PROCEEDINGS OF SCIENCE

Lepton flavour universality tests in rare $b \to s\ell\ell$ decays

C. Langenbruch[*†]
RWTH Aachen, Germany
E-mail: christoph.langenbruch@cern.ch

The coupling of the electroweak gauge bosons in the Standard Model is lepton flavour universal. Rare semileptonic $b \to s\ell^+\ell^-$ decays constitute sensitive probes for New Physics models that violate lepton flavour universality. Of particular interest are measurements of the branching fraction ratios $R_{K^{(*)}} = \mathscr{B}(B \to K^{(*)}\mu^+\mu^-)/\mathscr{B}(B \to K^{(*)}e^+e^-)$ which show some tension with the precise SM predictions. These proceedings summarise the latest results from the LHCb experiment on lepton flavour universality tests in rare $b \to s\ell^+\ell^-$ decays.

18th International Conference on B-Physics at Frontier Machines - Beauty2019 -
29 September / 4 October, 2019
Ljubljana, Slovenia

[*]Speaker.
[†]on behalf of the LHCb collaboration

1. Introduction

Lepton flavour universality is a central property of the Standard Model (SM), and is well established in decays of mesons [1, 2, 3], τ leptons [4, 5] and Z bosons [6]. Any clear deviation from the precise SM prediction would be an unambiguous sign of New Physics beyond the SM.

Rare semileptonic $b \to s\ell^+\ell^-$ decays are particularly interesting systems to study lepton universality, as they are forbidden at tree-level in the SM and only allowed at higher order, as shown in Fig. 1. New heavy particles predicted in models beyond the SM (*e. g.* leptoquarks or new heavy gauge bosons with potentially non-lepton universal couplings) could therefore give significant contributions to these processes.

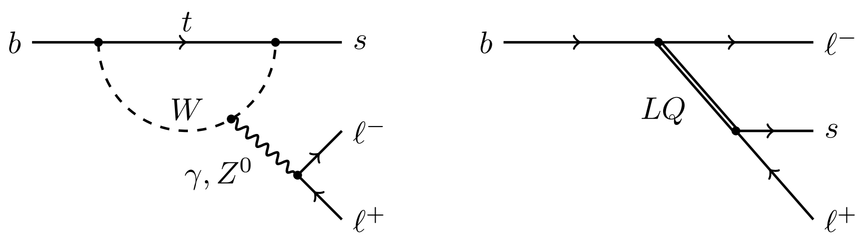

Figure 1: (Left) $b \to s\ell^+\ell^-$ decays are only allowed at loop-order in the SM. (Right) leptoquarks constitute a potential contribution to $b \to s\ell^+\ell^-$ decays beyond the SM.

The LHCb experiment is optimised for the study of rare decays of heavy flavour hadrons and CP violation and is thus ideally suited for lepton universality tests in $b \to s\ell^+\ell^-$ decays. The large $b\bar{b}$ production cross section at the LHC combined with the high efficiency of the LHCb trigger system provide large samples of rare heavy flavour decays. Furthermore, the excellent tracking and particle identification capabilities of the LHCb detector result in high reconstruction efficiencies. These proceedings summarise the latest results on lepton flavour universality tests from the LHCb experiment using data corresponding to an integrated luminosity of up to $5\,\mathrm{fb}^{-1}$ collected during the LHC Run 1 and 2.

2. Lepton flavour universality test R_K

The measurement of the branching fraction ratio $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ constitutes a sensitive test of lepton universality. In the q^2 region $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$, where q^2 is given by the invariant mass of the dilepton system squared $q^2 = m^2(\ell^+\ell^-)$, the SM predicts R_K to be unity. In particular hadronic uncertainties from form-factors and charm-loop contributions cancel in the ratio, and QED corrections do not exceed the level of $\mathcal{O}(1\,\%)$ [7].

LHCb determines R_K using data corresponding to $3\,\mathrm{fb}^{-1}$ taken during LHC Run 1 at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$ and $2\,\mathrm{fb}^{-1}$ taken during Run 2 at $\sqrt{s} = 13\,\mathrm{TeV}$ [8]. Experimentally, R_K is measured using the double ratio with the tree-level decays $B^+ \to K^+ J/\psi(\to \ell^+\ell^-)$ according to

$$\begin{aligned} R_K =& \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))} \\ =& \frac{N(B^+ \to K^+\mu^+\mu^-)}{N(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \times \frac{\varepsilon(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}{\varepsilon(B^+ \to K^+\mu^+\mu^-)} \\ & \times \frac{N(B^+ \to K^+J/\psi(\to e^+e^-))}{N(B^+ \to K^+e^+e^-)} \times \frac{\varepsilon(B^+ \to K^+e^+e^-)}{\varepsilon(B^+ \to K^+J/\psi(\to e^+e^-))}, \end{aligned} \tag{2.1}$$

where $\varepsilon(B^+ \to K^+\ell^+\ell^-)$ and $\varepsilon(B^+ \to K^+J/\psi(\to \ell^+\ell^-))$ denote the efficiencies for rare and tree-level decay and $N(B^+ \to K^+\ell^+\ell^-)$ and $N(B^+ \to K^+J/\psi(\to \ell^+\ell^-))$ the corresponding yields. The double ratio is experimentally advantageous as most systematic effects impact the efficiencies of the rare $b \to s\ell^+\ell^-$ decay and the corresponding tree-level decay similarly, and thus systematic uncertainties largely cancel in the ratio. This is because the final state kinematics of the rare and tree-level decays are similar as both are strongly boosted in the laboratory frame at LHCb. The efficiencies in Eq. 2.1 are determined using simulation and controlled and corrected using data-driven techniques. Trigger efficiencies, B kinematics and mass resolutions are controlled and corrected using the $B^+ \to K^+J/\psi$ control mode, and particle identification performance is corrected using high statistics control samples (*e.g.* $D^{*0} \to D^-\pi^+$).

Experimentally, the reconstruction of the electron mode is more challenging due to higher trigger thresholds for electrons and the more pronounced emission of Bremsstrahlung, which deteriorates the resolution of the reconstructed $e^\pm$ momenta. Figure 2 illustrates the different impact of Bremsstrahlung on q^2 and $m(K^+\ell^+\ell^-)$ for the dimuon and dielectron final states.

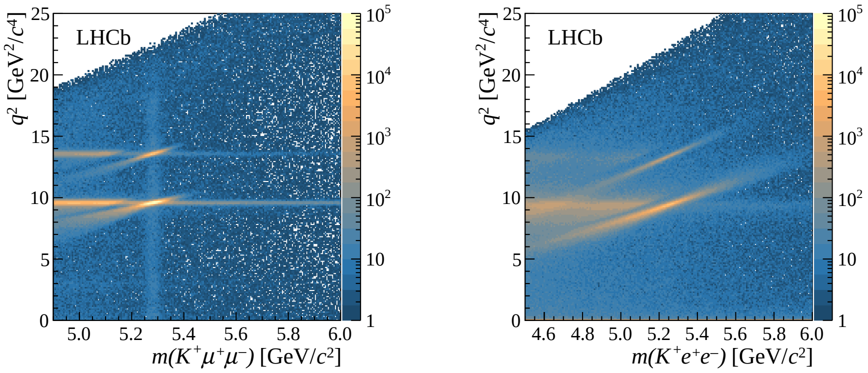

Figure 2: Reconstructed B^+ mass *vs.* q^2 for (left) the $K^+\mu^+\mu^-$ final state and (right) the $K^+e^+e^-$ final state. The tree-level decays $B^+ \to K^+J/\psi$ ($B^+ \to K^+\psi(2S)$) are clearly visible as peaks centred around the known B^+ mass and $q^2 = m^2(J/\psi)$ ($q^2 = m^2(\psi(2S))$). The rare decays are as visible as vertical bands. The electron modes exhibit worse resolutions compared to the muonic modes due to the more pronounced emission of Bremsstrahlung.

The $B^+ \to K^+J/\psi$ control mode is also used for the important cross-check via the single ratio

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))}, \tag{2.2}$$

which is known to be unity with a precision of better than 1% [4]. As systematic uncertainties arising from differences in reconstruction between electrons and muons do not cancel in this single ratio, $r_{J/\psi}$ constitutes a particularly stringent cross-check. The integrated value of $r_{J/\psi}$ is determined to be $r_{J/\psi} = 1.014 \pm 0.035$ in excellent agreement with unity. Furthermore, $r_{J/\psi}$ is found to be flat and independent of kinematics and run period. The double ratio

$$R_{\psi(2S)} = \frac{\mathscr{B}(B^+ \to K^+\psi(2S)(\to \mu^+\mu^-))}{\mathscr{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathscr{B}(B^+ \to K^+\psi(2S)(\to e^+e^-))}{\mathscr{B}(B^+ \to K^+J/\psi(\to e^+e^-))} \qquad (2.3)$$

is also found to be in good agreement with unity at $R_{\psi(2S)} = 0.986 \pm 0.013$.

The reconstructed B^+ mass distributions for the rare and control modes are shown in Fig. 3, where, for the control modes, the mass of the dilepton system is constrained to the known J/ψ mass. The fit results in yields of $N(B^+ \to K^+e^+e^-) = 766 \pm 48$, $N(B^+ \to K^+\mu^+\mu^-) = 1\,943 \pm 49$, $N(B^+ \to K^+J/\psi(\to e^+e^-)) = (344.1 \pm 0.6)\,\mathrm{k}$, and $N(B^+ \to K^+J/\psi(\to \mu^+\mu^-)) = (1\,161.8 \pm 1.1)\,\mathrm{k}$.

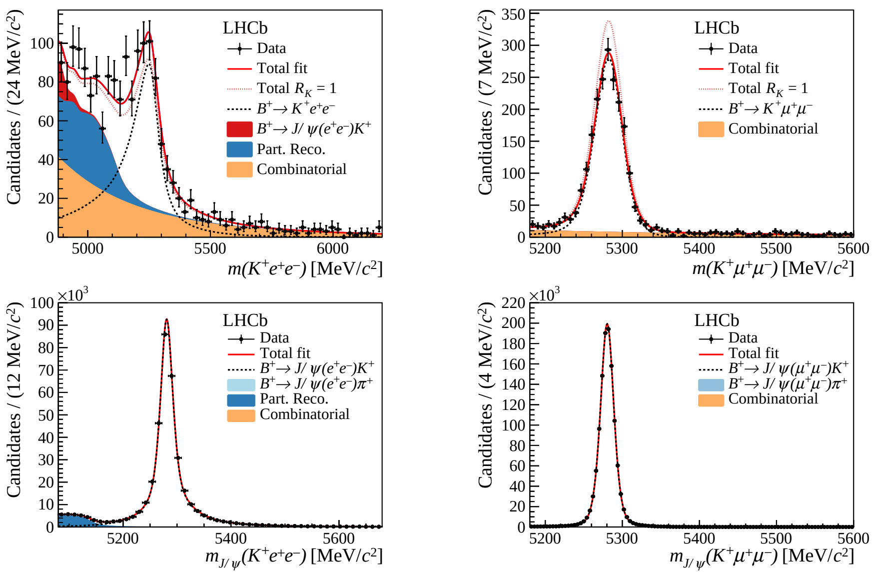

Figure 3: Reconstructed B^+ mass for (top left) the rare decays $B^+ \to K^+e^+e^-$, (top right) the rare decays $B^+ \to K^+\mu^+\mu^-$, (bottom left) the control mode $B^+ \to K^+J/\psi(\to e^+e^-)$, and (bottom right) the control mode $B^+ \to K^+J/\psi(\to \mu^+\mu^-)$. For the control modes, the mass of the dilepton system is constrained to the known J/ψ mass.

The resulting value for R_K is determined to be

$$R_K(1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4) = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}, \qquad (2.4)$$

where the first uncertainty is statistical and the second is systematic. The measurement is in tension with unity at 2.5 standard deviations (σ) [8], and compatible with and more precise than the LHCb Run 1 result [9]. Figure 4 compares the results by LHCb [8, 9] with results from the BaBar [12] and Belle [10, 11] collaborations which are compatible but exhibit larger uncertainties.

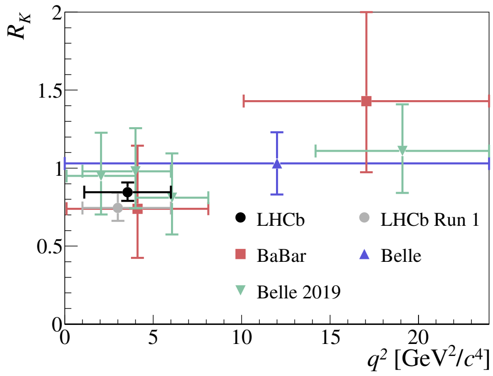

Figure 4: Measurements of R_K by LHCb [8, 9] in comparison with measurements by the BaBar [12] and Belle [10, 11] collaborations.

3. Lepton flavour universality test R_{K^*}

The observable $R_{K^*} = \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathcal{B}(B^0 \to K^{*0}e^+e^-)$ is closely related to R_K. As for R_K, hadronic uncertainties cancel in the ratio and R_{K^*} thus constitutes a clean test of lepton universality. LHCb measures R_{K^*} in two bins of q^2, given by $0.045 < q^2 < 1.1\,\mathrm{GeV}^2/c^4$ (low q^2) and $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ (central q^2), using data corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$ collected during the LHC Run 1 [13].

The tree-level decays $B^0 \to K^{*0}J/\psi(\to \ell^+\ell^-)$ are used to control and correct the efficiencies from simulation. Furthermore, they allow the determination of the single ratio $r_{J/\psi} = \mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))/\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))$, which is again found to be in good agreement with unity and flat in control variables. Figure 5 shows the distribution of the reconstructed B^0 mass for the rare mode in the two bins of q^2, as well as for the control modes.

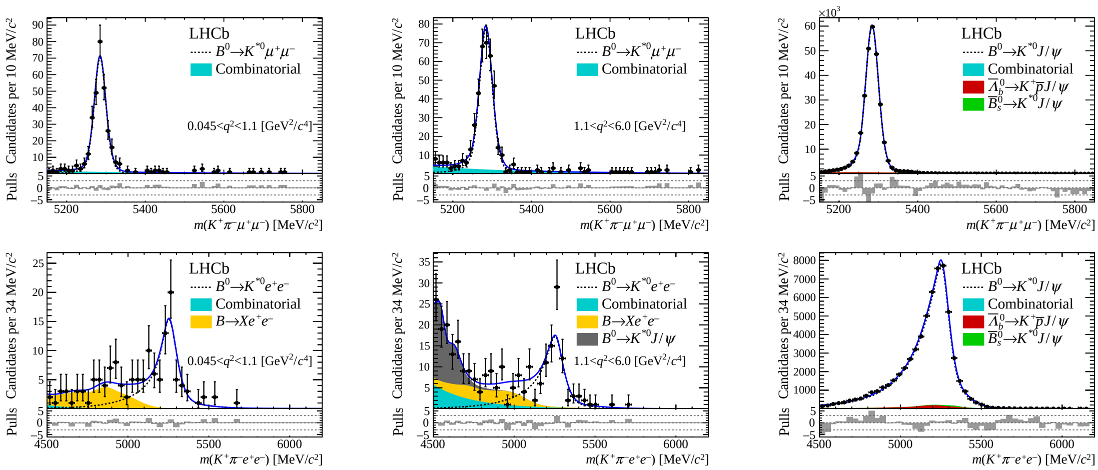

Figure 5: The reconstructed B^0 mass for (top left) the rare mode $B^0 \to K^{*0}\mu^+\mu^-$ at low q^2, (top middle) $B^0 \to K^{*0}\mu^+\mu^-$ at central q^2, (top right) the control mode $B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$, (bottom left) the rare mode $B^0 \to K^{*0}e^+e^-$ at low q^2, (bottom middle) $B^0 \to K^{*0}e^+e^-$ at central q^2, and (bottom right) the control mode $B^0 \to K^{*0}J/\psi(\to e^+e^-)$.

The numerical results for R_{K^*} are given by

$$R_{K^*}(0.045 < q^2 < 1.1\,\mathrm{GeV}^2/c^4) = 0.66^{+0.11}_{-0.07} \pm 0.03$$
$$R_{K^*}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.69^{+0.11}_{-0.07} \pm 0.05, \tag{3.1}$$

in tension with the SM predictions [7, 14, 15, 16, 27] at 2.1–2.3 σ at low q^2 and 2.4–2.5 σ at central q^2 [13]. Figure 6 shows the result by LHCb [13] in comparison with results from the BaBar [12] and Belle [10, 18] collaborations.

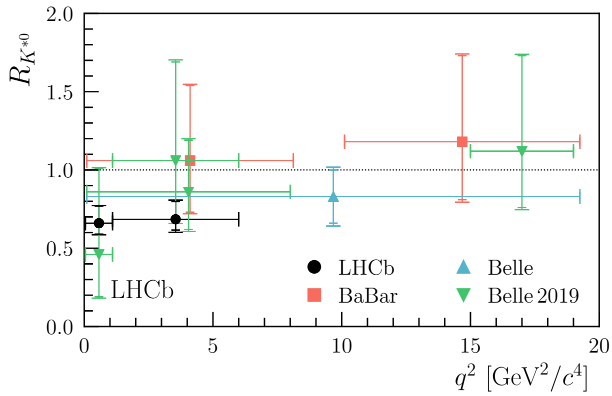

Figure 6: Measurement of R_{K^*} by LHCb [13] in comparison with measurements by the BaBar [12] and Belle [10, 18] collaborations.

4. Interpretation

The measurements of lepton flavour universality can be combined in global fits in an effective field theory framework. The global fits determine the effective couplings, the Wilson coefficients, corresponding to the different operators contributing to rare $b \to s\ell^+\ell^-$ decays. Figure 7 (left) shows a fit of the effective vector and axialvector couplings $\mathcal{C}_9$ and $\mathcal{C}_{10}$, using as input the lepton universality tests discussed in these proceedings [19]. Depending on the scenario, the global fit yields a tensions of 3–4 σ with the precise SM prediction. It should be noted that other global fits showing consistent results are available, *e. g.* Refs. [20, 21, 22].

The measurements of R_K and R_{K^*} are part of the so-called flavour anomalies in rare decays. Other anomalies in the rare decays include measurements of branching fractions [23, 24, 25] and angular distributions [26] of $b \to s\mu^+\mu^-$ decays. Adding these measurements in global fits increases the tension with the SM to the level of 5 σ, as shown in Fig. 7 (right). However, it should be noted that the SM predictions for the additional $b \to s\mu^+\mu^-$ measurements are not as precise as for the lepton universality tests, in particular the hadronic uncertainties associated to the charm-loop contributions are currently under discussion [27, 28, 29, 30].

5. Conclusions and outlook

Recent results on the lepton universality tests R_K and R_{K^*} in rare decays exhibit interesting tensions with the precise SM predictions. Global fits of these results yield a tension with the SM at

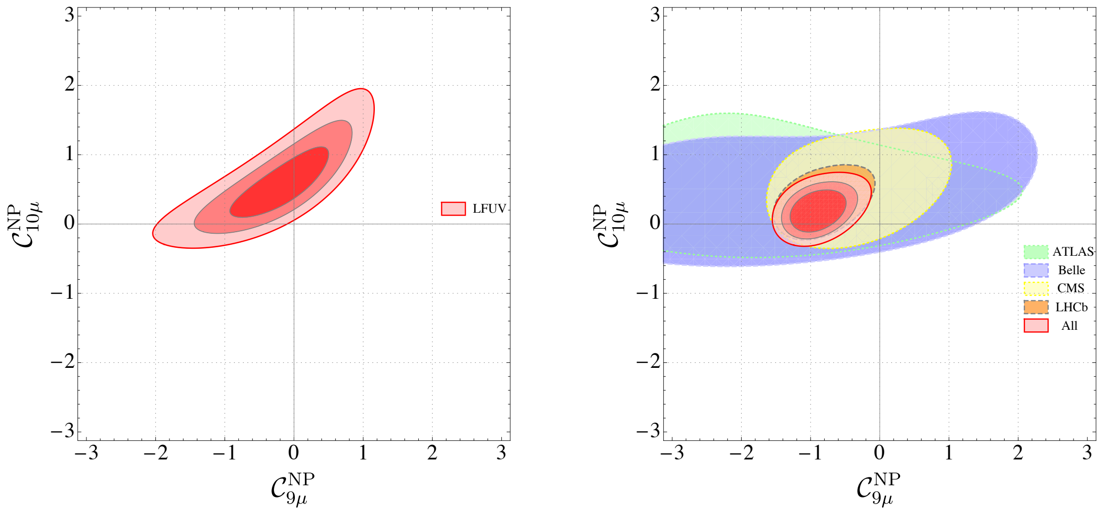

Figure 7: (Left) result of a global fit of the effective vector and axialvector couplings $\mathcal{C}_9$ and $\mathcal{C}_{10}$ using data on lepton universality tests in rare decays, and (right) including measurements of branching fractions and angular distributions of $b \to s\mu^+\mu^-$ decays in addition [19].

the level of 3–4$\,\sigma$. Including the flavour anomalies in $b \to s\mu^+\mu^-$ decays increases the significance of this tension to around $5\,\sigma$, however, the theory uncertainties for these observables are currently under discussion [27, 28, 29, 30]. Consistent New Physics explanations of the anomalies in rare decays are available in the form of leptoquarks (see *e. g.* Refs. [31, 32, 33, 34]) and new heavy gauge bosons (Refs. [35, 36, 37, 38]).

The measurements of R_K and R_{K^*} by LHCb are both statistically limited. Updates of both measurements including the full combined Run 1 and Run 2 data set are currently ongoing and eagerly awaited by the community. Since the conference, the measurement of R_{pK} [39] was presented by LHCb, which probes lepton universality using inclusive $\Lambda_b^0 \to pK^-\ell^+\ell^-$ baryon decays. Further tests of lepton universality are in preparation, including measurements of R_ϕ, $R_{K\pi\pi}$ and R_Λ. The large data samples available in the LHCb upgrade(s) will allow for unprecedented precision in lepton universality tests. Independent clarification on the anomalies is also expected from future measurements by the Belle II experiment.

Acknowledgments

C. L. gratefully acknowledges support by the Emmy Noether programme of the Deutsche Forschungsgemeinschaft (DFG), grant identifier LA 3937/1-1.

References

[1] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **88** (2013) no.3, 032007 doi:10.1103/PhysRevD.88.032007 [arXiv:1307.1189 [hep-ex]].

[2] C. Lazzeroni *et al.* [NA62 Collaboration], Phys. Lett. B **719** (2013) 326 doi:10.1016/j.physletb.2013.01.037 [arXiv:1212.4012 [hep-ex]].

[3] A. Aguilar-Arevalo *et al.* [PiENu Collaboration], Phys. Rev. Lett. **115** (2015) no.7, 071801 doi:10.1103/PhysRevLett.115.071801 [arXiv:1506.05845 [hep-ex]].

[4] M. Tanabashi *et al.* [Particle Data Group], Phys. Rev. D **98** (2018) no.3, 030001. doi:10.1103/PhysRevD.98.030001

[5] A. Pich, Prog. Part. Nucl. Phys. **75** (2014) 41 doi:10.1016/j.ppnp.2013.11.002 [arXiv:1310.7922 [hep-ph]].

[6] S. Schael *et al.* [ALEPH and DELPHI and L3 and OPAL and SLD Collaborations and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group], Phys. Rept. **427** (2006) 257 doi:10.1016/j.physrep.2005.12.006 [hep-ex/0509008].

[7] M. Bordone, G. Isidori and A. Pattori, Eur. Phys. J. C **76** (2016) no.8, 440 doi:10.1140/epjc/s10052-016-4274-7 [arXiv:1605.07633 [hep-ph]].

[8] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **122** (2019) no.19, 191801 doi:10.1103/PhysRevLett.122.191801 [arXiv:1903.09252 [hep-ex]].

[9] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **113** (2014) 151601 doi:10.1103/PhysRevLett.113.151601 [arXiv:1406.6482 [hep-ex]].

[10] J.-T. Wei *et al.* [Belle Collaboration], Phys. Rev. Lett. **103** (2009) 171801 doi:10.1103/PhysRevLett.103.171801 [arXiv:0904.0770 [hep-ex]].

[11] A. Abdesselam *et al.* [Belle Collaboration], arXiv:1908.01848 [hep-ex].

[12] J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D **86** (2012) 032012 doi:10.1103/PhysRevD.86.032012 [arXiv:1204.3933 [hep-ex]].

[13] R. Aaij *et al.* [LHCb Collaboration], JHEP **1708** (2017) 055 doi:10.1007/JHEP08(2017)055 [arXiv:1705.05802 [hep-ex]].

[14] B. Capdevila, S. Descotes-Genon, L. Hofer and J. Matias, JHEP **1704** (2017) 016 doi:10.1007/JHEP04(2017)016 [arXiv:1701.08672 [hep-ph]].

[15] N. Serra, R. Silva Coutinho and D. van Dyk, Phys. Rev. D **95** (2017) no.3, 035029 doi:10.1103/PhysRevD.95.035029 [arXiv:1610.08761 [hep-ph]].

[16] W. Altmannshofer, C. Niehoff, P. Stangl and D. M. Straub, Eur. Phys. J. C **77** (2017) no.6, 377 doi:10.1140/epjc/s10052-017-4952-0 [arXiv:1703.09189 [hep-ph]].

[17] S. Jäger and J. Martin Camalich, Phys. Rev. D **93** (2016) no.1, 014028 doi:10.1103/PhysRevD.93.014028 [arXiv:1412.3183 [hep-ph]].

[18] A. Abdesselam *et al.* [Belle Collaboration], arXiv:1904.02440 [hep-ex].

[19] M. Algueró, B. Capdevila, A. Crivellin, S. Descotes-Genon, P. Masjuan, J. Matias and J. Virto, Eur. Phys. J. C **79** (2019) no.8, 714 doi:10.1140/epjc/s10052-019-7216-3 [arXiv:1903.09578 [hep-ph]].

[20] J. Aebischer, W. Altmannshofer, D. Guadagnoli, M. Reboud, P. Stangl and D. M. Straub, arXiv:1903.10434 [hep-ph].

[21] A. Arbey, T. Hurth, F. Mahmoudi, D. M. Santos and S. Neshatpour, Phys. Rev. D **100** (2019) no.1, 015045 doi:10.1103/PhysRevD.100.015045 [arXiv:1904.08399 [hep-ph]].

[22] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini and M. Valli, Eur. Phys. J. C **79** (2019) no.8, 719 doi:10.1140/epjc/s10052-019-7210-9 [arXiv:1903.09632 [hep-ph]].

[23] R. Aaij *et al.* [LHCb Collaboration], JHEP **1406** (2014) 133 doi:10.1007/JHEP06(2014)133 [arXiv:1403.8044 [hep-ex]].

[24] R. Aaij *et al.* [LHCb Collaboration], JHEP **1509** (2015) 179 doi:10.1007/JHEP09(2015)179 [arXiv:1506.08777 [hep-ex]].

[25] R. Aaij *et al.* [LHCb Collaboration], JHEP **1611** (2016) 047 Erratum: [JHEP **1704** (2017) 142] doi:10.1007/JHEP11(2016)047, 10.1007/JHEP04(2017)142 [arXiv:1606.04731 [hep-ex]].

[26] R. Aaij *et al.* [LHCb Collaboration], JHEP **1602** (2016) 104 doi:10.1007/JHEP02(2016)104 [arXiv:1512.04442 [hep-ex]].

[27] S. Jäger and J. Martin Camalich, Phys. Rev. D **93** (2016) no.1, 014028 doi:10.1103/PhysRevD.93.014028 [arXiv:1412.3183 [hep-ph]].

[28] J. Lyon and R. Zwicky, arXiv:1406.0566 [hep-ph].

[29] M. Ciuchini, M. Fedele, E. Franco, S. Mishima, A. Paul, L. Silvestrini and M. Valli, JHEP **1606** (2016) 116 doi:10.1007/JHEP06(2016)116 [arXiv:1512.07157 [hep-ph]].

[30] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini and M. Valli, Eur. Phys. J. C **77** (2017) no.10, 688 doi:10.1140/epjc/s10052-017-5270-2 [arXiv:1704.05447 [hep-ph]].

[31] G. Hiller and M. Schmaltz, Phys. Rev. D **90** (2014) 054014 doi:10.1103/PhysRevD.90.054014 [arXiv:1408.1627 [hep-ph]].

[32] B. Gripaios, M. Nardecchia and S. A. Renner, JHEP **1505** (2015) 006 doi:10.1007/JHEP05(2015)006 [arXiv:1412.1791 [hep-ph]].

[33] I. de Medeiros Varzielas and G. Hiller, JHEP **1506** (2015) 072 doi:10.1007/JHEP06(2015)072 [arXiv:1503.01084 [hep-ph]].

[34] R. Barbieri, C. W. Murphy and F. Senia, Eur. Phys. J. C **77** (2017) no.1, 8 doi:10.1140/epjc/s10052-016-4578-7 [arXiv:1611.04930 [hep-ph]].

[35] W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Phys. Rev. D **89** (2014) 095033 doi:10.1103/PhysRevD.89.095033 [arXiv:1403.1269 [hep-ph]].

[36] A. Crivellin, G. D'Ambrosio and J. Heeck, Phys. Rev. Lett. **114** (2015) 151801 doi:10.1103/PhysRevLett.114.151801 [arXiv:1501.00993 [hep-ph]].

[37] A. Celis, J. Fuentes-Martin, M. Jung and H. Serodio, Phys. Rev. D **92** (2015) no.1, 015007 doi:10.1103/PhysRevD.92.015007 [arXiv:1505.03079 [hep-ph]].

[38] A. Falkowski, M. Nardecchia and R. Ziegler, JHEP **1511** (2015) 173 doi:10.1007/JHEP11(2015)173 [arXiv:1509.01249 [hep-ph]].

[39] R. Aaij *et al.* [LHCb Collaboration], arXiv:1912.08139 [hep-ex].