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Anomalous $tq\gamma$ Couplings and Radiative B Meson Decays

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Motivated by the recent ATLAS results in terms of the branching ratios $Br(t \to q\gamma)$, we consider the effects of the anomalous $tq\gamma$ couplings on the radiative B meson decays $\bar{B} \to X_D\gamma$ and $B \to V\gamma$ with V being light vector mesons ρ, ω, ϕ and K^*. Comparing with the corresponding experimental measured data, we obtain the constraints on anomalous $tq\gamma$ couplings.

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Top quark is the heaviest of ordinary particles and its flavor changing neutral current (FCNC) couplings are forbidden at tree level in the standard model (SM) and highly suppressed at loop level owing to the Glashow–Iliopoulos–Maiani mechanism. The SM predictions for the branching ratios of the top FCNC decays $t \to qx$ ($x = g$, γ, Z, and H) with q being an up or charm quark at the order of $O(10^{-12}$–$10^{-17})$,[1] which are beyond the range of present and even future experimental sensitivity. Many new physics scenarios beyond the SM predict the existence of the top FCNC couplings and some of these models can make the branching ratios of the top FCNC decays be significantly larger than those predicted by the SM, e.g., see Ref. [2]. Thus, observation of anyone of the top FCNC couplings (or called the anomalous top quark couplings) at high-energy collider experiments would imply discovery of the new physics signals.

Searching for the anomalous top couplings is one of the important goals of present and future collider experiments. Although any physical signature has not been detected, the experimental upper limits for some of these couplings are obtained. For example, the upper limits on the anomalous $tq\gamma$ couplings have been given by the CMS collaboration at 95% confidence level (CL) and assuming equal left- and right-handed couplings, which induce the branching ratios $Br(t \to c\gamma) < 0.17\%$ and $Br(t \to u\gamma) < 0.013\%$.[3] The high energy and high luminosity collider experiments will be more sensitive to the anomalous top couplings. Furthermore, the anomalous top couplings can affect the low-energy loop level processes involving the top quark. If these processes can be precisely measured, they can also give constraints on these couplings. For example, some of the K and B meson decay processes can be used to constrain the anomalous top couplings tqx.[4,5,6] Thus, studying virtual effects of the anomalous top couplings on some low-energy processes can be seen as supplement to direct detection of high energy collider experiments.

Recently, the ATLAS collaboration has announced the results at 95% CL in terms of the branching ratios $Br(t \to q\gamma)$,[7] which are $Br(t \to u\gamma) \leq 0.0061\%$ and $Br(t \to c\gamma) \leq 0.022\%$ for only the right-handed (RH) or left-handed (LH) $tq\gamma$ couplings. The future high energy collider experiments are expected to give more accurate results. Motivated by the recent ATLAS results and coming results, in this Letter we model-independently consider the effects of the anomalous $tq\gamma$ couplings on the radiative B meson decays $\bar{B} \to X_D\gamma$ and $B \to V\gamma$ with $D = d$ or s quark and V being light vector mesons ρ, ω, ϕ and K^*. The SM predictions and experimental measurements for the branching ratios of these decays have both been improved greatly in recent years. Therefore, based on Ref. [5], we reconsider the contributions of the anomalous $tq\gamma$ couplings to these decay processes and update existing constraints on the anomalous $tq\gamma$ couplings from the recent theoretical experimental results.

The Anomalous $tq\gamma$ Couplings and the Decays $\bar{B} \to X_D\gamma$. Many new physics scenarios beyond the SM can induce the anomalous top couplings, which can be uniformly described in a model-independent way by the effective Lagrangian without resorting to the detailed flavor structure of the specific new-physics model. Up to dimension-five operators, the general effective Lagrangian of the anomalous $tq\gamma$ couplings with q being u or c quark can be written as[1,8]

$$\mathcal{L} = -\frac{e}{\Lambda}\bar{q}\sigma_{\mu\nu}q^{\nu}(\lambda^{\rm L}_{tq\gamma}P_{\rm L} + \lambda^{\rm R}_{tq\gamma}P_{\rm R})tA^{\mu}, \qquad (1)$$

where $P_{\rm L,R} = (1 \mp \gamma_5)/2$ are chirality projection operators. Λ is the new-physics scale, which is taken as $\Lambda = 1$ TeV in our numerical calculation; $\lambda^{\rm L}_{tq\gamma}$ and $\lambda^{\rm R}_{tq\gamma}$ are the effective LH and RH couplings. In this study, we focus our attention on the effects of $tq\gamma$ couplings on the branching ratios for the radiative B meson decays $\bar{B} \to X_D\gamma$ and $B \to V\gamma$, thus we assume that $\lambda^{\rm L}_{tq\gamma}$ and $\lambda^{\rm R}_{tq\gamma}$ are real numbers.

Since the decay width of the top quark is domi-

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nated by the decay channel $t \to Wb$, the branching ratio of the decay $t \to q\gamma$ can be approximately expressed as

$$Br(t \to q\gamma) = \frac{\Gamma(t \to q\gamma)}{\Gamma(t \to Wb)}. \tag{2}$$

As the SM prediction for the decay width $\Gamma(t \to q\gamma)$ is exceedingly small,[1] one need only consider that contributed by the anomalous top couplings $tq\gamma$. At leading order, the decay widths $\Gamma(t \to q\gamma)$ and $\Gamma(t \to Wb)$ are given by

$$\Gamma(t \to q\gamma) = \frac{\alpha_e m_t^3}{\Lambda^2}(|\lambda^L_{tq\gamma}|^2 + |\lambda^R_{tq\gamma}|^2), \tag{3}$$

$$\Gamma(t \to Wb) = \frac{G_F m_t^3}{8\sqrt{2}\pi}|V_{tb}|^2\Big(1 - \frac{m_W^2}{m_t^2}\Big)^2\Big(1 + 2\frac{m_W^2}{m_t^2}\Big). \tag{4}$$

Here α_e and G_F are the fine structure constant and the Fermi coupling constant, m_t and m_W are the masses of the top quark and electroweak gauge boson W, respectively. In the above equations we have neglected the masses of the quarks q and b.

The decays $\bar{B} \to X_D\gamma$ with $D = d$ and s quarks are the theoretically clean and interesting FCNC processes, which are mainly contributed by the processes $b \to D\gamma$ at the partonic level. The $b \to D\gamma$ processes can be expressed by the effective Lagrangian[9]

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}V^*_{tD}V_{tb}\Big[\sum_{i=1}^{8} C_iQ_i + k_D\sum_{i=1}^{2} C_i(Q_i - Q^u_i)\Big]. \tag{5}$$

The Cabibbo–Kabayashi–Maskawa matrix element ratio $k_D = (V^*_{uD}V_{ub})/(V^*_{tD}V_{tb})$ is small for $D = s$, and it is not this case for $D = d$. C_i are the Wilson coefficients (WCs), $Q_{i=1-6}$ are the general effective four fermion operators. The dipole operators Q_7 and Q_8 are given by

$$Q_7 = \frac{e}{16\pi^2}m_b(\bar{D}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}, \tag{6}$$

$$Q_8 = \frac{g_s}{16\pi^2}m_b(\bar{D}_L\sigma^{\mu\nu}T^ab_R)G^a_{\mu\nu}. \tag{7}$$

The anomalous $tq\gamma$ couplings given by Eq. (1) can contribute to the FCNC processes $b \to D\gamma$ via two γ-penguin diagrams, one of which is proportional to $V^*_{qD}V_{tb}$ and the other is proportional to $V^*_{tD}V_{qb}$. Since $|V^*_{qD}V_{tb}| \gg |V^*_{tD}V_{qb}|$ with q being u and c quarks, the dominant contributions come from the diagram proportional to $V^*_{qD}V_{tb}$, and the contributions from the other diagram can be safely neglected. Furthermore, the anomalous $tq\gamma$ couplings contribute to the processes $b \to D\gamma$ via two independent chirality-flipped operators $m_q\bar{q}_R\sigma^{\mu\nu}t_LA$ and $m_t\bar{q}_L\sigma^{\mu\nu}t_RA$. Since $m_t \gg m_q$, we only consider the contributions from $m_t\bar{q}_L\sigma^{\mu\nu}t_RA$. Specifically, the contributions of the $tq\gamma$ couplings to the radiative decays $\bar{B} \to X_D\gamma$ can be expressed as the modified WC C_7, which can be written as[5]

$$\begin{aligned} C_7^{tc\gamma}(\mu_W) = \frac{\lambda^R_{tc\gamma}m_t}{\Lambda}\frac{V^*_{cs}}{V^*_{ts}}\Big[&-\ln\frac{\mu_W}{m_W} - \frac{1}{4} \\ &+ \frac{1}{2(x_c-1)(x_t-1)} + \frac{x_c^3}{2(x_c-1)^2(x_c-x_t)}\ln x_c \\ &+ \frac{x_t^3}{2(x_t-1)^2(x_t-x_c)}\ln x_t\Big] \end{aligned} \tag{8}$$

for the $b \to s\gamma$ process, and

$$\begin{aligned} C_7^{tu\gamma}(\mu_W) = \frac{\lambda^R_{tu\gamma}m_t}{\Lambda}\frac{V^*_{ud}}{V^*_{td}}\Big[&-\ln\frac{\mu_W}{m_W} - \frac{1}{4} \\ &+ \frac{1}{2(x_u-1)(x_t-1)} + \frac{x_u^3}{2(x_u-1)^2(x_u-x_t)}\ln x_u \\ &+ \frac{x_t^3}{2(x_t-1)^2(x_t-x_u)}\ln x_t\Big] \end{aligned} \tag{9}$$

for the $b \to d\gamma$ process. $X_q = m_q^2(\mu_W)/m_W^2$. Owing to the $tq\gamma$ couplings that do not bring any new operators, the renormalization group evolution of these WCs from the scale μ_W down to μ_b is just the same as that in the SM. It is necessary to note that, due to $|V_{cs}| > |V_{us}|$ and $|V_{ud}| > |V_{cd}|$, in the above equations we only consider the contributions of the anomalous $tc\gamma$ and $tu\gamma$ couplings to the decays $\bar{B} \to X_s\gamma$ and $\bar{B} \to X_d\gamma$, respectively.

The branching ratios of the decays $\bar{B} \to X_D\gamma$ can be generally expressed as[10]

$$\begin{aligned} &Br(\bar{B} \to X_D\gamma)_{E_\gamma > E_0} \\ &= Br(\bar{B} \to X_ce\bar{\nu})_{\rm exp}\frac{6\alpha_e}{\pi C}\Big|\frac{V^*_{tD}V_{tb}}{V_{cb}}\Big|^2[P_D(E_0) + N_D(E_0)], \end{aligned} \tag{10}$$

where $P_D(E_0)$ and $N_D(E_0)$ denote the perturbative and non-perturbative contributions, respectively. To regularize infrared-radiation divergence, the photon-energy cut E_0 must not be equal to zero. Considering the resolution of the detector, its value is phenomenologically taken as 1.6 GeV in the $\bar{B}$–meson rest frame. The factor C is

$$C = \Big|\frac{V_{ub}}{V_{cb}}\Big|^2\frac{\Gamma(\bar{B} \to X_ce\bar{\nu})}{\Gamma(\bar{B} \to X_ue\bar{\nu})}, \tag{11}$$

with the experimental value $C_{\rm exp} = 0.568 \pm 0.007 \pm 0.010$.[11]

Including the contributions of the anomalous $tq\gamma$ couplings, Eq. (10) can be simplified to[12]

$$Br(\bar{B} \to X_D\gamma) = R\Big|\frac{V^*_{tD}V_{tb}}{V_{cb}}\Big|[|C_{7D}(\mu_b)|^2 + N_D(E_\gamma)] \tag{12}$$

with

$$C_{7D}(\mu_b) = C_{7D}^{\rm SM}(\mu_b) + C_7^{tq\gamma}(\mu_b). \tag{13}$$

The WC $C_{7D}^{\rm SM}(\mu_b)$ can be determined by the next-next-leading order (NNLO) predictions for the decays

$\bar{B} \to X_D\gamma$, while $C_7^{tq\gamma}(\mu_b) = k_7 C_7^{tq\gamma}(\mu_W)$ with k_7 being assumed as 0.5696.[12] Then we have

$$R\left|\frac{V_{tD}^* V_{tb}}{V_{cb}}\right|^2 [|C_{7D}^{\rm SM}(\mu_b)+k_7 C_7^{tq\gamma}(\mu_W)]|^2 - |C_{7D}^{\rm SM}(\mu_b)|^2] = Br^{\rm TH}(\bar{B} \to X_D\gamma) - Br^{\rm SM}(\bar{B} \to X_D\gamma). \quad (14)$$

In our numerical calculation, we use the recent experimental average values obtained by the HFLAV collaboration[13] for $Br^{\rm exp}(\bar{B} \to X_D\gamma)$, while the NNLO values of $Br^{\rm SM}(\bar{B} \to X_D\gamma)$ have been given in Ref. [14], which are

$$Br^{\rm exp}(\bar{B} \to X_s\gamma) = (3.32 \pm 0.15) \times 10^{-4}, \quad (15)$$
$$Br^{\rm exp}(\bar{B} \to X_d\gamma) = (0.92 \pm 0.30) \times 10^{-5}, \quad (16)$$
$$Br^{\rm SM}(\bar{B} \to X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}, \quad (17)$$
$$Br^{\rm SM}(\bar{B} \to X_d\gamma) = (1.73^{+0.12}_{-0.22}) \times 10^{-5}, \quad (18)$$

for the minimum photon energy $E_\gamma = E_0 = 1.6\,{\rm GeV}$.

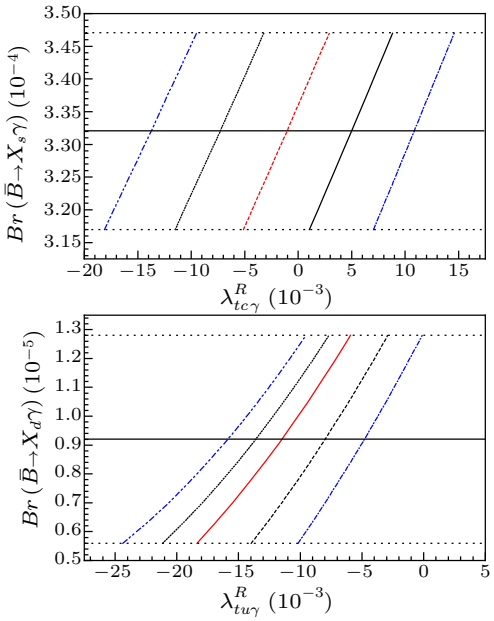

Fig. 1. The branching ratios (a) $Br(\bar{B} \to X_s\gamma)$ and (b) $Br(\bar{B} \to X_d\gamma)$ versus the coupling constants $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ for $\Lambda = 1\,{\rm TeV}$.

In Figs. 1(a) and 1(b) we plot the branching ratios $Br(\bar{B} \to X_s\gamma)$ and $Br(\bar{B} \to X_d\gamma)$ contributed by both the SM and $tq\gamma$ couplings versus the coupling constants $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ in the case of assuming the SM predictions within 1σ (dashed line) and 2σ (dotted line) ranges. The red solid lines correspond to the values of $Br^{\rm SM}[\bar{B} \to X_{d(s)}\gamma]$ taking their cental values. The horizontal solid and dotted lines represent the experimental cental value and deviations from it at $\pm 1\sigma$ error bars, respectively. One can see from Fig. 1 that the constraint from the experimental value of $Br(\bar{B} \to X_s\gamma)$ on the coupling $\lambda^{\rm R}_{tc\gamma}$ is stronger than that for the coupling $\lambda^{\rm R}_{tu\gamma}$ from $Br(\bar{B} \to X_d\gamma)$. If one demands that the theoretical predictions for $Br(\bar{B} \to X_s\gamma)$ and $Br(\bar{B} \to X_d\gamma)$ are consistent with the corresponding experimental values in the 1σ error range, then the values of $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ must be in the ranges of $-0.018 \sim 0.014$ and $-0.024 \sim -0.0001$, respectively, and there are $|\lambda^{\rm R}_{tc\gamma}| \leq 0.018$ and $|\lambda^{\rm R}_{tu\gamma}| \leq 0.024$. The predicted upper limits on $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ are both lower than those from the recent ATLAS results.[7] Our results for the anomalous $tc\gamma$ coupling are compatible with those from $Br(\bar{B} \to X_s\gamma)$ given in Ref. [5].

Table 1. The SM predictions and current experimental averages of the branching ratios $Br(B \to V\gamma)$, given in units of 10^{-6}.

Decay channel	SM	Experiment
$B^+ \to K^{*+}\gamma$	35.1 ± 7.8	39.2 ± 1.3
$B^0 \to K^{*}\gamma$	34.9 ± 7.8	41.7 ± 1.2
$B_s \to \phi\gamma$	43.3 ± 7.7	35.2 ± 3.4
$B^0 \to \rho^0\gamma$	0.65 ± 0.12	$0.86^{+0.15}_{-0.14}$
$B^+ \to \rho^+\gamma$	1.37 ± 0.26	$0.98^{+0.25}_{-0.24}$

The Anomalous $tq\gamma$ Couplings and the Decays $B \to V\gamma$. The exclusive decays $B \to V\gamma$ with V being light vector meson K^*, ρ, ω and ϕ are the same as the inclusive decays $B \to X_D\gamma$ at partonic level, which can be described by the processes $b \to D\gamma$. The relevant effective Lagrangian has been given in Eq. (5). Unlike the inclusive decays $B \to X_D\gamma$, which can be calculated perturbatively with high precision, the exclusive decays $B \to V\gamma$ become complicated due to considerable hadronic uncertainties.[15] However, various technical methods have been developed to study these decay processes and are not reviewed here.

The branching ratios of the decays $B \to V\gamma$ can be generally written as[16]

$$Br(B \to V\gamma) = \frac{G_{\rm F}^2 \alpha_{\rm e} m_B^3 m_b^2 \tau_B}{32\pi^4} s\left(1 - \frac{m_V^2}{m_B^2}\right)^3 |V_{tD}^* V_{tb}|^2 \cdot [T_1^V(0,\mu_b)]^2 |C_7^t(\mu_b) + k_D C_7^u(\mu_b)|^2 = R_D^V |C_7^t(\mu_b) + k_D C_7^u(\mu_b)|^2, \quad (19)$$

where τ_B is the lifetime of the meson B; m_B, m_b and m_V are the masses of the mason B, bottom quark b and light vector mason V, respectively. $T_1^V(0,\mu_b)$ is the process dependent form factor at $q^2 = 0$ and the scale μ_b. The factor $s = 1/2$ for ρ^0 and ω, while $s = 1$ for other light vector mesons.

To consider the contributions of the anomalous $tq\gamma$ couplings to the decays $B \to V\gamma$, we define the relative correction parameter A^V as

$$A^V = \frac{|C_7^t(\mu_b) + k_D C_7^u(\mu_b)|^2}{|C_7^{t,{\rm SM}}(\mu_b) + k_D C_7^{u,{\rm SM}}(\mu_b)|^2}, \quad (20)$$

where $C_7^i(\mu_b)$ contains the contributions from both the SM and the anomalous $tq\gamma$ couplings.

It is obvious that, for the parameter A^V, most of the high-order corrections and hadronic uncertainties cancel between numerator and denominator, making A^V sensitive to new-physics effects. Using the relation $A^V \leq Br^{\rm exp}(B \to V\gamma)/Br^{\rm SM}(B \to V\gamma)$, we

can obtain the constraints on the anomalous $tq\gamma$ couplings. In our numerical estimation, we will take the values of $Br^{\rm exp}(B \to V\gamma)$ as the current experimental averages,[13] which are collected in Table 1. The corresponding SM predictions are also listed in Table 1, which are given in Ref. [17] and references therein. The branching ratio of the decay $B_s \to \phi\gamma$ is the time-integrated $\bar{Br}(B_s \to \phi\gamma)$. Although the SM predictions and experimental measurements for $Br(B \to V\gamma)$ have not reached the expected precision, they agree with each other at the level of 1σ. Thus we expect that these decay processes can also give constraints on the anomalous $tq\gamma$ couplings. Our numerical results are summarized in Table 2. For comparison, the upper bounds on the couplings $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ from the recent ATLAS results[7] are also shown. One can see from Table 2 that the experimental measured values of $Br(B \to V\gamma)$ can indeed give constraints on the coupling constants $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$, which are comparable to those from the decays $B \to X_D\gamma$ and lower than the ATLAS results. The SM predictions and experimental measurements for $Br(B \to V\gamma)$ in this study and Ref. [5] differ from each other, so our results are slightly different from those given in Ref. [5].

Table 2. Constraints on the couplings $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ from the decays $B \to V\gamma$ for $\Lambda = 1$ TeV.

Decay channel	$\lvert\lambda^{\rm R}_{tc\gamma}\rvert$	$\lvert\lambda^{\rm R}_{tu\gamma}\rvert$
$B^+ \to K^{*+}\gamma$	0.0143	
$B^0 \to K^*\gamma$	0.0209	
$B_s \to \phi\gamma$	0.0275	
$B^0 \to \rho^0\gamma$		0.0103
$B^+ \to \rho^+\gamma$		0.0111
ATLAS results	0.0902	0.0475

In summary, radiative B meson decay plays an important role in precision of testing the SM and detecting the virtual effects of new physics beyond the SM. We reconsider the impacts of the anomalous $tq\gamma$ couplings on the radiative B meson decays $B \to X_{d(s)}\gamma$ and $B \to V\gamma$ in a model-independent way. It is found that the anomalous top couplings $tc\gamma$ and $tu\gamma$ can generate significant contributions to the decays $B \to X_s\gamma[B \to K^*(\phi)\gamma]$ and $B \to X_d\gamma(B \to \rho\gamma)$, respectively. With the current experimental average values of the branching ratios, the constraints on the couplings $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ are obtained. The 1σ upper bounds on $\lambda^{\rm R}_{tc\gamma}$ and $\lambda^{\rm R}_{tu\gamma}$ from the decay $\bar{B} \to X_{s(d)}\gamma$ are 0.018 and 0.024, respectively. The decays $B \to V\gamma$ can also generate strict constraints on these couplings, which are comparable to those from the decays $B \to X_D\gamma$.

References

[1] Eilam G, Hewett J L and Soni A 1991 *Phys. Rev. D* **44** 1473 [Erratum-ibid 1999 *Phys. Rev. D* **59** 039901]
Aguilar-Saavedra J A 2004 *Acta Phys. Pol. B* **35** 2695
Abbas G, Celis A, Li X Q, Lu J and Pich A 2015 *J. High Energy Phys.* **2015(06)** 005

[2] Atwood D, Reina L and Soni A 1996 *Phys. Rev. D* **53** 1199
Han T, Whisnant K, Young B L and Zhang X 1997 *Phys. Rev. D* **55** 7241
Lopez J L, Nanopoulos D V and Rangarajan R 1997 *Phys. Rev. D* **56** 3100
Aguilar-Saavedra J A and Nobre B M 2003 *Phys. Lett. B* **553** 251
Agashe G P K and Soni A 2005 *Phys. Rev. D* **71** 016002
Fajfer S and Kamenik J F 2007 *J. High Energy Phys.* **2007(12)** 074
Cao J J, Eilam G, Frank M *et al.* 2007 *Phys. Rev. D* **75** 075021
Baum I, Eilam G and Bar-Shalom S 2008 *Phys. Rev. D* **77** 113008
Zhang J J, Li C S, Gao J *et al.* 2009 *Phys. Rev. Lett.* **102** 072001
Gaitán R, Martinez R, de Oca J H M and Garcés E A 2018 *Phys. Rev. D* **98** 035031
Chiang C W, Dey U K and Jha T 2019 *Eur. Phys. J. Plus* **134** 210

[3] Khachatryan V *et al.* [CMS Collaboration] 2016 *J. High Energy Phys.* **2016(04)** 035

[4] Burdman G, Gonzalez-Garcia M C and Novaes S F 2000 *Phys. Rev. D* **61** 114016
Lee K Y 2006 *Phys. Lett. B* **632** 99
Fox P J, Ligeti Z, Papucci M, Perez G and Schwartz M D 2008 *Phys. Rev. D* **78** 054008
Lee J P and Lee K Y 2008 *Phys. Rev. D* **78** 056004

[5] Yuan X B, Hao Y and Yang Y D 2011 *Phys. Rev. D* **83** 013004
Li X Q, Yang Y D and Yuan X B 2011 *J. High Energy Phys.* **2011(08)** 075

[6] Li X Q, Yang Y D and Yuan X B 2012 *J. High Energy Phys.* **2012(03)** 018
Gong H, Yang Y D and Yuan X B 2013 *J. High Energy Phys.* **2013(05)** 062
Chen C and Nomura T 2019 *Eur. Phys. J. C* **79** 644
Kumbhakar S and Saini J 2020 *Eur. Phys. J. Plus* **135** 330

[7] Aad G, Abbott B, Abbott D C *et al.* [ATLAS Collaboration] 2020 *Phys. Lett. B* **800** 135082

[8] Bernreuther W 2008 *J. Phys. G* **35** 083001
Aguilar-Saavedra J A 2009 *Nucl. Phys. B* **812** 181

[9] Buchalla G, Buras A J and Lautenbacher M E 1996 *Rev. Mod. Phys.* **68** 1125
Chetyrkin K G, Misiak M and Munz M 1997 *Phys. Lett. B* **400** 206 [Erratum: 1998 *Phys. Lett. B* **425** 414]
Borzumati F and Greub C 1998 *Phys. Rev. D* **58** 74004
Gambino P and Misiak M 2001 *Nucl. Phys. B* **611** 338

[10] Hurth T, Lunghi E and Porod W 2005 *Nucl. Phys. B* **704** 56
Misiak M and Steinhauser M 2007 *Nucl. Phys. B* **764** 62
Benzke M, Lee S J, Neubert M and Paz G 2010 *J. High Energy Phys.* **2010(08)** 099

[11] Alberti A, Gambino P, Healey K J and Nandi S 2015 *Phys. Rev. Lett.* **114** 061802

[12] Buras A J, Merlo L and Stamou E 2011 *J. High Energy Phys.* **2011(08)** 124
Crivellin A and Mercolli L 2011 *Phys. Rev. D* **84** 114005

[13] Amhis Y S *et al.* [HFLAV Collaboration] 2019 arXiv:1909.12524[hep-ex]

[14] Misiak M *et al.* 2015 *Phys. Rev. Lett.* **114** 221801
Misiak M, Rehman A and Steinhauser M 2020 *J. High Energy Phys.* **2020(06)** 175

[15] For a review, see e.g.: Hurth T and Nakao M 2010 *Annu. Rev. Nucl. Part. Sci.* **60** 645

[16] Beneke M, Feldmann T and Seidel D 2005 *Eur. Phys. J. C* **41** 173
Ball P, Jones G W and Zwicky R 2007 *Phys. Rev. D* **75** 054004

[17] Paul A and Straub D M 2017 *J. High Energy Phys.* **2017(04)** 027
Ali A 2016 *Int. J. Mod. Phys. A* **31** 1630036