

1 Lepton-flavour universality tests at LHCb

2 MARTA CALVI ON BEHALF OF THE LHCb COLLABORATION

3 *Università di Milano Bicocca and INFN - Milano, Italy*

Summary. — The Standard Model predictions about the universality of the gauge boson couplings to charged leptons have been tested in B meson semileptonic decays. Several measurements of charged-current and neutral current processes were performed with a data sample collected with the LHCb detector in proton-proton collisions at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1} . This review presents recent results that manifest some anomalies challenging the SM paradigm. Prospects for future measurements to elucidate the origin of these anomalies are also discussed.

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5 1. – Introduction

6 The lepton flavour universality (LFU) of the electroweak couplings of the gauge boson
 7 to the charged leptons is an accidental symmetry of the Standard Model (SM) that is
 8 broken only by the Yukawa interaction. Differences among the semileptonic decays to
 9 electrons, muons or tau leptons should come only from their different masses. On the
 10 contrary, New Physics (NP) might couple differently to different lepton families. Hints of
 11 deviations from the SM predictions of LFU, emerging from measurements at the $\Upsilon(4S)$
 12 and from LHCb, as will be discussed in this report, have triggered a series of theoretical
 13 speculations about possible New Physics (NP) interpretation [3].

14 The measurements presented here employ a data sample collected in Run 1 with the
 15 LHCb detector, in proton-proton (pp) collisions at centre-of-mass energies of 7 and 8 TeV
 16 corresponding to an integrated luminosity of 3 fb^{-1} . The LHCb detector is a forward
 17 spectrometer in the pseudorapidity range 2-5 that is described in detail elsewhere [4].
 18 Relevant to these measurements are its excellent performance in the reconstruction of
 19 the primary vertices of the pp interaction (PV) and of secondary vertices of heavy-hadron
 20 and tau decays, the resolution on the track momentum determination and the capability
 21 to identify electron and muon leptons, pion, kaon and proton hadrons.

2. – Charged current transitions

Semileptonic decays are an ideal laboratory to test the LFU ansatz. The decays are precisely described in the SM and the visible branching ratios are high. The test variable, called $\mathcal{R}(\text{H}_c)$, is defined as the ratio of the branching ratios

$$\mathcal{R}(\text{H}_c) \equiv \frac{\mathcal{B}(\bar{\text{B}}^0 \rightarrow \text{H}_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{\text{B}}^0 \rightarrow \text{H}_c^+ \ell^- \bar{\nu}_\ell)}$$

where H_c is a charmed hadron and ℓ represents a light lepton. Only muons are used in the current LHCb measurements. Experimental uncertainty related to selection efficiencies and theoretical uncertainty cancel in the ratio to a large extent.

BaBar and Belle experiments have measured both $\mathcal{R}(\text{D}^*)$ and $\mathcal{R}(\text{D})$ [1, 2], the averages of their results show a deviation from the SM expectation which assumes lepton universality [5], of about 3 and 2 sigmas, respectively.

A first measurement of $\mathcal{R}(\text{D}^*)$ at a hadron collider was performed by LHCb, reconstructing the tau in its muonic decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ [6]. In this case the signal $\bar{\text{B}}^0 \rightarrow \text{D}^{*+} \tau^- \bar{\nu}_\tau$ and the normalization $\bar{\text{B}}^0 \rightarrow \text{D}^{*+} \mu^- \bar{\nu}_\mu$ modes have the same visible final-state particles. A good separation between the two modes is achieved by considering three key kinematic observables, computed in the B rest frame: the muon energy, E_μ^* , the missing mass squared, calculated as $m_{\text{miss}}^2 = (p_B^\mu - p_{\text{D}^*}^\mu - p_\mu^\mu)^2$, and the squared four-momentum transfer to the lepton system $q^2 = (p_B^\mu - p_{\text{D}^*}^\mu)^2$, where p_B^μ , $p_{\text{D}^*}^\mu$ and p_μ^μ are the four-momenta of the $\bar{\text{B}}^0$ meson, the D^{*+} meson and the muon. The momentum of B mesons produced in hadronic collisions is unknown, and the exact determination of the B momentum in the laboratory frame from the reconstructed final state particles is not possible when one or more neutrinos are present in the decay. However, the momentum direction is well determined from the unit vector to the B decay vertex from the associated PV. The Lorentz boost of the B meson along the beam direction is approximated by the boost of the visible $(\text{D}^{*+} \mu)$ system with a resulting resolution on the rest-frame variables of approximately 15-20 %, that is sufficient to preserve the differences among the two decay modes. A binned maximum likelihood fit is performed to data, simultaneous on the three observables, with templates for signal, normalization and background channels derived from simulation and control data samples. The distributions of the three observables are shown in Fig. 1. The result

$$\mathcal{R}(\text{D}^*) = 0.336 \pm 0.027(\text{stat.}) \pm 0.030(\text{syst.})$$

is in good agreement with previous measurements [1, 2] and 2.1 standard deviations above the SM expectation.

A second measurement of $\mathcal{R}(\text{D}^*)$ is performed with an independent and complementary data sample, with the tau lepton reconstructed in the three-prong hadronic decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ [7]. The large background from hadronic B decays is highly suppressed exploiting the significant separation between the B and the tau decay vertices, measured along the beam direction, and the structure of the tau decay, which includes kinematic and geometrical variables and the presence of intermediate resonances. In order to reduce experimental systematic uncertainties a normalization decay mode with a

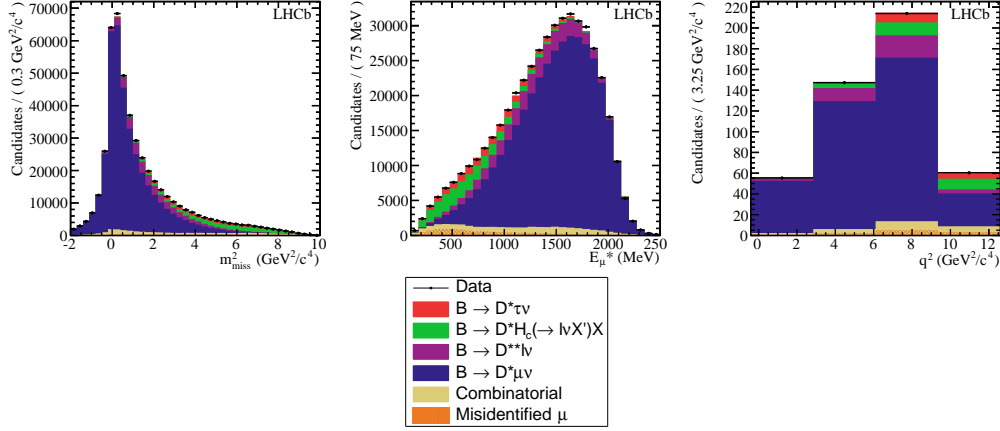


Fig. 1. – Distributions of (left) m_{miss}^2 , (middle) E_μ and q^2 of the selected candidates, overlaid with projections of the fit model with all normalization and shape parameters at their best-fit values.

similar final state is chosen, measuring $\mathcal{R}(D^*)$ from

$$\mathcal{K}(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} 3\pi)} = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{1}{\mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau)}$$

and

$$\mathcal{R}(D^*) = \mathcal{K}(D^*) \times \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} 3\pi)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}$$

where N_{sig} and ϵ_{sig} are the number of signal candidates and the total signal selection efficiency, and N_{norm} and ϵ_{norm} are the number of $\bar{B}^0 \rightarrow D^{*+} 3\pi$ candidates measured in the normalization sample and the corresponding selection efficiency. The values of the branching fractions for $\bar{B}^0 \rightarrow D^{*+} 3\pi$ and $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ are taken from references [9] and [10], respectively. More details on this measurement are presented in another talk at this Conference [8]. The result is

$$\mathcal{R}(D^*) = 0.291 \pm 0.019(\text{stat.}) \pm 0.026(\text{syst.}) \pm 0.013(\text{syst.}),$$

where the third uncertainty originates from the uncertainties on the external branching fractions. The value is compatible with the measurement in the muonic mode and with previous measurements. The average among the two LHCb measurements gives

$$\mathcal{R}(D^*) = 0.31 \pm 0.016(\text{stat.}) \pm 0.021(\text{syst.})$$

31 which is 2.2 standard deviations above the SM predictions.

32 The combination of all available measurements of $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$ which takes into
 33 account the correlation among the two observables, deviates from the SM prediction by
 34 4.1 sigmas.

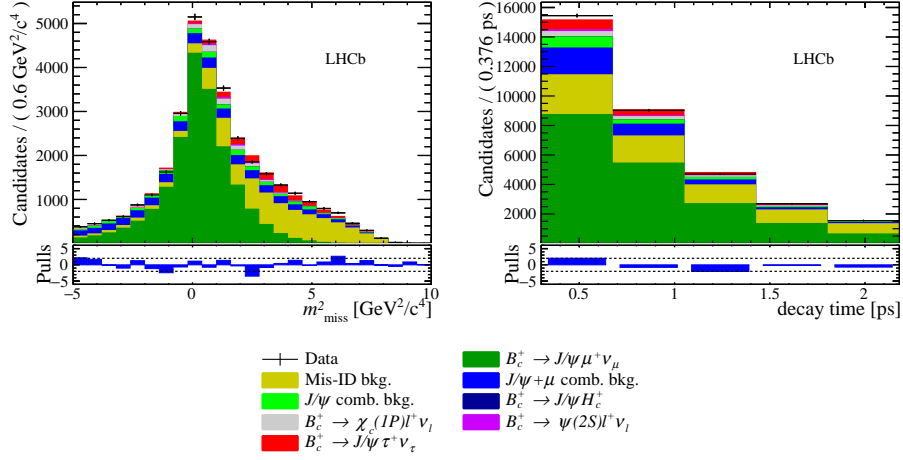


Fig. 2. – Distributions of (left) m_{miss}^2 and (right) decay time of the selected candidates, overlaid with projections of the fit model with all normalization and shape parameters at their best-fit values. Below each panel differences between the data and fit are shown, normalized by the Poisson uncertainty in the data; the dashed lines are at the values ± 2 .

It is important to understand the origin of this deviation with further measurements. Since all the available results refer to B meson decays, one direction to go is the test of LFU on decays of other types of b-hadrons. LHCb can take advantage of the copious B_c^- production in pp collisions to study the B_c^- counterpart of $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ that is $B_c^- \rightarrow J/\psi \tau^- \bar{\nu}_\tau$ [11]. Theoretical predictions for

$$\mathcal{R}(J/\psi) \equiv \frac{\mathcal{B}(B_c^- \rightarrow J/\psi \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B_c^- \rightarrow J/\psi \mu^- \bar{\nu}_\mu)}$$

are in the range 0.25-0.28 [12], the spread being due to uncertainties in the form factors, that have not been constrained experimentally yet. The tau lepton is reconstructed from its the muonic decay, and the J/ψ is reconstructed in $J/\psi \rightarrow \mu\mu$, yielding a three muon final state for both the signal and the normalization mode. A similar strategy as for the muonic $\mathcal{R}(D^*)$ measurement is followed, adding the tau decay time as a fourth fit observable. The time provides good separation of signal from background of semileptonic decays of lighter b-hadrons that have much longer lifetimes. The distributions of the missing mass squared and of the τ decay time are shown in Fig. 2. The measured value

$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\text{stat.}) \pm 0.18(\text{syst.})$$

is within 2 sigmas from the SM, again on the higher side.

Semileptonic decays of Λ_b baryons are under study at LHCb for a measurement of $\mathcal{R}(\Lambda_c^+) = \mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau) / \mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)$, that will test a decay with a different spin structure. The ratio $\mathcal{R}(\Lambda_c^{*+})$, with $\Lambda_c^{*+} \rightarrow \Lambda_c^+ \pi^+ \pi^-$, is another option, characterized by an additional secondary vertex in the experimental reconstruction and smaller feed-down from excited states, but miss the determination of the form factors. Other ongoing tests include the measurements of $\mathcal{R}(H_c)$ in $\bar{B}^0 \rightarrow D^- \mu^- \bar{\nu}_\mu$ or $\bar{B}_s^0 \rightarrow D_s^+ \mu^- \bar{\nu}_\mu$ decays.

Another direction for future measurement is the test of LFU in $b \rightarrow u\ell^-\nu$ transitions, instead of $b \rightarrow c\ell^-\nu$, to study the coupling of NP to a different quark family.

3. – Neutral current transitions

Flavour changing neutral currents are possible in the SM only at loop level, therefore $b \rightarrow s\ell^+\ell^-$ decays are suitable processes to unveil contributions of NP that can alter the rate of the process or change the angular distribution of final-state particles. For a test of LFU between the first and the second lepton families the ratio of branching ratios

$$\mathcal{R}_{K^{(*)}} = \frac{\mathcal{B}(B^0 \rightarrow K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B^0 \rightarrow K^{(*)}e^+e^-)}$$

is used. This is predicted in the SM to be unit with a permille precision, as hadronic effects largely cancel. The measurement of the decay rates is performed in different regions of the dilepton invariant mass squared, q^2 , that are sensitive to different type of NP contributions, outside charmonium resonances regions. Previous measurements of $\mathcal{R}_{K^{(*)}}$ performed at the $\Upsilon(4S)$ are consistent with the SM predictions, with a precision of 20-50 % [14, 15]. Larger data samples are available at LHCb, with excellent efficiency and momentum resolution in the muon decay mode, but lower efficiency and momentum resolution in the electron one, due to bremsstrahlung.

A measurement is performed using the 3 fb⁻¹ data sample of pp collisions [13]. The K^{*0} meson is reconstructed in the $K^+\pi^-$ final state, that is required to have an invariant mass within 100 MeV/ c^2 of the known $K^*(892)^0$ mass. Systematic uncertainties due to the different experimental efficiencies in the reconstruction of muons and electrons are reduced by measuring a double ratio, that normalize to the charmonium resonance mode

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(\mu\mu))} \times \frac{\mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(ee))}{\mathcal{B}(B^0 \rightarrow K^{*0}e^+e^-)}$$

A stringent test on the efficiencies is the check that the ratio of branching ratios in the resonance region is indeed consistent with unit, within one sigma, with a 4.5% precision. The invariant mass distributions of the selected candidates are shown in Fig. 3.

$\mathcal{R}_{K^{*0}}$ is measured to be $\mathcal{R}_{K^{*0}} = 0.66_{-0.07}^{+0.11}(\text{stat.}) \pm 0.03(\text{syst.})$ in the region $0.045 < q^2 < 1.1$ GeV²/ c^4 and $\mathcal{R}_{K^{*0}} = 0.69_{-0.07}^{+0.11}(\text{stat.}) \pm 0.05(\text{syst.})$ in the region $1.1 < q^2 < 6$ GeV²/ c^4 . These results are the most precise measurement of these quantity to date, statistically limited by the size of the electron sample. They are compatible with the SM expectations at the level of about 2.2 (2.4) sigmas in the low (high) q^2 region.

A similar measurement performed in the charged kaon decay modes $B^+ \rightarrow K^+\mu^+\mu^-$, $B^+ \rightarrow K^+e^+e^-$ [16] provided a similar result $\mathcal{R}_K = 0.745_{-0.074}^{+0.090}(\text{stat.}) \pm 0.036(\text{syst.})$ in the region $1.1 < q^2 < 6$ GeV²/ c^4 , 2.6 sigmas lower than the SM prediction that is of unit with $O(10^{-3})$ precision.

In conclusion LHCb is completing the analysis of Run 1 data on semileptonic B decays observing some deviations from the SM predictions that assume LFU. Other decay modes are under study and updates of current measurements exploiting Run 2 are foreseen in order to test the consistency of the anomalies and to allow test of NP models.

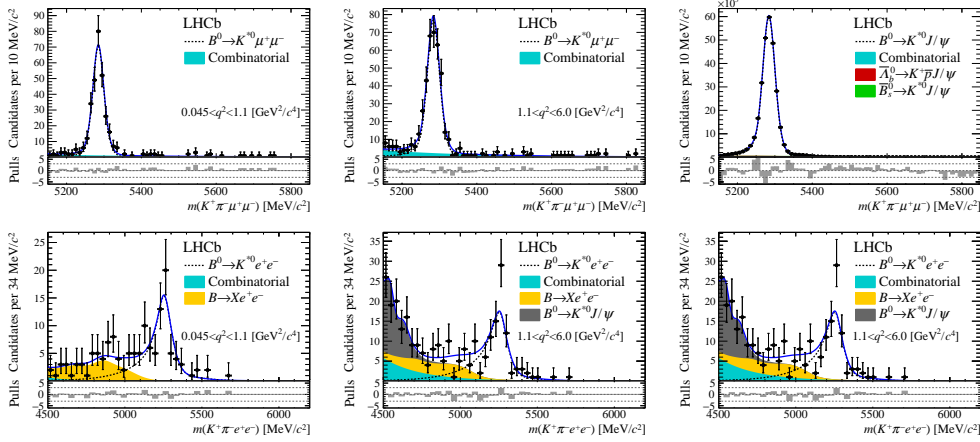


Fig. 3. – Top panel: fit to the $m(K^+\pi^-\mu^+\mu^-)$ invariant mass of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ in the (left) low- and (middle) central- q^2 bins and (right) of $B^0 \rightarrow K^{*0}J/\psi(\mu\mu)$ candidates. Bottom panel: fit to the $m(K^+\pi^-e^+e^-)$ invariant mass of $B^0 \rightarrow K^{*0}e^+e^-$ in the (left) low- and (middle) central- q^2 bins and (right) of $B^0 \rightarrow K^{*0}J/\psi(ee)$ candidates. The dashed line is the signal PDF, the shaded shapes are the background PDFs and the solid line is the total PDF. The fit residuals normalized to the data uncertainty are shown at the bottom of each distribution.

REFERENCES

- [1] BaBar collaboration, B. Aubert et al., Observation of the semileptonic decays $B \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$ and evidence for $B \rightarrow D\tau^-\bar{\nu}_\tau$, Phys. Rev. Lett. 100 (2008) 021801, arXiv:0709.1698. BaBar collaboration, J. P. Lees et al., Evidence for an excess of $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$ decays, Phys. Rev. Lett. 109 (2012) 101802, arXiv:1205.5442. BaBar collaboration, J. P. Lees et al., Measurement of an excess of $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons, Phys. Rev. D 88 (2013) 072012, arXiv:1303.0571.
- [2] Belle collaboration, A. Matyja et al., Observation of $B^0 \rightarrow D^{*+}\tau^+\nu_\tau$ decay at Belle, Phys. Rev. Lett. 99 (2007) 191807, arXiv:0706.4429. Belle collaboration, A. Bozek et al., Observation of $B^+ \rightarrow \bar{D}^{*0}\tau^+\nu_\tau$ and evidence for $B^+ \rightarrow \bar{D}^0\tau^+\nu_\tau$ at Belle, Phys. Rev. D 82 (2010) 072005, arXiv:1005.2302.
- [3] As an example see D. Buttazzo, A. Greljio, G. Isidori, D. Marzocca, B-physics anomalies: a guide to combined explanations, JHEP 11 (2017) 044, arXiv:1706.07808. and references therein.
- [4] LHCb collaboration, R. Aaij et al., LHCb detector performance, Int. J. Mod. Phys. A 30 (2015) 1530022, arXiv:1412.6352.
- [5] S. Fajfer, J. F. Kamenik, and I. Nisandzic, $B \rightarrow D^*\tau\bar{\nu}_\tau$ sensitivity to new physics, Phys. Rev. D 85 (2012) 094025, arXiv:1203.2654.
- [6] LHCb collaboration, R. Aaij et al., Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)$, Phys. Rev. Lett. 115 (2015) 111803, arXiv:1506.08614.
- [7] LHCb collaboration, R. Aaij et al., Measurement of the ratio of the $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$ and $\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$ branching fractions using three-prong τ -lepton decays, Phys. Rev. Lett. 120 (2018) 171802, arXiv:1708.08856.
- [8] LHCb collaboration, R. Aaij et al., Measurement of the $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$ branching fraction using three-prong τ decays, Phys. Rev. D 97 (2018) 072013, arXiv:1711.02505.
- [8] Christos Hadjivasiliou, Lepton-Flavour universality tests with semitauonic decays, these Proceedings.

- [9] LHCb collaboration, R. Aaij et al., Study of $\bar{B}^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ and $\bar{B}^0 \rightarrow D^{*-} K^+ \pi^- \pi^+$ decays, Phys. Rev. D87 (2013) 092001, arXiv:1303.6861.
- [10] BaBar collaboration, J. P. Lees et al., Measurement of the $\bar{B}^0 \rightarrow D^{*+} 3\pi$ branching fraction, Phys. Rev. D94 (2016) 091101, arXiv:1609.06802.
- [11] Belle collaboration, G. Majumder et al., Phys. Rev. D70 (2004) 111103, arXiv:hep-ex/0409008.
- [12] Heavy Flavor Averaging Group, Y. Amhis et al., Averages of b-hadron, c-hadron, and τ -lepton properties as of summer 2016, Eur. Phys. J. C77 (2017) 895, arXiv:1612.07233, updated results and plots available at <https://hflav.web.cern.ch>.
- [13] LHCb collaboration, R. Aaij et al., Measurement of the ratio of branching fractions $\mathcal{B}(B_c^- \rightarrow J/\psi \tau^- \bar{\nu}_\tau) / \mathcal{B}(B_c^- \rightarrow J/\psi \mu^- \bar{\nu}_\mu)$, Phys. Rev. Lett. 120 (2018) 121801, arXiv:1711.05623.
- [14] A. Yu. Anisimov, I. M. Narodetskii, C. Semay, and B. Silvestre-Brac, The B_c meson lifetime in the light-front constituent quark model, Phys. Lett. B452 (1999) 129, arXiv:hep-ph/9812514.
- [15] V. V. Kiselev, Exclusive decays and lifetime of B_c meson in QCD sum rules, arXiv:hep-ph/0211021.
- [16] M. A. Ivanov, J. G. Korner, and P. Santorelli, Exclusive semileptonic and nonleptonic decays of the B_c meson, Phys. Rev. D73 (2006) 054024, arXiv:hep-ph/0602050.
- [17] LHCb collaboration, R. Aaij et al., Test of lepton universality with $B^0 \rightarrow K^* \ell^+ \ell^-$ decays, decays JHEP 08 (2017) 055, arXiv:1705.05802.
- [18] BaBar collaboration, J. P. Lees et al., Measurement of branching fractions and rate asymmetries in the rare decays $B \rightarrow K^{(*)} \ell^+ \ell^-$, Phys. Rev. D86 (2012) 032012,
- [19] Belle collaboration, J.-T. Wei et al., Measurement of the differential branching fraction and forward-backward asymmetry for $B \rightarrow K^{(*)} \ell^+ \ell^-$, Phys. Rev. Lett. 103 (2009) 171801, arXiv:0904.0770.
- [20] LHCb collaboration, R. Aaij et al., Test of lepton universality using $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays, Phys. Rev. Lett. 113 (2014) 151601, arXiv:1406.6482.
- [21] Particle Data Group, C. Patrignani et al., Review of particle physics, Chin. Phys.C40 (2016) 100001 and 2017 update.