A, Isidori G and Marzocca D 2015 *JHEP* **07** 142 (*Preprint* `1506.01705`)
[5] Barbieri R and Tesi A 2018 *Eur. Phys. J.* **C78** 193 (*Preprint* `1712.06844`)
[6] Bordone M, Cornella C, Fuentes-Martin J and Isidori G 2018 *Phys. Lett.* **B779** 317–323 (*Preprint* `1712.01368`)

[7] Alves Jr A A *et al.* (LHCb) 2008 *JINST* **3** S08005
[8] Di Luzio L and Nardecchia M 2017 *Eur. Phys. J.* **C77** 536 (*Preprint* `1706.01868`)
[9] Tanabashi M e a (Particle Data Group) 2018 *Phys. Rev. D* **98**(3) 030001 URL `https://link.aps.org/doi/10.1103/PhysRevD.98.030001`
[10] Altmannshofer W, Stangl P and Straub D M 2017 *Phys. Rev.* **D96** 055008 (*Preprint* `1704.05435`)
[11] Kowalewski B (BaBar) 2013 *J. Phys. Conf. Ser.* **455** 012039
[12] Lees J P *et al.* (BaBar) 2013 *Phys. Rev.* **D88** 072012 (*Preprint* `1303.0571`)
[13] Huschle M *et al.* (Belle) 2015 *Phys. Rev.* **D92** 072014 (*Preprint* `1507.03233`)
[14] Sato Y *et al.* (Belle) 2016 *Phys. Rev.* **D94** 072007 (*Preprint* `1607.07923`)
[15] Aaij R *et al.* (LHCb) 2015 *Phys. Rev. Lett.* **115** 111803 [Erratum: Phys. Rev. Lett.115,no.15,159901(2015)] (*Preprint* `1506.08614`)
[16] Aaij R *et al.* (LHCb) 2018 *Phys. Rev. Lett.* **120** 171802 (*Preprint* `1708.08856`)
[17] Aaij R *et al.* (LHCb) 2018 *Phys. Rev.* **D97** 072013 (*Preprint* `1711.02505`)
[18] Amhis Y *et al.* (Heavy Flavor Averaging Group) 2017 *Eur. Phys. J.* **C77** 895 updated results and plots available at https://hflav.web.cern.ch (*Preprint* `1612.07233`)
[19] Bigi D and Gambino P 2016 *Phys. Rev.* **D94** 094008 (*Preprint* `1606.08030`)
[20] Bernlochner F U, Ligeti Z, Papucci M and Robinson D J 2017 *Phys. Rev.* **D95** 115008 [erratum: Phys. Rev.D97,no.5,059902(2018)] (*Preprint* `1703.05330`)
[21] Bigi D, Gambino P and Schacht S 2017 *JHEP* **11** 061 (*Preprint* `1707.09509`)
[22] Jaiswal S, Nandi S and Patra S K 2017 *JHEP* **12** 060 (*Preprint* `1707.09977`)
[23] Aaij R *et al.* (LHCb) 2013 *Phys. Rev.* **D87** 092001 (*Preprint* `1303.6861`)
[24] Lees J P *et al.* (BaBar) 2016 *Phys. Rev.* **D94** 091101 (*Preprint* `1609.06802`)
[25] Majumder G *et al.* (Belle) 2004 *Phys. Rev.* **D70** 111103 (*Preprint* `hep-ex/0409008`)
[26] Amhis Y *et al.* (HFLAV) 2017 *Eur. Phys. J.* **C77** 895 (*Preprint* `1612.07233`)
[27] Breiman L, Friedman J H, Olshen R A and Stone C J 1984 *Classification and Regression Trees* Statistics/Probability Series (Belmont, California, U.S.A.: Wadsworth Publishing Company)
[28] Aaij R *et al.* (LHCb) 2018 *Phys. Rev. Lett.* **120** 121801 (*Preprint* `1711.05623`)
[29] Anisimov A Yu, Narodetsky I M, Semay C and Silvestre-Brac B 1999 *Phys. Lett.* **B452** 129–136 (*Preprint* `hep-ph/9812514`)
[30] Kiselev V V 2002 Exclusive decays and lifetime of B_c meson in QCD sum rules unpublished (*Preprint* `hep-ph/0211021`)
[31] Ivanov M A, Korner J G and Santorelli P 2006 *Phys. Rev.* **D73** 054024 (*Preprint* `hep-ph/0602050`)
[32] Hernández E, Nieves J and Verde-Velasco J M 2006 *Phys. Rev. D* **74**(7) 074008
[33] Bordone M, Isidori G and Pattori A 2016 *Eur. Phys. J.* **C76** 440 (*Preprint* `1605.07633`)
[34] Aaij R *et al.* (LHCb) 2017 *JHEP* **08** 055 (*Preprint* `1705.05802`)
[35] Aaij R *et al.* (LHCb) 2014 *Phys. Rev. Lett.* **113** 151601 (*Preprint* `1406.6482`)
[36] Descotes-Genon S, Hofer L, Matias J and Virto J 2016 *JHEP* **06** 092 (*Preprint* `1510.04239`)
[37] Hurth T, Mahmoudi F and Neshatpour S 2016 *Nucl. Phys.* **B909** 737–777 (*Preprint* `1603.00865`)
[38] Capdevila B, Crivellin A, Descotes-Genon S, Matias J and Virto J 2018 *JHEP* **01** 093 (*Preprint* `1704.05340`)