IL NUOVO CIMENTO **39 C** (2016) 324
DOI 10.1393/ncc/i2016-16324-8

Colloquia: La Thuile 2016

Rare beauty and charm decays

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received 26 July 2016

Summary. — Rare beauty and charm decays can provide powerful probes of physics beyond the Standard Model. These proceedings summarise the latest measurements of rare beauty and charm decays from the LHCb experiment at the end of Run 1 of the LHC. Whilst the majority of the measurements are consistent with SM predictions, small differences are seen in the rate and angular distribution of $b \to s\ell^+\ell^-$ decay processes.

1. – Introduction

In the Standard Model (SM) the only flavour violating process is the weak charged-current interaction. The other SM interactions are flavour conserving. The probability for changes between different flavours is controlled by the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. Flavour-changing-neutral-current (FCNC) quark level transitions that take one (up-) down-type quark into another (up-) down-type quark of a different flavour are forbidden at tree level and proceed only through suppressed loop order processes. Beauty and charm hadron decays that proceed via $b \to s$, $b \to d$ and $c \to u$ quark level transitions are therefore rare in the SM. In many extensions of the SM (referred to as BSM models), new TeV mass-scale particles can enter in competing Feynman diagrams modifying the SM predictions for the rate or angular distribution of the decays.

These proceedings summarise the latest result on rare b and c hadron decays from the LHCb experiment using data collected during Run 1 of the LHC. The dataset corresponds to an integrated luminosity of $3\,\mathrm{fb}^{-1}$, collected in pp collisions at centre-of-mass energies of $7\,\mathrm{TeV}$ and $8\,\mathrm{TeV}$ in 2011 and 2012, respectively. The inclusion of charge conjugate processes is implied throughout these proceedings, unless otherwise noted.

2. – Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

The angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay provides a large number of observables that are sensitive to BSM effects. The angular distribution of the decay is described by the dimuon invariant mass squared, q^2, and three decay angles: the angle between the direction of the μ^+ (μ^-) and the direction of the B^0 ($\bar{B}^0$) in the dimuon rest frame, θ_ℓ; the angle between the direction of the K and the direction of the B^0 ($\bar{B}^0$) in the K^{*0} rest-frame, θ_K; and the angle between the plane containing the μ^+ and μ^- and the plane containing the K and π in the B^0 ($\bar{B}^0$) rest frame, ϕ. The *CP* averaged angular distribution can be written in terms of eight observables (see for example ref. [1]),

$$
\begin{aligned}
(1) \qquad \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\,\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[& \tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_L\cos^2\theta_K \\
& + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell \\
& - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
& + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\
& + \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\
& + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],
\end{aligned}
$$

where F_{L} is the longitudinal polarisation fraction of the K^{*0} meson, A_{FB} is the well-known forward-backward asymmetry of the dimuon system. The observables S_3–S_9 cancel when integrating over the ϕ angle.

The LHCb experiment has performed the first full angular analysis of the decay using its Run 1 dataset [2]. It has also performed a first measurement of *CP* asymmetries in the angular distribution of the decay. Four of the angular observables measured by LHCb are shown in fig. 1 as functions of q^2. The observables F_{L}, A_{FB} and S_3 are consistent with SM expectations. The observable S_4 is not shown here, but is also consistent with the SM expectation. Small differences are, however, seen between S_5 and its SM prediction. The *CP* averaged observables S_7–S_9 and the *CP* asymmetries A_3–A_9 are also not shown here. These are all consistent with zero, which is the SM expectation for these observables. The same set of observables has also been measured using a moment analysis of the angular distribution, leading to compatible results.

The statistical uncertainty on the angular observables in fig. 1 is determined using a variant of the Feldman-Cousins technique, where the nuisance parameters are treated with the so-called plug-in method [3]. The systematic uncertainty on the observables is small (~ 0.01) compared to the statistical uncertainty arising from the size of the dataset.

In ref. [4] an alternative set of angular observables is proposed with reduced SM uncertainties. These observables exploit symmetries of the angular distribution at small q^2 (in QCD factorisation and SCET) to construct a set of observables that are free from uncertainties on the $B^0 \to K^{*0}$ form-factors at leading order. The full set of these observables is also measured by LHCb in ref. [2]. The observable P_5', which is related to S_5 through $P_5' = S_5/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}$, is shown in fig. 2. In the two bins from $4 < q^2 < 6\,\mathrm{GeV}^2/c^4$ and $6 < q^2 < 8\,\mathrm{GeV}^2/c^4$, the data are 2.8 and 3.0 standard deviations (σ) away from the SM predictions of ref. [5]. The Belle Collaboration has also recently produced a measurement of P_5' in ref. [6]. Their measurement is consistent with (but less precise than) the one from LHCb. The Belle measurement is 2.1σ from the SM prediction of ref. [5] in the range $4 < q^2 < 8\,\mathrm{GeV}^2/c^4$.

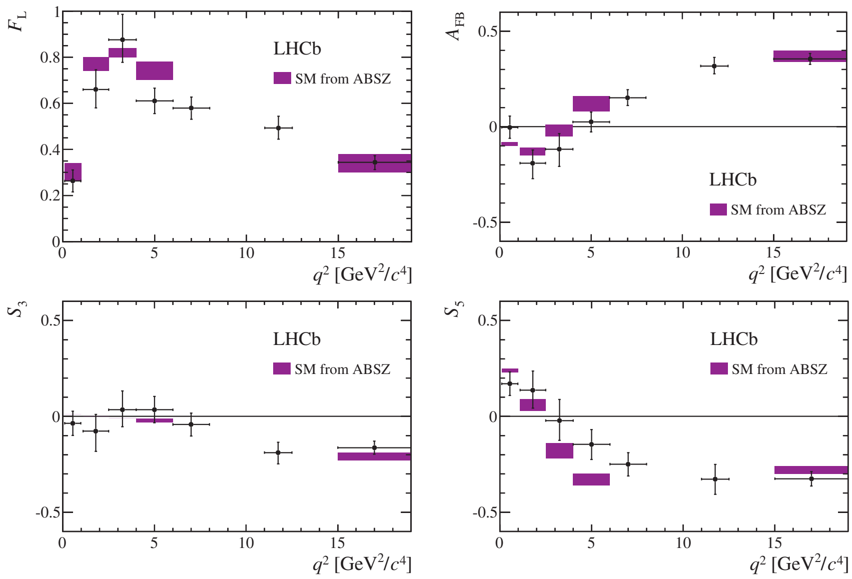

Fig. 1. – Angular observables F_{L}, A_{FB}, S_3 and S_5 in the $B^0 \to K^{*0}\mu^+\mu^-$ decay as a function of the dimuon mass squared, q^2. The data overlay a SM prediction based on refs. [7, 8]. No prediction is shown close to the J/ψ or $\psi(2S)$ resonances, where the assumptions used to compare the SM predictions are thought to break down. Figure reproduced from ref. [2].

3. – $B_s^0 \to \phi\mu^+\mu^-$ branching fraction

The LHCb experiment has also measured the angular distribution of the $B_s^0 \to \phi\mu^+\mu^-$ decay using its Run 1 dataset [9]. Unfortunately this is not a flavour specific final state and so it is not possible to determine the P_5' observable without tagging the flavour of the B_s^0 meson at production. The set of time integrated obervables measured in this full angular analysis are compatible with SM predictions. Reference [9] also provides

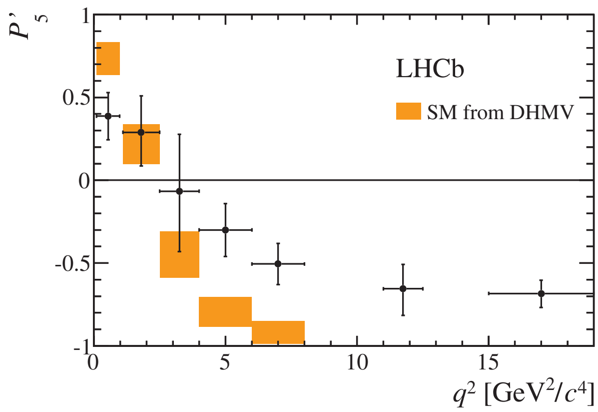

Fig. 2. – Angular observable P_5' for the $B^0 \to K^{*0}\mu^+\mu^-$ decay as a function of the dimuon mass squared, q^2. The data overlay a SM prediction from ref. [5]. Figure reproduced from ref. [2].

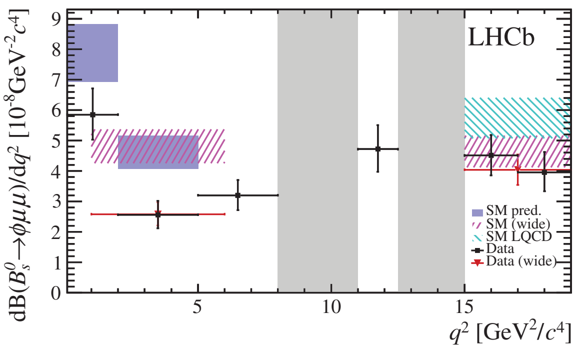

Fig. 3. – Differential branching fraction of the $B_s^0 \to \phi\mu^+\mu^-$ decay as a function the dimuon mass squared, q^2. The date overlay two SM predictions; one uses $B_s^0 \to \phi$ form-factors computed using light-cone sum-rules [7,8] and the other form-factors from Lattice QCD [10]. Figure reproduced from ref. [9].

the most precise measurement of the differential branching fraction of the decay to date. This measurement is shown in fig. 3. At small values of q^2, the data are significantly below SM predictions. In the range $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$, the data are $3.3\,\sigma$ below the SM prediction from refs. [7,8].

4. – $B^+ \to \pi^+\mu^+\mu^-$ branching fraction

Rare $b \to d\mu^+\mu^-$ decays have a much smaller branching fraction than $b \to s\mu^+\mu^-$ decays in the SM, due to the additional CKM suppression of $|V_{td}/V_{ts}| \sim 1/25$. The LHCb experiment has performed a first measurement of the differential branching fraction of the $B^+ \to \pi^+\mu^+\mu^-$ decay using its full Run 1 dataset in ref. [11]. The dataset contains $\sim 100\, B^+ \to \pi^+\mu^+\mu^-$ candidates with a signal-to-background ratio of about two-to-one. Using particle identification information from its Ring Imaging Cherenkov detectors the LHCb experiment is also able to reduce background from $B^+ \to K^+\mu^+\mu^-$ decays, where the K^+ is misidentified as a π^+, to a manageable level. The differential branching fraction for the decay as a function of q^2 is shown in fig. 4. The data is in general consistent with SM predictions. In the first q^2 bin there is an enhancement of the branching fraction from light resonances (ρ and ω). Only ref. [12] includes an explicit calculation of these contributions.

The branching fractions of $B^+ \to \pi^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$ decays can be used to determine the CKM matrix elements $|V_{td}|$ and $|V_{ts}|$ [13]. These measurements provide and interesting extra set of constraints, which are complementary to extractions of $|V_{td}|$ and $|V_{ts}|$ from the B^0 and B_s^0 oscillation frequencies Δm_d and Δm_s, see, *e.g.*, the review in ref. [14].

While direct *CP* asymmetries are expected to be small in $b \to s\mu^+\mu^-$ decays, due to the small size of $|V_{ub}V_{us}^*|$ compared to $|V_{tb}V_{ts}^*|$, they can be larger for $b \to d\mu^+\mu^-$ processes. The LHCb experiment has measured the direct *CP* asymmetry of $B^+ \to \pi^+\mu^+\mu^-$ decays to be [11]

$$A_{CP}[B^+ \to \pi^+\mu^+\mu^-] = -0.11 \pm 0.12 \pm 0.01, \tag{2}$$

which is consistent with SM expectations.

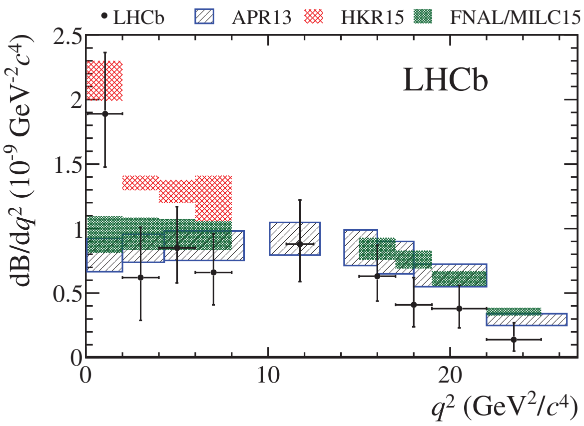

Fig. 4. – Differential branching fraction of the $B^+ \to \pi^+\mu^+\mu^-$ decay as a function of the dimuon mass squared, q^2. The data overlay SM predictions from refs. [12, 15, 16]. Figure reproduced from ref. [11].

5. – Lepton universality tests in $b \to s\ell^+\ell^-$ decays

In the SM, the three different generations of lepton carry the same charges and couple equally to the SM gauge bosons (the photon, W and Z). The only exception to this is the Higgs boson's coupling to mass but the impact of the Higgs on rare $b \to s\ell^+\ell^-$ decays is negligible. Consequently the ratio of partial widths,

$$R_{K^{(*)}} = \Gamma[B \to K^{(*)}\mu^+\mu^-] \Big/ \Gamma[B \to K^{(*)}e^+e^-] \tag{3}$$

is expected to be unity up to small differences in phase-space for the different lepton masses. In the SM, $R^{\rm SM}_{K^{(*)}}[1,6] = 1.000 \pm 0.001$ in the range $1 < q^2 < 6\,{\rm GeV}^2/c^4$ [17]. This prediction is theoretically clean, since hadronic uncertainties completely cancel in the ratio.

Using its full Run 1 dataset the LHCb experiment measures

$$R_K[1,6] = 0.745\,^{+0.090}_{-0.074}\,^{+0.035}_{-0.035}, \tag{4}$$

which is $2.6\,\sigma$ from the SM expectation of unity [18]. A value of $R_K < 1$ corresponds to a deficit of dimuon events with respect to dilectron events. This was a prediction of one class of model trying to explain the result of the global fits to the angular variables in $B^0 \to K^{*0}\mu^+\mu^-$ [19].

For the R_K measurement, the most important experimental issues arise from FSR and Bremsstrahlung. This causes the electrons to radiate a significant amount of energy in the detector, which must be corrected for in the analysis. The migration of events in q^2 due to the FSR/Bremsstrahlung is corrected for using samples of simulated events where PHOTOS is applied and the simulated particles are passed through a full simulation of the detector.

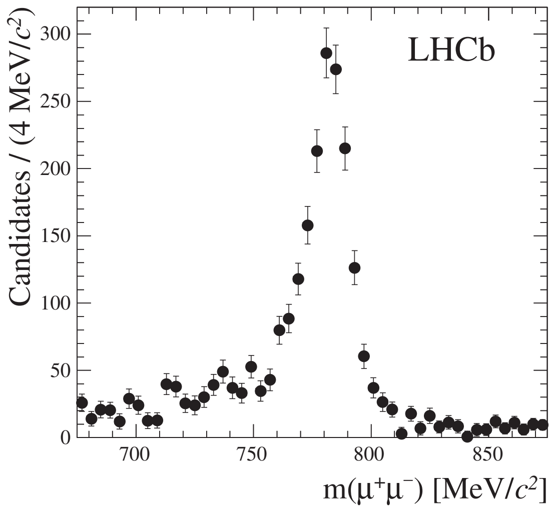

Fig. 5. – Background subtracted dimuon mass distribution of $D^0 \to K^-\pi^+\mu^+\mu^-$ decays. The data are consistent with the dimuon pair originating from decays of the ρ and ω mesons. Figure reproduced from ref. [20].

6. – $D^0 \to K^-\pi^+\mu^+\mu^-$ branching fraction

The short-distance contribution to $c \to u\ell^+\ell^-$ decays is expected to be tiny in the SM, due to the small size of the down-type quark masses compared to the mass of the W boson. Long-distance contributions involving light-quark resonances can, however, be much larger. In the region around the ρ and ω, LHCb measures [20]

$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}\,. \tag{5}$$

The background subtracted dimuon mass distribution of the $D^0 \to K^-\pi^+\mu^+\mu^-$ decays is shown in fig. 5. There is no evidence yet for any short-distance $c \to u\mu^+\mu^-$ contribution to the decay.

7. – Search for $B^0 \to \mu^\pm e^\mp$ and $D^0 \to \mu^\pm e^\mp$ decays

In the SM decay, lepton flavour is essentially conserved. Neutrino oscillation can lead to lepton flavour violating decays, but at a rate that would be unobservable at any experiment. Any evidence for charged lepton flavour violation (LFV) would be an unambiguous sign of BSM physics. The LHCb experiment has searched for evidence of lepton flavour violation in the decays $B^0_{(s,d)} \to \mu^\pm e^\mp$ using a dataset corresponding to $1\,\mathrm{fb}^{-1}$ recorded in 2011 [21]. No evidence for any signal is seen and limits are placed on the branching fractions

$$\begin{aligned} \mathcal{B}(B^0 \to \mu^\pm e^\mp) &< 1.4 \times 10^{-8} \text{ at 90\% CL}, \\ \mathcal{B}(B^0_s \to \mu^\pm e^\mp) &< 2.8 \times 10^{-9} \text{ at 90\% CL}. \end{aligned} \tag{6}$$

The LHCb experiment has also recently looked for evidence of LFV in $D^0 \to \mu^\pm e^\mp$ decays using its full Run 1 dataset [22]. The analysis uses D^0 mesons produced in $D^{*+} \to D^0\pi^+$

decays. The small mass difference between the D^{*+} and the D^0 is exploited to reduced combinatorial backgrounds. In order to achieve the best sensitivity the analysis is also performed simultaneously in bins of a multivariate classifier, which has been designed to separate signal from combinatorial background. The major challenge for the analysis is to control mis-identified backgrounds from $D^0 \to \pi^+\pi^-$ decays. This source of backgrounds peaks in both D^{*+} and D^0 mass close to the signal. No evidence for any signal is seen and a limit is set on the resulting branching fraction of

$$\mathcal{B}(D^0 \to \mu^\pm e^\mp) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL.} \tag{7}$$

This is the most precise test of LFV in charm meson decays to date.

8. – Summary

There have been several attempts to interpret the results of the angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays by performing global fits to the data [8, 23, 24]. The global fits typically also include constraints coming from the branching fractions of $b \to s\ell^+\ell^-$ decays, which tend to lie below SM predictions by between 1 and $3\,\sigma$, and the measured branching fraction of the $B_s^0 \to \mu^+\mu^-$ decay [25]. In general, the fits show that the data can be explained in a consistent way by modifying the strength of the vector current in the SM, through the Wilson coefficient C_9. The negative shift of C_9 favoured by the angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays would also reduce the tension between the data and predictions for the branching fractions of $b \to s\mu^+\mu^-$ decays.

A shift in C_9 could be explained by the presence of a new vector gauge boson [19,26,27] or by models involving leptoquarks [28, 29]. The discrepancy has also led to a discussion of the SM uncertainties. In particular, on the level of hadronic contributions to the decay involving intermediate $c\bar{c}$ loops. Unfortunately these processes are hard to estimate and also contribute to the vector current operator of the decay in the SM. Progress is needed from both the experimental and theoretically communities to disentangle the two.

If the hint of lepton universality violation seen in $B^+ \to K^+\ell^+\ell^-$ decays is confirmed with a larger dataset (or seen in related decays) this would be unambiguous evidence of BSM physics. Paired with the angular measurements from $B^0 \to K^{*0}\mu^+\mu^-$, it can also provide interesting insights into the structure of any new theory. Many models that introduce non-universal lepton couplings also introduce LFV at a level that is just below existing experimental limits, which could be observed with the LHC Run 2 dataset.

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This work is supported by the Royal Society.

REFERENCES

[1] Altmannshofer W., Ball P., Bharucha A., Buras A. J., Straub D. M. and Wick M. *JHEP*, **01** (2009) 019.
[2] Aaij R. *et al.* *JHEP*, **02** (2016) 104.
[3] Sen B., Walker M. and Woodroofe M. *Stat. Sin.*, **19** (2009) 301.
[4] Descotes-Genon S., Hurth T., Matias J. and Virto J., *JHEP*, **05** (2013) 137.
[5] Matias J., Mescia F., Ramon M. and Virto J., *JHEP*, **04** (2012) 104.
[6] Abdesselam A. *et al.*, arXiv:1604.04042 (2016).
[7] Bharucha A., Straub D. M. and Zwicky R., arXiv:1503.05534 (2015).

[8] Altmannshofer W. and Straub D. M., *Eur. Phys. J. C*, **75** (2015) 382.
[9] Aaij R. *et al.*, *JHEP*, **09** (2015) 179.
[10] Horgan R. R., Liu Z., Meinel S. and Wingate M., *Phys. Rev. D*, **89** (2014) 094501.
[11] Aaij R. *et al.*, *JHEP*, **10** (2015) 034.
[12] Hambrock C., Khodjamirian A. and Rusov A., *Phys. Rev. D*, **92** (2015) 074020.
[13] Du D., El-Khadra A. X., Gottlieb S., Kronfeld A. S., Laiho J., Lunghi E., Van de Water R. S. and Zhou R. *Phys. Rev. D*, **93** (2016) 034005.
[14] Olive K. A. *et al. Chin. Phys. C*, **38** (2014) 090001.
[15] Ali A., Parkhomenko A. Ya. and Rusov A. V. *Phys. Rev. D*, **89** (2014) 094021.
[16] Bailey J. A. *et al. Phys. Rev. Lett.*, **115** (2015) 152002.
[17] Bobeth C., Hiller G. and Piranishvili G., *JHEP*, **12** (2007) 040.
[18] Aaij R. *et al. Phys. Rev. Lett.*, **113** (2014) 151601.
[19] Altmannshofer W., Gori S., Pospelov M. and Yavin I. *Phys. Rev. D*, **89** (2014) 095033.
[20] Aaij R. *et al.* arXiv:1510.08367 (2015).
[21] Aaij R. *et al. Phys. Rev. Lett.*, **111** (2013) 141801.
[22] Aaij R. *et al. Phys. Lett. B*, **754** (2015) 167.
[23] Descotes-Genon S., Hofer L., Matias J. and Virto J., arXiv:1510.04239 (2015).
[24] Ciuchini M., Fedele M., Franco E., Mishima S., Paul A., Silvestrini L. and Valli M., arXiv:1512.07157 (2015).
[25] Khachatryan V. *et al. Nature*, **522** (2015) 68.
[26] Gauld R., Goertz F. and Haisch U. *Phys. Rev. D*, **89** (2014) 015005.
[27] Buras A. J. and Girrbach J. *JHEP*, **12** (2013) 009.
[28] Hiller G. and Schmaltz M. *Phys. Rev. D*, **90** (2014) 054014.
[29] Buras A. J., Girrbach-Noe J., Niehoff C. and Straub D. M. *JHEP*, **02** (2015) 184.